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Combined Heat and Power Generation Systems for Optimum Environmental and Economic Performance: A Case Study in Catalonia

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To my wife, Noelia – her unconditional support helps me get everything I set out

Being with you is the most beautiful, lovely and wonderful thing that ever happened to me. Thanks for making me happy and fill my life with joy whenever you reward me with your smile.

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Abstract

In the current energy conjunction, with an expected growth of energy consumption in a context of fossil fuel depletion, more focus is being placed on renewable energy sources (RES) for electricity generation. To enhance their deployment worldwide, hybrid renewable energy systems (HRES) are a trendy alternative, because they can effectively take advantage of scalability and flexibility of these energy sources, since combining two or more allows counteracting the weaknesses of a stochastic renewable energy source with the strengths of another or with the predictability of a non-renewable energy source.

This work presents an optimization methodology that was developed for life cycle cost optimization and multi-objective cost and environmental impact optimization of a grid-connected HRES based on solar photovoltaic, wind and biomass power. In such a system, biomass power seeks to take advantage of locally available forest wood biomass in the form of wood chips to provide energy in periods when the photovoltaic (PV) and wind power generated are not enough to match the existing demand and, additionally, produce thermal energy when a combined heat and power (CHP) scheme is adopted. The developed model was tested in a sample township in central Catalonia using real wind, solar irradiation and electricity demand data from a certain location on an hourly basis.

To assess different situations and system layouts, four different case studies were carried out and the model was adapted to each of the situations analyzed. Sensitivity analyses that allowed detecting to which variables the system was more sensitive in each situation were performed. In all cases, the model responds well to changes in the input parameters and variables while providing trustworthy sizing solutions.

When looking to a grid-connected HRES consisting of PV and wind power technologies, the results of its cost optimization show that it would be economically profitable in the studied rural township in the Mediterranean climate region of central Catalonia (Spain), being the system paid off after 18 years of operation out of 25 years of system lifetime.

Placing the focus into a grid-connected PV-wind-biomass HRES, the results show that such a system could be installed with smaller upfront investments than the previous case, counteracted by higher life-cycle costs. However, such a system would have benefits in terms of energy autonomy and environment quality improvement, as well as in term of job opportunity creation as biomass is the RES with greater impact on local job opportunities creation.

The same system was also analyzed under a multi-objective perspective, considering not only its life-cycle cost, but also its life-cycle environmental impact. In that case, the results show that they are contradicting criteria. Low environmental impact layouts highly dependent on RES

have higher costs than the ones more reliant on the electricity from the public grid, which present high environmental impact. Results also show that improving the rate of return on investment in HRES would be a very beneficial measure to encourage the use of renewable energies for electricity production, as it has significant positive outcomes in terms of both cost and environmental impact reduction.

The last hypothesis analyzed was the possibility of adopting a CHP scheme. In that case, the system showed lower return on investment rates, making it profitable after around 10 years that are required to pay back the initial investment. That is a result of the usage of thermal energy produced through biomass conversion, which makes more efficient the whole system as that energy is, otherwise, thrown away. The trade-offs between cost and environmental impact show again that small investments on renewable energies (RE) have great returns in terms of environmental impact reduction, especially when the starting point is the current grid situation with more than 50% of energy sources being fossil fuel-based with their associated environmental impact.

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Nomenclature

RES	Renewable energy source	kW/kWh	Kilowatt/kilowatt hour
HRES	Hybrid renewable energy system	MW/MWh	Megawatt/Megawatt hour
PV	Photovoltaic	kWe/MWe	Kilowatt/Megawatt of electric power
CHP	Combined Heat and Power	kWth/MWth	Kilowatt/Megawatt of thermal energy
RE	Renewable energy	O&M	Operation and maintenance
LCA	Life cycle assessment	PHS	Pumped hydro storage
WOK	Web of knowledge	CAES	Compressed air electricity storage
CO_2	Carbon dioxide	SMES	Superconduction magnetic energy storage
GHG	Greenhouse gases	BESS	Battery energy storage system
CH_4	Methane	GA	Genetic algorithm
N_2O	Nitrous oxide	MILP	Mixed integer linear programming
EU	European Union	PSO	Particle swarm optimization
US	United States	OECD	Organization for economic cooperation and development
DH ó DHS	District heating (systems)	EPA	Environmental Protection Agency
CCHP	Combined cooling, heat and power	OMIE	Nominated Electricity Market Operator (Spanish acronym)
ICE	Internal combustion engine	kWp	Kilowatt peak
GT	Gas turbine	IPCC	Intergovernmental panel for Climate Change
ST	Steam turbine	NREL	National renewable energy laboratory
ORC	Organic Rankine cycle	NPV	Net present value
BIGCC	Biomass integrated gasification combined cycle	EI	Environmental impact
HRSG	Heat recovery steam generator	WT	Wind turbine
LHV	Lower heating value	m^2	Square meters
HHV	Higher heating value	IDAE	Spanish Institute for energy diversification and saving

1. Introduction

The present research is found in the current context of fluctuating energy prices, fossil fuel depletion and global climate change as a path to effectively close some research gaps in the field of hybrid renewable energy systems for electricity generation.

A hybrid renewable energy system (HRES) is an electricity generation system that, appropriately used as a substitute for conventional non-renewable and centralized electricity production plants, will help to move from a centralized generation scheme towards a distributed generation structure while reducing the carbon footprint of electricity generated and empowering consumers as self-generators of their own electricity consumed.

In this introduction it is sought to introduce (see §0 and 1.2) and formulate (see §1.4) the problem that has been identified and that will be tried to address with the current research, as well as to set out the objectives, including the main purpose and the specific and secondary objectives, and the hypotheses of this research.

1.1. Statement of the Problem

Current world energy price are trending towards a generalized increase in price as a result of the volatility and growth of fossil fuels price in the global market. Moreover, in the recent decades there has been a growing concern about the climate change and its causes, among which highlight the emissions caused by the industrial activity and, especially, by fossil fuels combustion.

Spain, as an industrialized country, is not exempt of these problems and in the case of energy usage, it has a very high-emitting electricity production system due to the usage of fossil fuels for more than fifty percent of the production of electricity [1]. In addition to the emissions derived from such circumstance, there is also a high energy dependency from external countries [2], as Spain does not have indigenous fossil fuel resources.

Conversely, renewable energy sources (RESs) are a more clean form of energy production with very low carbon emission patterns. REs have the advantage of being widely available all over the world. The usage of this form of energy is a goal worth pursuing from the environmental, social and economic points of view. REs systems would also reduce the energy dependency of the country as they are indigenous energy sources.

Among all the regions of Spain, Catalonia is one of the autonomous communities with more forest biomass availability [3]. In addition, it also has great wind resource availability due to its strategic situation near the Mediterranean Sea and mostly plane orography, and a high solar irradiation thanks to its privileged Mediterranean climate. However, there is a missed latent potential for generating electricity from these renewable resources.

One mechanism to enhance the development of renewable energy usage is the transition to a distributed generation scheme because one of the main drawbacks of renewable energies is their low spatial density. Another of the disadvantages of RESs is their inherent variability caused by their weather-dependency.

HRES would be effective means to face these disadvantages of RES that complicate their deployment. A HRES effectively combine two or more energy sources, being at least one of them renewable, to produce electricity with higher reliability than a single RES-based system would do. Therefore, the weakness of availability of one energy source can be counteracted by a strength of another as the availability patterns of solar and wind resources have been proven to do [4–6]. However, little work has been done in the field of HRES design and optimization that would help to reduce the high capital investments required for a HRES installation or to reduce their payback periods in order to achieve an earlier capital recovery and profit-making. Moreover, the environmental impact and reliability of HRES could also be improved thanks to optimization procedures, improving the global performance of such kind of electricity production systems.

1.2. Significance of the Problem

The transition to a distributed electricity generation scheme based on renewable energy production is an important goal of many industrialized countries because of the advantages that would derive from such change. Not only CO_2 emissions and costs associated to energy production and electricity transport losses would fall, but also the transition to the Smart Grid in a context of increased energy independency would be enhanced, enabling also the creation of own-production units for consumers [7].

In addition, renewable energy production is a key industrial sector in Spain, and more employment could be created, especially in rural areas where the availability of forest biomass would make it possible to strengthen the industrial activity in biomass harvesting, transport and pre-processing steps.

Moreover, the expected transition from a fossil fuel-driven fleet into an electricity-driven fleet, especially among industrialized countries, will add up a significant number of loads into the grid (the EU target for Spain is 2,500,000 electric vehicles by 2020 [8]) requiring grid improvement and installed generation power increase. In this context, the installation of HRESs would improve grid resilience to such expected demand increase while also assuring that electricity generation patterns are more sustainable and environmentally-friendly.

Optimization of HRES is an effective means for the pursuit of the aforementioned goals, and would reduce the drawbacks that these systems have for their deployment.

1.3. Objectives

To effectively deal with the stated problem (see §1.1 and §1.2), the objectives detailed in the following subsections have been set. They have been divided into a main objective that corresponds to the general purpose of the research (see §3.1), and a number of specific and particular objectives (see §3.2). Some complimentary and secondary objectives that will be indirectly addressed throughout the research have been also set (see §3.3).

Additionally, a number of tasks have been also laid out (see §3.4), tasks that will be addressed through the methodology explained in the following section (see §4) and that will serve as research path milestones.

1.3.1. Main objective/Statement of purpose

The main purpose of this research was to develop a model of energy production for HRES and to optimize system sizing according to a minimum life-cycle cost and/or minimum environmental impact criteria, provided that it fulfilled some constraints such as supplying a certain power demand or combined heat and power demand or using forest biomass at a sustainable rate, to name but a few.

The model of HRES combined the renewable energy sources of solar irradiation, wind and forest biomass, together with a grid connection that increases flexibility of the system.

1.3.2. Specific and particular objectives

With aim to address the aforementioned purpose, the researcher addressed the following specific objectives:

- Definition of which is, among the currently available optimization methodologies, the most appropriate one for economic cost and/or environmental impact minimization.

- Development of an algorithm based on the selected optimization methodology to optimize the following HRES parameters for an electricity generation system:
    - Cost of the system throughout lifetime.
    - Multi-objective optimization of both cost and environmental impact of the system throughout lifetime.
- Development of an algorithm based on the selected optimization methodology to optimize the following HRES parameters for a combined heat and power system:
    - Multi-objective optimization of both cost and environmental impact of the system throughout lifetime.
- Although the developed systematic approach is expected to be of general application, a validation of the procedure through a case study at a township scale will be done as follows:
    - Optimization of a grid-connected HRES designed to meet the electricity demand of a certain location from the following points of view:
        - Cost minimization
        - Cost and environmental impact minimization (multi-objective optimization)
    - Optimization of a grid-connected HRES designed to meet both the electricity and heat demand of a certain location from the following point of view:
        - Cost and environmental impact minimization (multi-objective optimization)

1.3.3. Complementary objectives and Secondary objectives

Aside from the specific objectives described above, this research also entails addressing some additional objectives. These include the following ones:

- Establish cooperation and collaboration relationships with local governmental authorities to make realistic and feasible suggestions about HRES for electricity or combined heat and power production at a township scale.
- Encourage the transition from a centralized generation scheme towards a distributed generation scheme through the minimization of costs and environmental impact of HRESs implementable at regional level.
- Enhance the creation of employment opportunities in rural areas of Catalonia through the development of economically, environmentally and socially sustainable economic activities in the field of electricity production using RESs.

- Improve the level of awareness of local population about the importance and benefits of adopting a decentralized electricity generation scheme as well as to inform them about what does it take to make such transition and how they contribute to it.

1.4. Hypotheses

The present research will be made upon the following hypotheses:

- The best obtained weather data for wind speed and solar irradiation are reliable and consistent since they come from public Meteorological services.
- The best obtained demand data are reliable and consistent since they come from utilities.
- The electricity demand of a single town can be extrapolated from aggregated data of similar regions in terms of population distribution and economic activity, if necessary.
- The environmental impact of an electricity production system can be assessed using the CO_2 emissions associated to its entire life time.
- The life cycle environmental impact can be quantified using life cycle assessment (LCA) data from available literature for all the technologies.
- The thermal energy demand can be estimated by means of a thermal balance of standard households in the township under study.
- Based on the above-mentioned hypotheses, a HRES based on solar photovoltaic power, wind power and forest biomass power can be designed, modelled and optimized in terms of minimum cost and/or environmental impact based on the renewable energy production patterns and the electricity demand of a certain region.

2. State of the art

The literature review is a very important research stage aimed to achieve a good and deep understanding of the current state of the art in the field of study. It is important to do a thorough search and review process in order to be aware of the stage at which the scientific knowledge is and to better set up the goals of the research and to identify the novelty and relevance of it.

The main topics covered were renewable energy production from solar PV, wind and forest wood biomass modelling and optimization of sizing of renewable energy production systems.

In the following sections, the methodology of the literature review performed, as well as the main information obtained are synthesized and explained.

2.1. Methodology for the review of the literature

This state of the art assessment process has been based on the use of several scientific sources, mainly through the thorough and comprehensive search in electronic databases among which highlight:

- ScienceDirect
- IEEEXplore
- Google Scholar
- Thomson Reuters Web of Knowledge (WOK)

After an initial screening of the main journals dedicated to the topics under study, i.e. renewable energy production, hybrid renewable energy systems and optimization, the following ones have been selected as journals of interest for both basing the research and publishing the useful outcomes of it:

- Applied Energy
- Applied Thermal Energy
- Energy Conversion and Management
- Energy Conversion, IEEE transactions on
- Renewable Energy
- Renewable and Sustainable Energy Reviews
- Solar Energy
- Energy Policy

The most used keywords have been: *optimization*, *hybrid (renewable) energy system*, *solar PV*, *wind*, *biomass*, *biomass gasification*, *CHP*, *genetic algorithm* and *multi-objective optimization*, among many more.

The accessed papers can be classified in four wide categories: those related with renewable energy power production with special emphasis on those related with biomass combined heat and power production and the calculation of thermal demand, those related with life-cycle environmental impact of renewable energy production, those related with optimization methodologies and those related hybrid renewable energy systems.

2.2. Renewable energy sources (RES) – General description

This section summarizes the main findings that the literature review has led to. First, a short introduction with a general description of the importance that RES have gained over past decades and the reasons behind that are presented. Then, a description of the most widely used RES, namely wind, solar and biomass energy sources is presented. It is important to highlight that the performed literature review was focused on the local context of the study, central Catalonia. This is why the literature review was extensively done on biomass resource and why also wind and solar power are presented, whereas other relevant sources such as hydro or other less relevant are not presented here.

2.2.1. Justification of RES usage

Over the past decades, the levels of greenhouse gases (GHG) in the atmosphere and, specifically, of the most prevalent one, carbon dioxide (CO_2), have raised way over safe limits of Earth's boundaries [9]. Particularly, CO_2 levels have risen from around 280 ppm of pre-industrial era [9,10] to near-400 ppm at present time [11] continuing to grow at increasing rates [12]. Among the identified causes of worldwide GHG emissions, energy production and consumption is claimed to be the main one. In particular, CO_2 emitted from the combustion of fossil fuels for transportation, industry, electricity and heat production is the major contributor to the greenhouse effect [13]. Energy production is expected to have continuous growth during next decades [14], shaping a context of current and future global environmental issues, namely sea-level rise, weather pattern changes [15], worsening agriculture production [16] and producing water shortages in some places and intense flooding in some others [17,18]. Such changes will likely have significant implications in ecology, economics and public conflicts and policy [19]. In addition to these environmental concerns, fossil fuels have another important drawback: despite the fact that they are the main energy source throughout the world, they entered in a depletion process over the last decades, a concern to be added to the environmental degradation that they contribute to [14,20]. In a free-market economy, this means increasing prices and thus decreasing competitiveness. Moreover, in countries with low or even no indigenous fossil fuel availability, their usage results in energy dependency on foreign countries.

REs are an appealing alternative for tackling the climate change global issue, which is widely recognized as the major challenge that is going to be faced in the upcoming future due to the major implications in terms of water resources stress increases [17,18] or global air and ocean temperature increases [15], among others. These major changes in climate patterns are already being observed and there is scientific consensus on being particularly affected by the anthropogenic global GHG emissions increase [15], including CO_2, methane (CH_4) and nitrous oxide (N_2O). In particular, the current anthropogenic GHG emissions could already be beyond planet boundaries [9], hence being of critical importance to deal with such issue in a quick and effective manner.

In this context, REs are an alternative worth exploring, as they are effective means for climate change prevention and mitigation [21], with undeniable external benefits in terms of environment quality and economic value, especially in the case of PV power, wind power and biomass power [22], which are the focus of the present work.

These sources of energy are often indigenous sources of virtually perpetual energy, scalable and carbon neutral [23], helping to reduce the energy dependency of countries that implement them at mid-scale.

These technologies will help to implement the distributed generation model which consists in energy production close to both renewable energy sources (RES) and consumption. In fact, they are currently considered viable and even the best available solution in certain conditions for microgrid implementation [24] thanks to the easy scalability of small modular units in which the generation from these source rely on [25]. Consequently, large production plants could be partially substituted by small- and micro-scale plants [7]. Distributed generation, in turn, has been labeled as a key tool to address the problems of security of supply, CO_2 emissions and to improve the efficiency of energy systems [26], as well as to overcome the problem of rising electricity costs and shortages [23]. Distributed generation has social benefits in terms of encouragement of development in rural areas by providing electricity at those places where the grid transmission is not reliable [23,27] and by generating new income opportunities through revaluation of local resources [28]. Therefore, several public policies have been set up in many countries in order to increase the share of RESs to the electricity supply, including the goal of reaching 33% of electricity share in the European Union (EU) and the United States (US) or the goal of 35% share in Asian countries such as China or India by 2020.

Hence, RESs could address several issues, highlighting an improvement of security of supply, reduction of CO_2 emissions as these sources are carbon-free (PV or wind power) or carbon neutral (biomass), being thus a viable alternative to de-carbonize the energy generation, and improve energy systems' efficiency [26] as a result of energy transport requirements reductions. RESs would also help to develop rural areas with the creation of job opportunities, especially in the case of forest wood biomass resource, which requires labor force in the fields of forest management and harvesting [29] and helps preventing landscape quality and biodiversity [30]; and revaluation of local resources currently misused [28]. Besides, in isolated regions or communities, they could help to reduce electricity generation costs because they are currently economically competitive [31,32].

However, REs have an inherent stochastic nature, which is their main drawback. Whereas fossil fuel-based energy production is predictable and fully controllable, RE-based electricity generation is highly dependent on weather conditions which are not predictable with the accuracy required for electricity supply. To overcome this issue, HRES combining two or more energy sources can partially counteract the weaknesses of one source with the strengths of another [14]. For example, wind and solar irradiation daily and even seasonal patterns complement each other. In addition, they can be combined with a more predictable energy source such as biomass power that can be dispatched on demand [15].

2.2.2. Biomass power production and CHP

This section is aimed to review the current performance of the available technological alternatives to convert biomass into electricity with or without heat production. The focus is placed on those technologies suitable for the usage of local forest wood chips to lower the transportation requirements and thus the environmental impact of the entire electricity supply chain. In the context of the Mediterranean basin, due to the relatively low growth rates of indigenous tree species, this means that only small-scale and micro-scale technologies are suitable because at greater scales the available feedstock would be insufficient to meet the demand of a stand-alone biomass large-scale power plant.

The review does not only consider electricity generation technologies but also CHP technologies that take advantage of the excess heat from combustion of solid or gasified biomass. Therefore, the analysis of performance includes both the electrical efficiency, which accounts for the performance of a technology when producing electricity, and the total efficiency, which accounts for electrical and thermal efficiencies. The usage of CHP applications improve the efficiency of a power plant by a factor between 2 and 3 because of the easiness to harness the thermal energy compared with the electrical energy. The main drawback, however, is that it is required a heat demand close to the production plant due to the difficulty to transport and distribute this kind of energy, especially in the Mediterranean region where district heating systems (DHS) are not generalized.

It is widely claimed that among all the RES, biomass is one of the most promising options. Particularly, the fact of being based on proven technologies, its flexibility of operation and installation [23], easy and efficient scalability and low and stable price because of being often a waste product [27] are strong reasons for its use. Moreover, biomass is the only renewable source that can be used in solid, liquid or gaseous form [33,34], which allows using it for industrial purposes in the case of solid biomass, for electricity and heat production when it is in both gaseous and solid phases, and for transportation purposes for liquid biofuels [35]. It also offers the possibility of having the plants near the resource, thus minimizing transportation costs [36] that lead to environmental impact reduction due to a more efficient utilization [37]. In addition, biomass is, together with hydro, the unique RES that can be stored and continuously used to have a predictable output not dependent of weather [3], so it would reduce the requirement of storage systems mentioned above. Finally, another important advantage of biomass is its flexibility to be converted to several forms of energy. Therefore, combined heat and power (CHP) technologies or combined cooling heat and power (CCHP) [38], which have better efficiencies [39], lower consumption [40] and CO_2 emissions [26] than heat and electricity production individually, can be used. Biomass-fueled CHP systems have low operating and maintenance costs, high total efficiencies and low noise, vibration and emissions levels [26]. Moreover, heat pumps can be integrated with CHP plants to relocate the excess heat produced from the production site to a consumption node or to a storage facility [41]. CHP technologies reach the highest efficiencies if woody biomass is used rather than non-woody biomass [42], so it is interesting to use primary forest biomass and sub-products from sawmills for these purposes. Another important aspect to be considered is the quality of the wood chips, since current technologies require specific quality standards according to the end-user needs [43].

In Europe, nowadays, about one half of the forests are privately owned, and most of these ownerships are small-scale holdings. These holdings average between two and four hectares in Western Europe countries such as Spain and apply different management styles related to livelihood systems rather than to economic purposes [44]. In particular, in Spain most of the forest owners are retired foresters (46%) or absentee owners (41%) [44], which means that few or null proper forest management should be expected. This entails a high risk of wild fires with ecological and also economic and social implications [45], especially during the dry summer season in the Mediterranean area [46,47]. This risk has increased over the past decades in both number and severity due to increased drought conditions together with both inappropriate management practices and abandonment of forests and agricultural lands that facilitate an over-accumulation of dead fuels [48]. This lack of programmed management leads to increased homogeneity of landscape that facilitates fire continuity and propagation [49]. Hence, improved management strategies adapted to the new paradigm of warmer and drier climates and focused on fuel load reduction would reduce the risk of forest fires [48]. Otherwise, fire reduction capacity will be overwhelmed in the future due to increased dryness and droughts triggered by climate change [50].

Through the promotion of forest biomass usage as a RES in the Mediterranean basin, which is a region with high potential [51], it may be given economic value to forest resources currently untapped, sawmill operators could increase their income by converting hardwood sawmill residues to woodchips [52], rural employment in the energy sector could be created [44,53] and the national energy industry could be supported whereas partial energy independency would be achieved in rural areas. Moreover, forest management would be improved [54], but it is important to stress that new management strategies should be sustainable, preserving primary production, carbon storage capacity and biological diversity [47] while also minimizing wild fire risk and increasing their biomass productivity rates [55]. Otherwise, human pressure historically borne by Mediterranean forests, especially in the Northern rim [47], would jeopardize the continuity of those forests.

Biomass is characterized by having low energy density and by being spread, problems that increase harvesting and transportation costs [56,57]. This is the case of Mediterranean forests, where biomass availability is especially low when compared with other forested areas with less importance of dry periods and better ownership schemes. Considering this particularity of low biomass production together with the disaggregated ownership in small portions of land, it can be concluded that energy production from wood forest biomass in Mediterranean forests is, regardless of the available technology, limited to small-scale projects that would take advantage of the limited available biomass within a single or a few properties found in the vicinities of the power plant [36].

Among the forest woody biomass useful for electricity and heat generation, wood chips are one of the trendiest options. This is so because wood chips can be easily obtained and do not require additional treatment such as densification processes which are necessary for pellets production [57] nor require additional energy input in the drying process as they can be dried by only leaving them covered. Therefore less energy consumption and associated environmental impacts are involved in the wood chips process. Moreover, they are low ash-content biomass fuels [58] that do not generate co-products, and burn better than entire logs because wood chips have more contact surface with the air flow. However, pellets still dominate the wood biomass market [59] but wood chips are starting to gain importance. Nowadays, wood chips are mainly obtained from forest harvesting (from stem and whole tree wood) and remnants of forest operations, from sawmills residues and from lignocellulose energy crops [60], but their harvesting is expected to grow as they will likely be obtained from stumps and round wood as well [54].

Biomass can be converted into other forms of energy by means of biological conversion, chemical conversion and thermochemical conversion. The former, known as bio-digestion, is suitable for moist biomass as it uses microorganisms to produce gas from biomass. Chemical conversion produces biofuels such as ethanol or other chemical products such as furfural by using enzymes [61]. The latter is appropriate for dry biomass [62] as it is based on the application of heat and pressure, and is more efficient for electricity and heat generation than digestion [63,64]. Chemical conversion mechanisms are left out of this research because they are not focused on electricity generation but on biofuels production. Between biological and thermochemical conversion mechanisms, the latter are reviewed in this study because wood chips are quite dry, or can be dried without using additional amounts of energy, so these technologies are well-suited for these applications.

Thermochemical conversion of wood chips into another form of usable energy for electricity and heat production can be done essentially in two ways (primary conversion technologies): through direct combustion or gasification. It could be added pyrolysis as the third primary conversion technology, but since this process is directed to transportation fuels production [34,65] due to the maximization of liquid fraction in the process [66], and since nowadays there are no commercial plants for electricity production based on this process [67], pyrolysis is omitted in this analysis.

These primary conversion technologies are coupled with secondary conversion technologies responsible for the electricity production and, additionally, heat production. Direct combustion converts the chemical energy stored within the wood chips in thermal energy that can later be harnessed using steam engines or steam turbines and their variation of organic Rankine cycles (ORC) and with external combustion engines, also called Stirling engines. On the other hand, gasification converts the chemical energy of biomass into a low-heating value gaseous fuel, also known as syngas, which makes this process more polyvalent than direct combustion [68]. The chemical energy of this gas can be utilized by means of gas turbines, internal combustion engines (ICE) or Stirling engines as well. All mentioned conversion paths accept the use of both electricity production and CHP, depending on the exploitation or not of the excess heat available after electricity generation. Some CHP layouts combine two different secondary technologies, for example, gas turbine for electricity production and steam turbine for heat retrieval.

The different alternatives for electricity and heat production using wood chips as a fuel source are represented in Fig. 1.

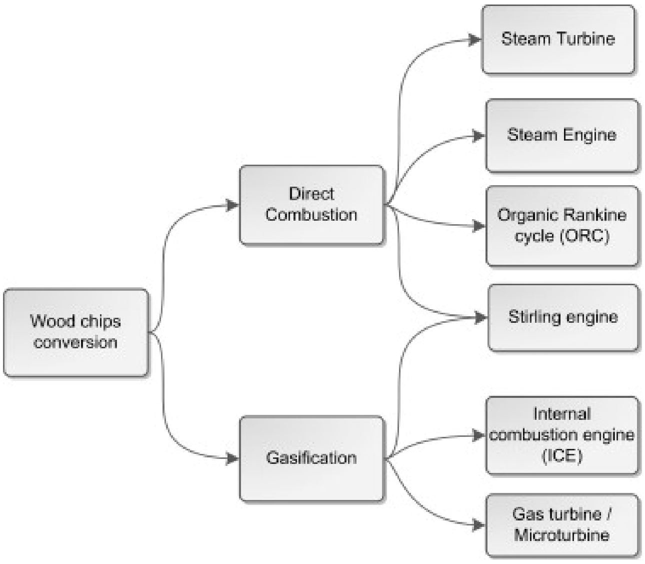


Fig. 1. Wood chips conversion paths to electricity and heat

It is noteworthy to mention that these conversion paths are nowadays at different development stages. For example, direct combustion coupled with steam turbine and gasification coupled with ICE are the most deployed options due to more commercial viability and maturity [23,69]. GTs are also appealing, while other technologies are still at demonstration, development or research stage. Therefore, the only biomass-to-electricity conversion paths currently feasible at a commercial level are the ones summarized in the figure below:

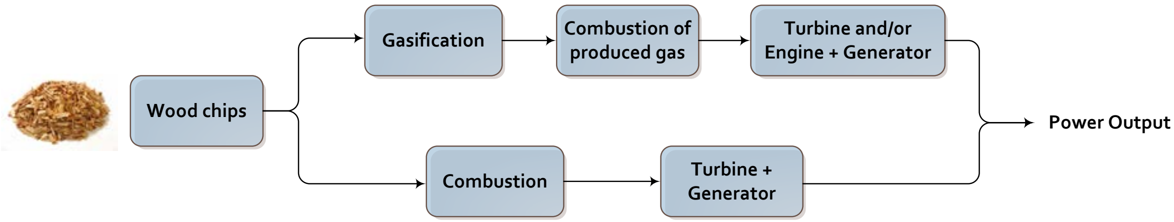


Fig. 2. Block diagram of biomass-based power generation systems

2.2.2.1. Primary conversion technologies

Direct combustion

This thermochemical process consists in the complete oxidation of biomass in an aerobic environment [66], releasing heat at the level of 800-1000 ºC, typically. Despite the fact that direct combustion applications are the most mature technologies [58] and account for more than 90% of the biomass-based worldwide capacity installed [70], they have in average higher emissions due to smaller efficiencies than gasification applications [65]. Although the heat released in the combustion process can be harnessed using several conversion technologies, steam production to then generate electricity in a steam turbine is the most common conversion path [71].

Direct combustion can be performed in different combustors, among which highlight pile burners, stoker grates, bubbling or circulating fluidized beds and suspension burners [71]. Each one has its own particularities, for example, fluidized beds are suitable for large-scale plants (>10 MWth) while stoker grates are more appropriate for small-scale layouts (<6 MWth) with higher moisture content [58]. In addition to these combustors, there are some non-conventional alternatives such as suspension burners or WholeTree®. In general terms, it can be asserted that fixed-bed grates are preferable for micro-scale applications and that increasing boiler sizes result in the usage of moving grates but the kind of fuel is also influential and hence chip boilers are more suitable for moving grates layouts [59].

Table I summarizes the different types of combustors currently available.

Table I Direct combustion technologies summary. Personal compilation based on [71]

Combustor	*Principle of operation*
Pile burner	Fuel is fed forming a pile and then combusted in a two-stage combustion chamber. Limited to cyclic operation
Stoker grate	Improved version of the pile burner by moving the grate and thus improving ash collection and spreading of the fuel. It can have continuous operation
Bubbling fluidized bed	Fuel has free movement in the combustor while an air or oxygen stream passes through it, creating equilibrium between fuel and fluid
Circulating fluidized bed	Same as bubbling fluidized bed with increased fluid velocities thus the fluid entrains the fuel
Suspension burners	Fuel is burnt suspended within the fluid
WholeTree® energy	Integrated wood conversion process including growing, harvesting, transportation and combustion of whole trees as wood fuel

Gasification

This process consists in the partial oxidation of biomass in a low-oxygen content environment [68,72,73]. The main product of this process is a low-heating value gas, called syngas, that can be used for heating and cooking purposes as well as for electricity generation [64,74]. This process also generates hydrogen, methanol or other biobased products such as alcohols or polyesters [75]. It is worth distinguishing between syngas obtained from thermochemical gasification and biogas obtained from anaerobic or aerobic digestion. Although the main components of both gases are the same, the processes and their conversion efficiencies are completely different: electricity is produced through gasification at efficiencies about 30-35% for dry biomass, dropping with higher moisture contents down to 15% for moisture contents about 70% in weight, matching the efficiency of electricity production from anaerobic digestion which do not depend of moisture content [76].

The main driving factors of the gasification reaction are the temperature, time of residence and particle size. In general, it can be asserted that higher particle sizes and times of residence lead to higher gasification rates of the fuel and the temperature increase results in an increase in hydrogen content and yield of syngas but also in a decrease in methane content and thus in lower heating value (LHV) [77].

The gasification process has several advantages, among which highlight its versatility and flexibility to be combined with different secondary conversion technologies [71]. In addition, this process allows to use biomass fuels at a wider range of moisture content than direct combustion does; and, thanks to the different gasification technologies available, i.e., the different kinds of gasifier commercially available, it can be used from as low as kilowatt-scale to as high as hundred megawatt-scale [23], which makes it highly adaptive to different niches [70].

Gasification can be performed in different reactors, called gasifiers, that may be classified according to the gasification agent (air, steam, oxygen), the operating pressure (atmospheric, pressurized), the source of heat (indirectly or directly heated) or according to the fluid-biomass contact interface [78], which is the most common one. There are, accordingly, fixed bed, fluidized bed and entrained flow reactors following the latter criterion [23,64,71,79,80].

Fixed bed reactors are characterized by having biomass fuel in an almost static position while the gasification agent flows through it. The direction in which the fluid passes through the fuel establishes where the different reaction zones are located [81] and distinguish, in turn, three different subtypes of fixed-bed reactors: updraft, downdraft and cross-flow. The first has a counter-current flow of gasification agent, the second has a co-current flow, and in the third case the fluid is introduced by one side, exiting by the opposite.

Fluidized bed reactors are characterized by introducing a third agent, the fluidizing material into the equation and thus reducing the slagging of the reaction [82] and improving the uniformity and adjustability of the temperature distribution [64,80] increasing the biomass conversion rate up to 100% [83]. According to the velocity of the gasification agent flow, two different types exist: bubbling fluidized bed and circulating fluidized bed. In the former, equilibrium is reached between the fluidizing material and the fuel, while in the latter higher velocities are achieved, so the fuel is entrained by the fluidizing material. Fast internal circulating fluidized bed is a recent improvement that includes a combustion zone in addition to the gasification zone increasing the velocity of the reaction due to increased temperature in the reactor [84].

Last type of gasifier is the entrained flow reactor, in which the fuel is introduced in powdered form together with the gasification fluid [78].

Table II summarizes the different types of gasification reactors currently available.

Table II Gasification technologies summary. Personal compilation based on [79]

Gasifier	*Principle of operation*
Fixed bed reactors	
Direct current	Gasification fluid flows in the same direction as biomass fuel
Counter current	Gasification fluid flows in the opposite direction to biomass fuel
Cross-flow	Gasification fluid is introduced from one side exiting from the opposite while biomass fuel moves up-down
Fluidized bed reactors	
Bubbling fluidized bed	Frictional forces of fluidizing material in movement and biomass fuel weight reach equilibrium
Circulating fluidized bed	Frictional forces of fluidizing material in movement are higher than biomass fuel weight so the biomass particles are entrained by the fluid
Entrained flow reactors	
Suspension flow or dust cloud	Small particles of fuel are entrained by the gasification fluid before being introduced into the reactor

2.2.2.2. Secondary conversion technologies

There are many secondary conversion technologies, some of them more appropriate for direct combustion technology and others for gasification technologies (see Fig. 1). The conversion efficiencies of these technologies vary depending on the technology used and the output scale

[85]. In general, however, it can be asserted that the bigger is the output, the higher is the efficiency regardless of the technology.

Internal combustion engine (ICE)

The internal combustion engine is a well-known and well-proven technology, widely used for transportation vehicles but also of relevance in the field of electricity generation, CHP and CCHP. ICEs comprise the Otto engine that works with spark-ignition and the Diesel engine, both requiring a liquid or gaseous fuel which is combusted in an internal combustion chamber. The former is more suitable for small-scale applications while the latter is more appropriate for large-scale ones [86]. ICEs are widely used thanks to their durability, affordability and good performance [87].

Due to their mode of operation, they have better performances with smooth consumption profiles [88]. Otherwise, some storage system can be added to the system to smoothen the consumption profile [89]. In any case, they have been labeled as an efficient solution for small- and micro-scale applications [84] due to low upfront costs and good part-load performance [38,90] so better return on investment rates are achieved at such scales of electricity generation [87].

External combustion engine (Stirling engine)

The Stirling engine is a proven technology that historically did not enjoy the significance that acquired recently. This engine is named after Robert Stirling, the inventor of the Stirling cycle in which are based the two versions of this engine, free-piston and kinematic. In this thermodynamic cycle, combustion takes place in an external combustion chamber so the technology is suitable for fuels in all phases, solid, liquid or gaseous.

Stirling engines have low maintenance requirements [26] and noise levels [7], especially when compared with the ICE [91]. These benefits, together with their good performance and high thermal efficiency and output [92], especially compared with that of its main competitor Diesel engine [93], at very low output scales make Stirling engines a suitable option for residential dwellings and other micro-scale applications. Their main drawback, however, is precisely their novelty and lack of proven operation for biomass conversion to electricity [94].

Steam engine

The steam engine is a well-known technology based on the use of steam produced through thermal evaporation of water or another working fluid to drive an engine. Its mode of operation enables it to be fueled with all kinds of fuels, although historically it has been mainly used with solid fuels.

Steam engines are well-proven technologies, with a high level of maturity. However, their relatively low performance and inability to take advantage of excess heat is driving their current replacement by steam turbines [90].

Steam turbine (ST)

Steam turbines are based on the thermodynamic Rankine cycle, a technology that, as the similar technology of the steam engine, is well-proven and mature with a high level of deployment.

As the combustion takes place in a boiler before transferring the heat through a heat exchanger to evaporate the working fluid, steam turbines accept all kinds of fuels. In the case of biomass, bark, sawdust, wood chips and pellets can be used [95]. A pre-drying stage is recommendable before the combustion in order to increase the efficiency. Otherwise, the efficiency drop may have great impact [96]. The main advantage of STs is their high time availability [87].

Organic Rankine cycle (ORC)

ORCs are a slight variation of steam turbines in which water is replaced as a working fluid by “organic” fluids. Toluene or n-pentane are used as working fluids for high-temperature ORCs with more than 200 kWe of output, thus obtaining high efficiencies and allowing the production of heat. On the other hand, for low-temperature ORCs, those with less than 200-250 kWe of output, lower efficiencies and the impossibility of setting up CHP layouts, the working fluids used are hydrocarbons [94,97]. The low vaporization temperature of these organic fluids make it possible to set up Rankine cycles with lower temperature than that of the conventional ones, thus enabling the use of low-heating value fuels like biomass, without lowering the efficiency [98–100]. As they are based on the Rankine cycle, ORCs are appropriate for combustion of solid fuels although the low working temperature make them suitable even for geothermal or solar applications [100,101].

In addition to increased efficiency of the thermodynamic cycle, ORC applications also offer the advantage of reduced blade damage risk [102], good part-load operation [103] and lack of requirement of a pre-heating stage [100], mainly due to decreased vaporization temperature of organic fluids compared with water.

Gas turbine (GT) – Biomass integrated gasification combined cycle (BIGCC)

GT technology consists in the combustion of previously compressed gaseous fuels in an internal combustion chamber and the subsequent expansion of the combustion gases in a turbine. When a gasification unit, gas cleaning unit and a heat recovery steam generator (HRSG) are integrated together with the GT, the system is called BIGCC [104–106]. BIGCC can also be laid out with a gas engine [107], but the alternative of the GT is the most deployed due to its high exhaust temperatures [87]. Inside the designation of BIGCC, there are many possible combinations depending on the gasification technology or including or not the HRSG [108]. All these conversion pathways require a gaseous fuel to operate.

BIGCC is a high-efficient process [109], especially for large-scale applications, in which BIGCC beats equivalent-size steam turbine [106] and gas engine [110] layouts. Their main drawback is that, since they are based on existing natural gas-based technology, modifications in the fuel handling system are required because syngas yields higher mass flows than natural gas due to its lower heating value. This modification can be an increase in gas pressure or a decrease in gas temperature or de-rating, the most usual alternative, at the turbine inlet [111]. In addition, such GTs are limited to large-scale applications (>1 MWe). Hence, this technology is not considered in the efficiency comparison section performed in this study.

Microturbine

Microturbines are down-scaled versions of GT, being more suitable for small-scale applications. Accordingly, microturbines can be used in places with low biomass production rates such as Mediterranean forests. The electric output of these devices ranges from a few kWe up to 500 kWe [101] although some authors limit this output to 250 kWe [26].

In microturbines, the compressor and the turbine have a solidary shaft, so less maintenance requirements are necessary due to their simplicity [7]. Their performance is quite good even with biomass-based fuels, with which better efficiencies can be achieved than with diesel fuel [86] or than with ICE technology, although being less commercially proven [83].

Other GT-based designs

Besides microturbines, other GT-based designs exist or are under development. Among them, it is worth mention externally-fired GT, evaporative GT, bottoming cycles or co-firing of GT.

The externally-fired GT is a modified version of GT in which the combustion chamber is replaced by a heat exchanger. Therefore, the combustion can take place outside the turbine [112] and thus a cleaner fluid operates the thermodynamic cycle and solid fuels are accepted for the operation besides the gaseous ones [113]. It is usual to add an auxiliary burner of high-LHV fuel, e.g. methane, to raise the temperature up to the design point of the turbine inlet [87] operating in a co-firing mode. The turbine cycle can be an open cycle with working fluid discharge or a closed loop with re-usage of the working fluid, thus reducing the maintenance requirements [114].

The evaporative GT consists in a GT layout in which water is vaporized in the air stream before combustion [115] to increase the mass flow [116] and thus the efficiency [117].

Another option is the bottoming cycle, based on the usage of the excess heat to produce more electricity through another steam cycle placed at the exhaust of the GT [101,118], providing an alternative to those situations where heat has no demand.

Finally, another appealing option, especially in terms of efficiency, is the co-firing of biomass fuels with fossil fuels [119–121]. This alternative provides a cost-effective electricity generation process even using biomass with high-moisture content [122]. In particular, biomass has a higher cost on a unit energy basis than coal, meaning that co-firing with coal is worth pursuing from an economic point of view [123]. The co-firing can be done essentially in two ways: with two cycles, the topping one fueled with fossil fuel and the bottoming one fueled with biomass; or, conversely, with a single generation cycle fueled with a mix of fossil and biomass fuels.

R&D alternatives

In addition to the above mentioned commercialized layouts, there are other layouts currently under development. Salomón, Savola [90] mention pulverized-fired GTs and powdered-fueled ICEs.

Wood-fired ICEs are also studied by [124] who claim that particulates of less than 30 microns can be used to fire a conventional Diesel engine. They state that the process is feasible but the fuel injection system should be improved to overcome the issue of matching powder feeding and dust cleaning in a continuous operation engine.

Table III summarizes the available secondary conversion technologies with a brief summary of their principles of operation.

Table III Summary of biomass conversion secondary technologies suitable for wood chips conversion. Personal compilation based on [7,23,67,69,101,106,119]

Secondary technology	*Primary technology*	*Principle of operation*
ICE (Otto, Diesel)	Gasification, Pyrolisis	Heat from combustion in an internal combustion chamber drives a piston through gas expansion
Stirling engine	Combustion Gasification Pyrolysis	Heat from combustion in an external combustion chamber drives a piston through gas expansion
Steam engine	Combustion	Steam generated through thermal evaporation of a fluid drives an engine
Steam turbine	Combustion Gasification	Steam generated through thermal evaporation of a fluid is expanded in a turbine
ORC	Combustion Gasification	Same as steam turbine with organic fluid as working fluid

Secondary technology	*Primary technology*	*Principle of operation*
GT / BIGCC	Gasification Pyrolysis	Clean gas is compressed, then is burnt in a combustion chamber by then be expanded in a turbine Gasification cycle is attached to a GT-based CHP cycle
Microturbine	Gasification	Same as GT with power output < 500 kWe
Externally-fired GT	Combustion Gasification	Same as GT with combustion chamber replaced by a heat exchanger
Evaporative GT	Gasification	GT in which water is vaporized on the air stream before combustion to increase mass flow
Bottoming cycles	Gasification	Bottoming cycle of a CHP replaced by a steam turbine to increase electricity generated
Co-firing	Combustion Gasification	(1) Mix of biomass and fossil fuels (2) Topping cycle fueled with a fossil fuel and bottoming cycle fueled with biomass
Pulverized wood-fired GT, ICE or Stirling	Combustion	GT, Diesel or Stirling engine fired with micro-particulates of pulverized wood

2.2.2.3. Technology efficiencies comparison

This section is aimed to describe the electrical and total efficiencies of actual and simulated power plants found in the literature. The efficiencies account for the entire process at the power plant, and are calculated using the LHV of the fuel, except otherwise indicated. The choice of LHV is justified because the moisture content of biomass fuels is not homogeneous among different types of biomass, sites and applications, thereby, since LHV accounts for the moisture content, it provides a better estimate of the actual conditions at which the power plant is operating.

The electrical efficiency of a certain power plant can be defined as the electrical power output (Pout) divided by the chemical energy stored within the fuel at the entrance of the power plant, which can be obtained, in turn, multiplying the LHV of the fuel by the amount of fuel required for the generation of electricity.

$$\eta_e = \frac{P_{out}(kWe)}{LHV\ (MJ/kg) \cdot m(kg)} \tag{1}$$

The total efficiency includes the thermal output of CHP plants (H_{out}). Thereby, it can be calculated as follows:

$$\eta_e = \frac{P_{out}(kWe) + H_{out}(kWth)}{LHV\ (MJ/kg) \cdot m(kg)} \tag{2}$$

When looking at the efficiencies of the different available alternatives, it is important to distinguish between the different scales of energy production. Hence, micro-scale technologies, those with less than 50 kWe of output; small-scale technologies, with output between 50 kWe and 1 MWe; and large-scale technologies, with an electrical output greater than 1 MWe, exist [125].

ICEs are usually coupled with gasification in biomass-based plants since they are based on natural gas technology.

In the literature, it can be found efficiencies and other technical characteristics for natural gas fueled ICE micro-CHP systems, which range between 20% and 31% for electricity generation and between 50% and 90% for cogeneration [7,86,126,127]. Small-scale devices reach a slightly higher efficiencies of 25% and 90% at 100 kWe of power output [92].

Data of actual power generation or CHP plants fueled with wood chips or similar biomass fuels are of more interest for the present review. Electrical efficiencies of micro-scale plants are between 13% and 25% [81,84,128–133] and total efficiencies between 60% and 74% [130,132]. At small-scale level, slight increases are found: electrical efficiencies are 12.5-28% [62,107,128,129,134,135] and total efficiencies can reach 96% [128]. As expected, large-scale plants perform better. In particular, electrical efficiencies of 25-30% have been proven [107,128] with total efficiencies around 81% [128].

Stirling engines are deployed for smaller applications, namely for micro-and small-scale CHP systems due to their high thermal efficiency even with low electrical efficiencies. In particular, micro-CHP Stirling-based units have electrical efficiencies of 9.2-33% while the total efficiencies range between 65% and 92% [7,26,86,126,136–141]. At small-scale, Stirling engines reach 12-35% of electrical efficiency and 85-90% of total efficiency [92,94]. These figures are supported by Simbolotti [80], who claim that efficiencies are around 11-20% for Stirling engines with less than 100 kWe of electric output. Alanne and Saari [88] provide data for natural gas-fueled Stirling engines, which reach electrical efficiencies around 25-35% compared with the 15% obtained using syngas at similar scale. Large-scale data is not available for Stirling engines since these devices are only suitable for micro- and small-scale applications whereas they are rapidly beaten at greater sizes.

Data found for steam engines show low efficiencies: at micro-scale, 16% of electrical efficiency is reached [27] and a small-scale CHP system has been proven to reach 10% and 80% of electrical and total efficiencies [37].

More data can be found for STs. In addition, this technology coupled to a combustor is especially suitable for excess heat usage and, together with the high maturity degree have made it the most deployed biomass conversion solution for the last decades. At large-scale, electrical efficiencies can be as low as 15% reaching up to 44% as the output power increases [85,95,96,119,142,143] while total efficiencies are always over 60% [23,95,143]. With micro-scale systems, the electrical efficiency drops to 6-8% [144].

STs are also used with gasification layouts, the efficiencies of such power plants are reported to be 19-36.4% and 80-94%, increasing with the power output [79,82,145]

A better solution for small-scale Rankine cycles is the ORC. With this variation of conventional ST cycle, electrical and total efficiencies of 7.5-13.5% and 60-80% are obtained at micro-scale [94,99], efficiencies that grow up to 7.5-23% and 56-90% for small-scale plants [94,98,99,102,103] and up to 15% and 82-89% for the large-scale ones [146,147].

GTs offer good performance at large scale. In particular, electrical efficiencies between 22% and 50% have been reported for cogeneration plants by several authors [85,95,96,109,148–154]. Total efficiencies are claimed to be about 76-90% also at large scale [95,109,152–154].

Microturbines, the small version of GTs, reach electrical efficiencies between 12.3% and 26% for micro-scale units [7,86,155,156] and total efficiencies in the range 62-73% [7,86]. Small-scale microturbines perform slightly better, with electrical efficiencies of 25.2-33% [7,69,86,101,112,155,157–159] and total efficiencies of 62-89% [7,86,159], decreasing with the pressure ratio at levels greater than the optimum and increasing with the temperature at the turbine inlet [158].

The efficiency of externally-fired GTs is claimed to be around 30% for large-scale layouts of several MWe [95,119]. In addition, there are several experiences of externally-fired GTs at micro-scale fueled with biomass. For example, electrical efficiencies of 15-17% and total efficiencies around 80% have been obtained for a 30 kWe externally-fired micro gas turbine fed with pellets [144,160]. At even smaller sizes, the efficiency drops down to 7.8% as demonstrated for a 5 kWe externally-fired micro gas turbine [108]. Conversely, at small-scale, the electrical efficiencies obtained are 14.6% using pulverized biomass alone and 18.4% using pulverized biomass along with natural gas [112].

Evaporative gas turbines have not been deeply tested nor are found in commercial plants. However, simulations yield electrical efficiencies as great as 45% due to the increased mass flow, so it is a promising technology [115].

With co-firing of biomass, better efficiencies can be obtained. However, the two proposed layouts perform different: in a small-scale plant, with the co-firing of biomass and natural gas in a topping cycle electrical efficiencies between 46% and 49.6% are obtained while with a natural gas-fired topping cycle and a biomass-fired bottoming cycle the electrical efficiency is around 38-41%. Nevertheless, it still performs better than a stand-alone biomass plant equivalent in size, which only reaches 35.5% or 38% of electrical efficiency depending of the type of turbine used, ST or GT [120]. The same pattern is also shown in Domenichini, Gasparini [123].

Efficiency data and comparison

Biomass conversion efficiencies have been continuously improving over the past years due to the learning curve effects and upscaling required for advanced applications [70]. However, and especially in recent years, significant efforts have also been made on R&D of small-scale applications that have improved their performance [88] as a result of the growing involvement of governments, mainly in the EU [26].

With aim to summarize and understand the current state of the art of biomass conversion efficiencies and how they vary with regards to scale and type of conversion technology, a comprehensive review of data published in the literature was performed.

Electrical and total efficiencies of biomass conversion technologies, along with type of fuel, accessed source and power plant output and location, are summarized in Table IV and plotted in Fig. 3 and Fig. 4. As previously mentioned, large-scale plants are not considered in this analysis due to the unsuitability to use these technologies in Mediterranean forests using only locally available resources. This approach leaves out of scope BIGCC layouts, co-firing layouts based on both ST or GT technologies, and most of ST-based plants.

Table IV Biomass conversion technologies' efficiencies. Personal compilation based on indicated sources

Power Plant	*Loc.*	*Po*[1] *(kWe)*	η_e[2] *(%)*	η_{tot}[3] *(%)*	*Tech.*	*Fuel*	*Ref.*
Honda EP 5500 GX340	Brazil	5.5	12.82	N/A	ICE	Wood chips (eucalyptus)	[76]
Naresuan University	Thailand	10	10	N/A	ICE	Wood chips	[123]
GM Corsa Engine	Brazil	15	21.42	51.42	ICE	Wood	[125]
Viking Gasification Plant, Tech University of Denmark	Denmark	18.55	25.1	93	ICE	Wood chips	[79,122]
CTFC	Spain	20	25	74	ICE	Forest residues	[124]

Power Plant	*Loc.*	*Po*[1] *(kWe)*	η_e[2] *(%)*	η_{tot}[3] *(%)*	*Tech.*	*Fuel*	*Ref.*
Ford DSG423	USA	28	20.6	N/A	ICE	Red oak wood	[127]
Ford DSG423	USA	28	23	N/A	ICE	Pine wood	[127]
Long Ashton Research Station	UK	30	20	60	ICE	Wood chips	[126]
Suranaree University of Technology	Thailand	100	17.72	N/A	ICE	Wood chips	[123]
BERI project	India	120	18	81	ICE	Wood chips	[155]
Not specified	China	200	12.5	N/A	ICE	Agricultural residues	[128]
Tianyan Ltd	China	200	15	N/A	ICE	Forest and agricultural residues	[101]
Tervola	Finland	470	24	82	ICE	Wood residues	[63]
Harboøre	Denmark	700	28	96	ICE	Wood chips	[122]
Tianyan Ltd	China	1000	16	N/A	ICE	Forest and agricultural residues	[101]
Putian Huaguang Miye Ltd, Fujian Province	China	1000	17	N/A	ICE	Sawdust, rice husk or straw	[129]
Guangzhou Institute of Energy Conversion	China	1000	17	N/A	ICE	Rice husk	[128]
Experimental system	Performance test	2.7	12.3	N/A	Microturbine	Biogas	[150]
University of Science Malaysia (USM)	Malaysia	5	7.82	30.5	Microturbine	Wood	[108]
Capstone 330 (30 kWe)	Performance test	30	26	N/A	Microturbine	Biogas	[81]
ETSU B/U1/00679/00/REP	UK	30	17	80	Microturbine	Wood pellets	[138]
Chinese village trigeneration system	China	75	28	86	Microturbine	Agricultural residues	[64]
Viking Gasification Plant, Tech University of Denmark	Denmark	140	28.1	N/A	Microturbine	Wood chips	[152]
National Technical University of	Greece	225	26.1	70.7	Microturbine	Dry biomass	[153]

Power Plant	*Loc.*	*Po*[1] *(kWe)*	η_e[2] *(%)*	η_{tot}[3] *(%)*	*Tech.*	*Fuel*	*Ref.*
Athens							
Notthingham	UK	1.5	7.5	80	ORC		[93]
Notthingham	UK	2.71	13.5	80	ORC		[93]
Admont, Styria	Austria	400	7.4	48.2	ORC	Wood chips, sawdust	[96]
Lienz CHP plant	Austria	1000	15	104	ORC	Wood chips	[96]
Australian Nat University rural electricity supply syst	Fiji Islands	25	22	N/A	Steam Engine	Sawmill, crop wastes	[17]
Hartberg, Styria	Austria	730	10	80	Steam Engine	Wood chips, bark, sawdust	[30]
Lion Powerblock	manufacturer	2	10.4	94	Steam Turbine	Wood pellets, Natural Gas, Oil	[121]
Kiuruvesi	Finland	900	11	85	Steam Turbine	Bark, sawdust, wood chips	[63]
Karstula	Finland	1000	8	85	Steam Turbine	Bark, sawdust	[63]
Harboøre Varmeværk	Denmark	1000	28	94	Steam Turbine	Wood chips	[74]
Älvkarleby	Sweden	0.8	20	80	Stirling Engine	Wood pellets	[63]
Sunmachine pellet test	manufacturer	1.38	14.3	72.1	Stirling Engine	Wood pellets	[134]
Sunmachine pellet	manufacturer	1.5	20	90	Stirling Engine	Wood pellets	[134]
Sunmachine pellet	manufacturer	3	25	90	Stirling Engine	Wood pellets	[134]
Sunmachine	manufacturer	3	20.1	90.6	Stirling Engine	Wood pellets	[121]
Sunmachine	manufacturer	3	20	90	Stirling Engine	Wood pellets	[120]
DISENCO	N/A	3	18.4	92	Stirling Engine	Wood pellets	[121]
Joanneum Research (Institute of Energy Research)	Austria	3.2	23.5	-	Stirling Engine	Wood chips	[133]
Joanneum Research (Institute of Energy Research)	Austria	30	26	-	Stirling Engine	Wood chips	[135]
Technical	Denmark	31	9.2	90	Stirling	Wood chips	[131]

Power Plant	*Loc.*	*Po*[1] *(kWe)*	η_e[2] *(%)*	η_{tot}[3] *(%)*	*Tech.*	*Fuel*	*Ref.*
University of Denmark					Engine		
Technical University of Denmark	Denmark	75	11.7	85.9	Stirling Engine	Wood chips	[130]
SOLO161 Stirling	Germany	2	22	92	Stirling Engine	Wood chips	[16]
BAXI Ecogen	manufacturer	6	13.5	94.6	Stirling Engine	Wood chips	[120]
SOLO161 Stirling	Italy	9	24	96	Stirling Engine	Wood chips	[132]
SOLO161 Stirling	manufacturer	9	25	97.2	Stirling Engine	Wood chips	[120]

[1] Power output
[2] Electrical efficiency
[3] Total efficiency

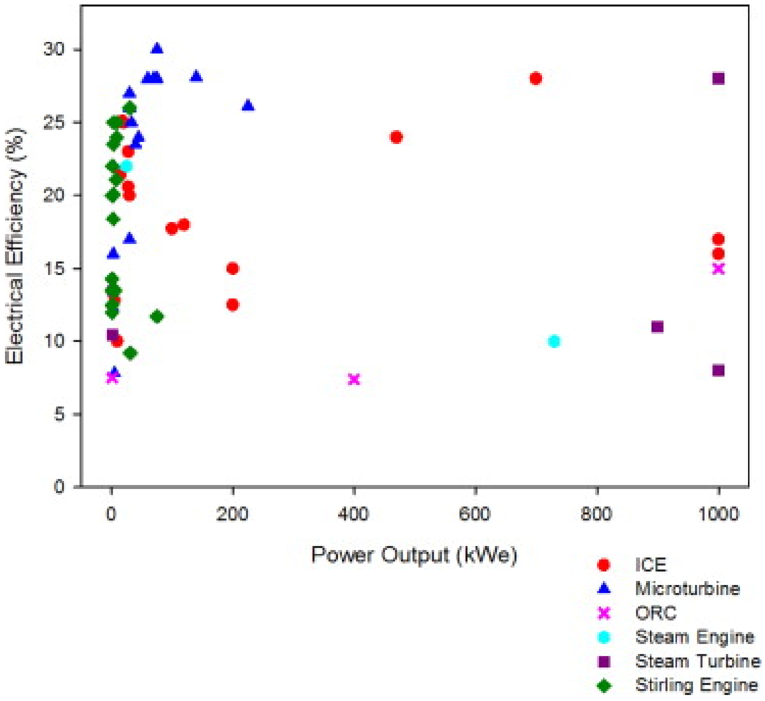


Fig. 3 Electrical efficiencies of biomass conversion technologies. Personal compilation based on indicated sources.

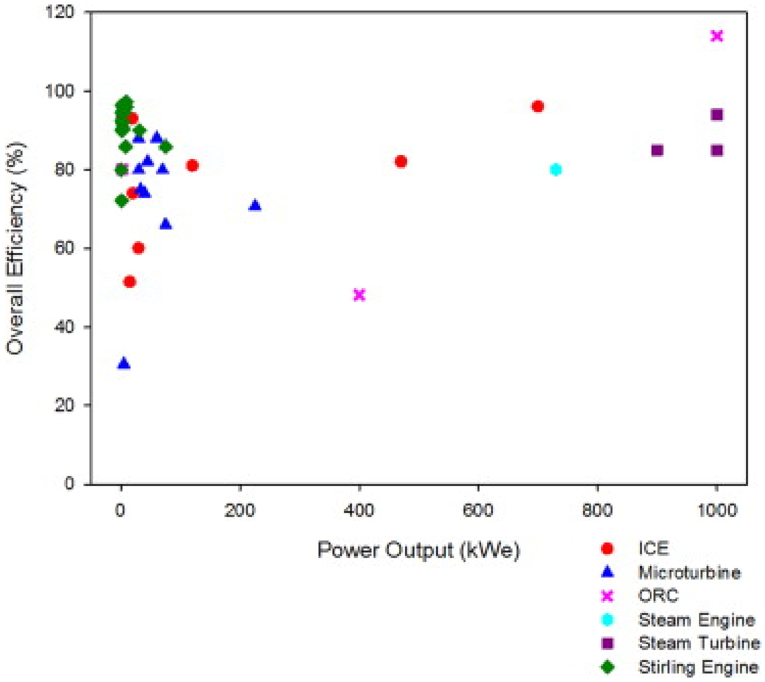


Fig. 4 Total efficiencies of biomass conversion technologies. Personal compilation based on indicated sources.

The data accessed from the literature show that there are many technology combinations, that is, primary conversion technology coupled with a secondary conversion technology, available. The appropriateness of each one depends on several factors, among which highlight the scale of electricity generation, the demanded amount of heat or the type and availability of biomass resource. For example, Stirling engines prove very good performance with outputs of a few kWe, especially when there is a heat demand due to their high thermal efficiency. However, as the scale of electricity generation increases, they are surpassed by ICEs which show the greatest efficiencies at small-scale for electricity generation. ORCs are suitable for power outputs in the order of hundreds of kWe and at higher sizes they are overtaken by conventional Rankine cycles (STs) which are a very efficient technology for a few MWe of installed power, both having high thermal efficiencies. The bigger electrical power generation facilities have outputs as great as 100–120 MWe, for which BIGCC is the best option in terms of electrical efficiency. However, such large-scale technologies are not suitable to use local wood chips in the Mediterranean forests because the amount of feedstock required to fuel these plants would jeopardize the survival and health of the forests. The high thermal efficiency of all technologies, increasing total efficiencies up to 80–100% suggest that looking for a heat demand would be a goal worth pursuing even when a facility is designed and sized for electricity generation purposes.

It is also important to remark that the efficiency increases with the power output, showing an asymptotic behavior especially for biomass-to-electricity conversion. At micro-scale, 25–26% is the current technological limit of biomass conversion to electricity efficiency; at small-scale, it increases a bit reaching values close to 30% and at large-scale, efficiencies as great as 45–47% can be obtained for electricity generation. These values are obviously greater when the thermal efficiency is considered: total efficiencies can be greater than 100% at large-scale and even at micro-scale due to the good behavior of Stirling engines and STs at their respective scales and provided that flue-gas condensation is used [90] to cool the working fluid down below its dew point. With this process, heat from the atmospheric air can be recovered thus enhancing the efficiency to values greater than 100% because the efficiency is calculated in relation to energy input from biomass not including the energy stored within the atmospheric air in form of heat.

2.2.2.4. Costs of technologies

Other important factors that drive the selection of technology in current power plants are investment, operation and maintenance (O&M) costs. Regarding the investment costs, it is worth mentioning that these conversion technologies are at different developmental and commercial stages, so different cost structures should be expected. Regarding the O&M costs, those technologies involving less moving parts or, in the case of gasification, those that have low tar production rates, require less maintenance than those with rotating components or high tar production rates. Accordingly, those technologies based on direct combustion use to require less investment costs as gasification and gas pre-cleaning stages are not required [113].

This is the reason underlying the fact that the most usual biomass conversion to electricity path is through direct combustion and steam turbine [67]. Although it is not the most efficient technology for electricity production, it requires less investment and O&M costs [66] due to its high maturity and commercial viability [23]. In addition, their high time availability also results in lower costs of electricity produced [161].

In an analogous way, there are differences between the gasification technologies: fixed bed reactors, in particular the downdraft ones due to their low tar content of the produced gas [79] and [81], require lower investments [80] and engine cleaning operations [23] than fluidized bed reactors. Therefore, fixed bed reactors are the most suitable alternative for small-scale gasification applications [64,107] that are constrained to have low O&M costs [69,162] while fluidized beds have been claimed to be more appropriate for mid- and large-scale applications [64,70,86,107]. However, fixed bed reactors have two major drawbacks: they require a fuel with low-moisture content at the inlet and they drop the gas at high temperature at the outlet [23,79]. In addition, fixed bed reactors produce a low-heating value gas [163], which is only a minor problem in small-scale plants. On the other hand, fluidized bed reactors are constrained to be fueled with low-size and low-density fuels such as sawdust [64,80], especially in the case of circulating fluidized bed reactors [135].

It is not surprising that ICEs using syngas obtained from biomass gasification are also a commercially viable alternative for biomass conversion to electricity [23] due to the high level of maturity of ICE’s technology that lower the investment costs.

This asymmetrical deployment of technologies shows that the cost of the conversion technologies is a driving factor when it comes to the choice of a technology combination and energy source. However, even though biomass conversion technologies are more expensive than those for fossil fuel conversion, the lower price of the fuel may counteract the difference in capital investment [59]. Hence, it is of paramount importance to work in distributed generation schemes that take advantage of local resources to produce electricity and heat, thus reducing the costs associated to transportation of the energy source. For such purpose, wood chips are an interesting alternative because they can be easily obtained on-site, transported and processed with low energy requirements in the entire process. Moreover, it is worth mention that such usage of local wood chips could also have the economic and social benefits associated to wildfires′ avoidance, particularly relevant in the context of Catalonia [164], and environmental preservation. The consequences of such wildfires are important economic costs and losses to society comparable with those of big catastrophes such as hurricanes derived from fire extinction and damage relief, property losses and tourism affectations [165]; as well environmental damages such as CO_2 release and increased risk of erosion in hilly areas [45], particulates emissions [165] or ecosystems services affectations [166]. Including these avoided costs of wildfires into the economic study of biomass-based conversion technologies, these technologies would have lower electricity generation costs thus being more competitive than they are at present.

2.2.3. Wind power

Wind power is currently the major renewable energy source for electricity production all over the world thanks to its current competitiveness in terms of costs and resource availability. This type of energy is characterized by its lack of pollutant emissions and fossil fuel usage [167] as well as by its low land-use requirements. Therefore, it can be considered one of the best renewable energy sources. The main drawback of this technology is that its moving parts require periodical maintenance operations.

A block diagram of the working principle of wind power can be represented as follows:

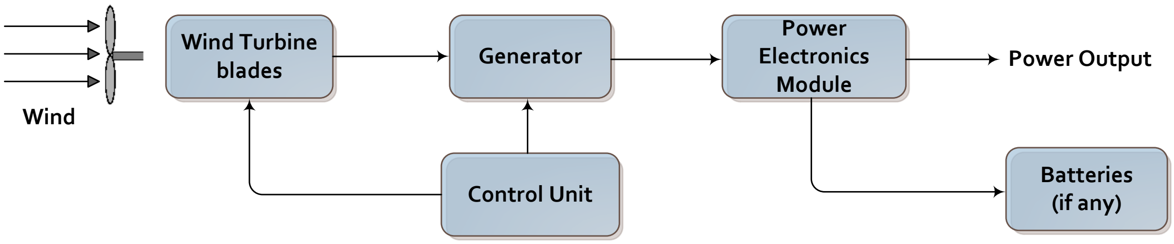


Fig. 5 Block diagram of wind power generation systems

Currently, the most usual wind turbines are large-scale generators (about 1 to 5 MW of installed capacity), typically installed in farm layouts; but small-scale grid-connected wind turbines are enjoying a growing popularity [168]. Thanks to the wide availability of this renewable resource, wind power has a great potential for being used as a renewable source in a distributed energy scheme, although it requires a backup technology if a high-reliability system is pursued.

Electricity production of wind turbines is directly linked to the wind speed distribution, usually similar to a Weibull probabilistic distribution [5].

2.2.4. Solar PV power

PV power is a growing renewable energy source with a promising future. It shows flexibility and scalability of installation and easiness of operation. Due to its lack of moving parts, solar PV has low operational costs whereas also shows a lack of pollutant emissions during its use phase [169]. The main drawback is the necessity of high capital investment at the installation stage [169] which has been drastically reduced during the last decade, a reason for pursuing an optimal size that will avoid overcapacity installation, thus reducing unnecessary costs.

A standard solar photovoltaic power generation installation can be represented as follows:

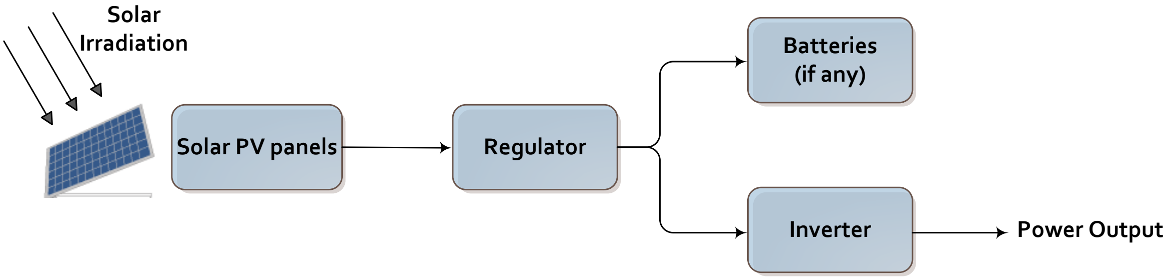


Fig. 6 Block diagram of solar PV power generation systems

The rate of electricity produced by solar PV panels is dependent on the solar irradiation which is, in turn, linked with the clearness index that follows the Holland and Huget probabilistic distribution [5] besides other factors such as the apparent motion of the sun and the geographical location. Besides, the type of PV modules' efficiency also affects the performance. For instance, there are several c-Si and thin-film PV technologies that are currently being commercialized with efficiencies ranging between 10% and 30% of ideal conversion efficiency [170].

Solar PV power generation has a great potential to enable the transition to a distributed generation scheme thanks to its easy scalability and the fact that the resource is virtually available all over the world. However, the intermittency of this resource makes it necessary to lay out power systems that not only rely on solar PV, but also on other sources, renewable or non-renewable, and/or storage systems that could serve as a backup for solar PV power [171].

In addition, the deployment of solar PV generation would trigger and support new direct and indirect jobs for the PV supply chain [170].

2.3. Hybrid renewable energy systems (HRES)

2.3.1. Definition

Hybrid renewable energy system (HRES) stands for a power or a combined heat and power production system based on the hybridization of two or more energy sources, being a RES. These systems can be adapted to the RESs available on-site, therefore, they might combine different energy sources based on the available sources [3,5].

An important reason for the interest attracted recently by HRESs is their remarkable ability to foster the deployment of renewable energies, currently the better alternative for CO_2 emissions reduction given the numerous hurdles to be overcome by nuclear energy [172] for electricity production worldwide, as they are systems that can be replicated at many different scales [25], thus enhancing the transition from a centralized production–distribution scheme to a more distributed model, such as interlinked microgrids, for which renewable energies have been pointed to as an efficient solution [24]. In addition, the use of such energy sources would improve the development of rural areas, creating job opportunities, as well as revaluating local resources not currently used [28]. This is especially significant in the case of forest wood biomass, a RES that, not only stimulates socio-economic progress of rural areas preserving landscape quality and biodiversity [30], but also would help to create wealth and job opportunities in the fields of forest management and harvesting [29].

2.3.1. Characteristics

It is a common practice to complement the production pattern of one source with the pattern of another [173], usually that happens when combining solar PV, with its high energy production during daytime and summer, and wind power, with its high energy production during nighttime and winter. This kind of HRES are usually complemented with a fossil-fuel based energy source such as a diesel engine [24,174–191], with or without an storage device, to take advantage of its ability to be dispatched on demand [3]. Another alternative, regardless of the presence of a diesel engine, is to combine one or more of the aforementioned RES with a storage system, the most common options are battery storage [6,31,32,192–204] and pumped hydro storage (PHS) [205–210]. The storage alternative is highly necessary in those cases when a stand-alone, i.e. islanding scheme is adopted to counteract the lack of an electricity grid that can back up the electricity generation whenever RES are not available. However, despite this requirement that may increase the whole system cost, stand-alone systems might be worth installing in rural and remote areas without access to the grid as the storage system cost would overtake the cost of extending the grid. On the other hand, if a grid-connected scheme is feasible to implement, the grid carries out the storage function of the system [211–213] and hence, storage is not strictly required.

2.4. Storage technologies / Reliability of supply

Despite the undeniable benefits of RES, they also have an undeniably important drawback: from the three most exploited sources, hydroelectric, wind and PV power, two of them, namely wind and PV, are weather-or climatic-dependent [214], meaning that it cannot be assured their dispatch on demand because they only can be produced when the natural resource is available. To face and overcome this issue, more flexibility has to be achieved to ensure permanent meeting of demand by the supply side. Among the available grid-scale flexibility achievement techniques, which include demand-side management, over capacity installation and large-scale storage systems, the latter are the best option because they allow maximizing the usage of generation without impacting the consumers' habits of use of electrical power [215]. Large-scale storage systems include conventional batteries (Li-ion, sodium sulfur or lead-acid batteries), flow batteries (vanadium redox or zinc-bromine), compressed air electricity storage (CAES) and PHS. Carrasco and Franquelo [216] also consider flywheels, hydrogen fuel cells, supercapacitors and superconducting magnetic energy storage (SMES) as feasible alternatives. If small-scale solutions, namely micro-wind turbines or stand-alone photovoltaic systems are chosen, battery energy storage systems (BESS) to be used as a backup are even more necessary due to their scalability and low cost [217]. Hence, additional costs should be attributed to the installation of these RESs if the requirement of storage is taken into account when designing a so-called hybrid system that includes renewable energy production technologies and storage systems [214]. Moreover, the small size of these systems adds another potential issue: the integration of many small power sources instead of a few large ones requires additional control measures to ensure stability, prevent failures and make mid- and long-term electricity production estimations [218,219]. According to some sources [220], the setup of large energy farms, both wind and photovoltaic that supply power as a single power unit is also required in order to ease their integration into the electric grid.

2.5. Optimization of HRES

Optimization is a research field that is currently attracting interest for its usability in the design of systems or components in which many variables are involved. That is the case of HRES design, because to effectively size a HRES it is required to assess the main constraints, including the load demand profile that restricts the demand of the system, as well as the wind speed and solar irradiation that restrict the supply. When performing such assessment, optimization technologies are a useful tool that support and inform decision-makers providing optimal designs according to pre-established criteria.

In the thorough literature review that was performed to properly assess the current state of the art on the topic of HRES optimization, it was observed that most of the accessed HRES design and optimization papers are focused on stand-alone HRESs [24–26,28,31,32,178,200,201,206–208,221] rather than grid-connected ones because the formers show better economic feasibility than the latter as they are intended to substitute small grids fueled with non-indigenous fossil fuels [24,31,32,207]. Some of these researches rely on existent optimization software usage, such as HOMER [25,32,187,192,205] while others develop some optimization methodologies based on different optimization methodologies such as genetic algorithms (GA) [24,178,201,207,208,222,223] or dynamic programming methods [184], such as the mixed integer linear programming (MILP) [31]; whereas others only model and simulate the problem with different input values to analyze the results [213,221,224].

One of the key aspects of HRES optimization problems is the input data. For HRES optimization, both the atmospheric data related with RE generation, that is, solar irradiation and wind speed, and the load demand data are of critical importance. From the performed literature survey, it was observed that some works do not use actual data sets and instead, estimate weather-related variables [31,184,192,205] and/or the electricity demand [32,192,200,205,207,208]; whereas others use full year actual data sets for these variables [24,25,178,187,223].

Many of the accessed papers do not include real on-time data in the analysis, a circumstance that we believe that weakens the analysis due to the lack of accuracy when capturing both daily and seasonal patterns. We also observed a scarcity of grid-connected HRES optimization researches and, particularly, none that introduced on-time electricity sale and purchase according to actual market prices and depending on rather the system has a surplus or a lack of electricity production compared with the electricity demand.

2.6. Summary

Among the RES, forest wood biomass is one alternative with great potential for electricity and heat production due to being an indigenous source in many countries and being based on well-known technologies with good performance. In particular, wood chips are an appealing alternative because they are a cheap fuel with low energy requirements for their production and with very stable burning or gasification performance due to their higher contact surface compared with other solid biofuels. The usage of such resource would have undeniable benefits, among which highlight the reduction of greenhouse gas emissions and the proper management of forests, leading to more efficient environmental preservation, the creation of green jobs in rural areas and wildfires′ risk reduction. In addition, if the available feedstock is locally used, the energy requirements and associated CO_2 emissions would be minimized. However, in the Mediterranean region, this circumstance thresholds the usage of biomass at the micro- and small-scale levels.

This study has reviewed the different technologies for wood chips conversion to electricity and heat, with especial focus on the performance of micro- and small-scale technologies. The comparison between the different available alternatives show that the most suitable technology depends on many factors, highlighting the scale of electricity production, the existence of heat demand or the associated costs among others. The overall data analyzed shows that electricity production performance of those technologies that use wood chips as fuel is quite good, improving with greater outputs, and that taking advantage of additional heat produced is a very important goal because it increases the total efficiency up to values close to 90–100% even at very small scales of energy production.

From the literature survey, it has been noticed a scarcity of papers focused on grid-connected HRES, and, aside from the work published by the authors [225,226], none of the accessed papers is focused on the hybridization of PV, wind and biomass power sources – being the latter the one that provides backup to the formers – or uses real on-time electricity sale and purchase prices according to actual market pool and hourly discrimination tariff prices. This work also proposes to use the forest wood biomass in a sustainable way, i.e. without surpassing the self-growth rate of local forests so the locally available resource can be used avoiding resource depletion or scarcity at mid- or long-term. This is introduced in the work through the inclusion of the price of sustainably-harvested forest wood biomass as well as estimating the forested area required to feed the system. The novelty of this work can be, therefore, justified from these characteristics, as well as from a multi-objective analysis that allows decision-makers not only to perform informed decisions but also to understand the trade-offs between system cost and environmental impact.

In the present research, solar PV, wind and biomass have been hybridized in different combinations (see Chapter 4 for further detail on system layout) to take advantage from the complementary seasonal and daily patterns of wind and solar resources and to incorporate the flexibility provided by the biomass, since it is an energy source that can be dispatched on demand [3]. The layout includes grid connection, from which the system would take the advantage of having more flexibility and adaptability to actual demand at those cases when the indigenous energy sources are not enough to cover the demand.

3. Framework and methodology

This chapter is aimed to describe the methodology designed to optimize HRES system sizing according to a minimum cost criterion or to a multi-objective cost and environmental impact criteria. In the first section a short introduction and summary of the methodology is presented, in the second section it is analyzed the choice of the sample township where the optimization methodology was tested and the reasons behind such choice. Third and fourth sections are the description of the methodology itself.

3.1. Introduction

The methodology here described is thought to provide decision-makers an optimal solution once the performance and economic variables and the solar irradiation, wind and electricity demand patterns are known, provided that natural tree growth rate thresholds are not exceeded. The optimization is performed by means of a GA.

For the sake of easiness of development, improvement and validation as well as flexibility of the optimization model designed the research was divided in different stages, i.e. the optimization model was developed and tested under different conditions of RES availability or optimization criteria. However, in all cases the system shares a certain core characteristics, such as its grid connection, the hybridization of solar PV and wind power subsystems and the introduction of life-cycle cost as an optimization criterion.

The first stage of the research was focused on life-cycle cost optimization of a grid-connected PV-wind HRES for electricity production.

The second stage of the research was focused on the life-cycle cost optimization of a HRES improved with respect the previous one. This improvement consisted in adding a certain degree of autonomy given by forest wood biomass, which is a controllable source of energy [3] since it can be stored in wood chip or pellet form reducing storage requirements [227], together with the reliability assurance mechanism of grid connection [223,226]. In addition, these three sources of energy are recognized to be the RESs with higher social, economic, and environmental benefits [22].

After that, the multi-objective optimization was incorporated by adding the life-cycle environmental impact as the second optimization criterion. By doing so, a set of optimal solutions was obtained, i.e. a Pareto front, to analyze the trade-offs between life-cycle cost and environmental impact minimizations.

The fourth last step was to introduce the thermal demand of a neighborhood of the sample population that fitted the scale of the HRES being studied for electricity production alone. Hence, the PV-wind-biomass HRES required to supply the township's demand would not waste the thermal energy produced by the biomass electricity generation system.

It is also important to remark the willingness of this research to carry out a comprehensive cost and environmental impact assessment. In the case of life-cycle cost, it means that the assessment is characterized by performing an analysis that not only includes the initial investment and the expected incomes of the system, but also all the expected costs and revenues throughout lifetime of the system [228]. Thus, the developed methodology intends to optimize the life cycle cost focusing on all the expected costs of a certain system during its lifetime as well as the expected revenues. In the case of life-cycle environmental impact, it means that the assessment is characterized by accounting for CO_2 emissions, which was chosen as a representative metric of environmental impact, from cradle to grave of the electricity generation equipment, so solar PV and wind energy technologies do have environmental impact due to their manufacturing, transport and installation processes.

In addition to the cost and environmental impact treatment from a life cycle perspective, this work intends to be an original approach to HRES cost optimization through the use of hourly data for both weather variables and electricity demand; the utilization of genetic algorithm methodology that allows to fully control the modeling and input parameters; and through the calculation at each hour of the day of cost and revenues derived from electricity sale and purchase at market and retail prices respectively thus not seeing the electricity production as steady profits but looking at it as a dynamic cost term, strongly linked to actual market conditions. Moreover, the methodology was tested by means of a case study with real on-site data.

Another important aspect is the system scale. The methodology here described was designed to be usable in a range of different scales because the model allows changing system size easily by increasing or decreasing the number of PV modules and/or wind turbines. Hence, the proposed HRES optimization model can be used in many different places and at many different scales of generation by only adapting the weather, electricity demand, components' performance and cost variables to the new constraints.

In the following subsections there are explained the context of the study undertaken, the system layout for the different stages of the research and main characteristics of the employed methodology are detailed.

3.2. Sample choice

The focus of this research was to hybridize RES found in central Catalonia rural villages, being this context applicable to other Mediterranean climate areas such as other Iberia peninsula regions, Italy, southern France or Greece and the Balkans.

With the purpose of testing the designed methodology, a particular location was chosen as a case study sample. Such location is Santa Coloma de Queralt, a rural township in central Catalonia, a region characterized by having a Mediterranean climate with moderately high solar irradiation averaging around 1650 kWh/(m^{2}year) [229], throughout the year and also by having a medium wind potential of 3.7 m/s at 35 m above ground level [229] as there are no big orographic obstacles. Furthermore, Central Catalonia is also a region with high on-site forest wood biomass availability [51,230], facilitating the exploitation of such a resource in a sustainable way, i.e., with minimum transportation requirements and allowing the use of locally available resources below the rate of growth of indigenous tree species.

The sample township has 2931 inhabitants and a population density of 86.6 inhabitants/km^2, thus meeting the OECD criteria for rural population [231] since it is below 150 inhabitants/km^2. The system sizing is done for the entire township with 1271 residential dwellings [232].

Regarding the third renewable energy source considered in the study, the availability should be measured in terms of available tons per year. Given the vocation of this study of preserving the sustainability of resource use, the annual growth rate of forest trees was used instead of the amount of biomass readily available in the forest. In this manner, the available biomass resource will be always a similar amount, depending of the rain and solar irradiation of the year, and the forest survival will not be jeopardized by an abusive use of it. Consequently, the growth rate of Mediterranean pine and oak forests of 1.6 metric tons of dry wood per hectare and year [230,233] was used to estimate the amount of available biomass. To obtain the total mass of available resource to be used for the system, this value was multiplied by the area of forested area in the township under study and surrounding area, which equals 2200 hectares. The resulting figure was corrected to tons of wood at 15% of moisture content, the value at which the biomass usually enters the gasifier after a pre-drying process [234]:

$$Available\ biomass = \frac{1.6\ tn_{0\%}}{h \cdot year} \cdot \frac{1.15\ tn_{15\%}}{1\ tn_{0\%}} \cdot 2200\ h = 4048 \frac{tn}{year} \tag{3}$$

3.3. Methodology

The methodology here described was designed to be a useful and innovative mechanism that could help to improve PV–wind–biomass grid-connected HRES design, according to a minimum cost criterion. Such optimization is performed by means of a genetic algorithm-based model, by applying an approach from a life-cycle perspective when addressing the system cost. From such a point of view, all costs and revenues throughout the lifetime of the system should be considered, that is, initial investment, expected incomes, and costs from electricity sale or purchase, operation, and maintenance costs, component replacement (if required) and component sale at the end of the lifetime [223,228].

Another aspect worth highlighting is the use of real data with an hourly accuracy, allowing the model to compute the hourly discrimination electricity tariffs and market price, as well as the daily and seasonal patterns of involved stochastic RESs, solar irradiation, and wind speed. When looking at that in the literature, it has been observed that some works, rather than using real hourly data, they rely on estimated weather-related variables [31,184,192,205] and/or electricity demand data [32,200,205,207,208]. The present work would be included in the group of papers that rely on actual data with hourly accuracy [24,25,178,186,187,223], being able to capture both hourly and seasonal weather and demand pattern changes.

Moreover, the inclusion of forest wood chips as biomass fuel has been made, considering environmental criteria, which is a novel perspective. For example, instead of considering that the biomass-based fuel is acquired at current market cost, the acquisition cost of fuel obtained from sustainable harvesting and processing practices has been considered. Such insight means a higher fuel cost compared with current market prices, but it helps in reducing the current mismanagement of Mediterranean forests, which leads to increased forest wildfires risk [46,235]. To compensate for such an economic handicap, the authors have also proposed a novel biomass unit pattern of operation, based on the maximization of unit efficiency by always working at full load and selling the excess of electricity, if any, to the grid. Such an operation pattern, not only increases the entire system efficiency, but also ensures that biomass is used in an optimum way so the scarce indigenously available resource is not wasted.

Another important aspect of the methodology presented in this article is the fact that it is based on the use of real on-time data for a sample location, used to validate the results and behavior of the developed optimization model.

Besides, the methodology is also thought to be applicable at different scales of energy generation. Considering the typology of the different renewable power subsystems, the proposed HRES cost-optimization methodology can be used in a wide range of different scales and locations. To do so, the user only has to change the input variables related to the system scale, such as biomass or wind subsystems' installed capacities and efficiencies, and related to location, such as solar irradiation and wind speed data series.

In the following subsections the optimization methodology is thoroughly described. First of all, the location where the system is to be installed is selected for validation purposes, a sample rural township in Central Catalonia. Then, the input data required is described and presented for the validation sample. The third step of the methodology consists in the optimization model design and application, and it is detailed including the physics that support it.

3.3.1. Input data gathering

In order to ensure the reliability of the results provided by the algorithm, all the data was gathered from several trustworthy sources. For the single objective optimization models, these data are classified into three groups, i.e. stochastic variables as weather-related variables and electricity demand, equipment costs and financial variables, and equipment efficiency and performance data. In the multi-objective optimization analysis, the life-cycle environmental impact was measured through life-cycle CO_2 emissions, the fourth group of input data. All data come from trustworthy sources which are indicted.

3.3.1.1. Renewable energy availability data collection

The stochastic variables relevant for this model are the weather-related variables required to model the production of renewable energy as well as the electricity demand that is sought to be supplied. The selected accuracy is one datum per hour during an entire year, which allows capturing the seasonal and daily variability of these magnitudes without forcing the algorithm to manage a huge amount of data. The selected period of analysis is year 2011 because that is the last year with all the data readily available from the accessed sources.

Table V lists the hourly series of these variables, and Fig. 7 show the patterns of them for a random labor day, April 19th.

Table V Hourly Series of Stochastic Variables

Data	*Value*	*Source*
Solar irradiation (W/m2)	Vector of 8760 points corresponding to 24 hours per 365 days	[229]
Wind speed at 6 m (m/s)	Vector of 8760 points corresponding to 24 hours per 365 days	[229]
Electricity demand profile (kWh)	Vector of 8760 points corresponding to 24 hours per 365 days	[236][237]

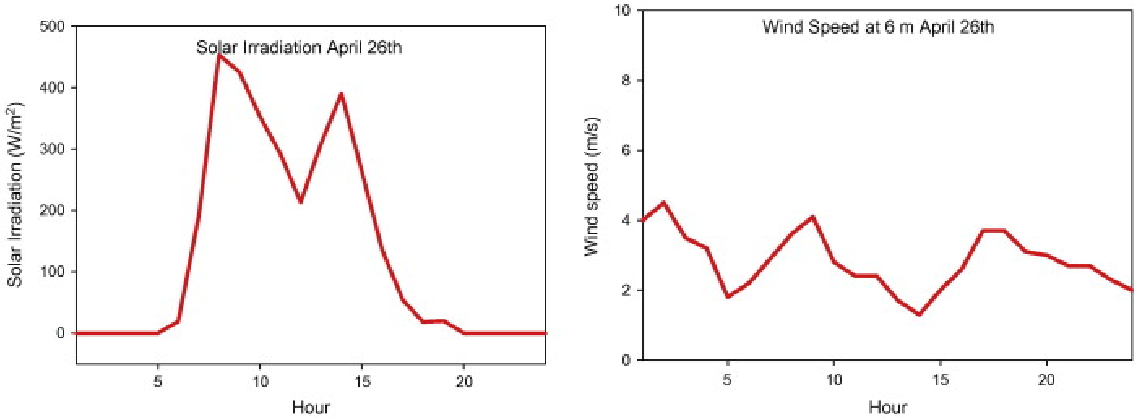


Fig. 7 Hourly series of a random day for solar irradiation (a) and wind speed measured at 6m above ground (b)

Regarding to the wind speed data, the measured data corresponds to an anemometer placed at 6 m of altitude. The chosen wind turbine can be installed with a layout of 30, 36 and 40 m of rotor altitude [238] so an extrapolation of wind speed has been performed using the power law equation that is a robust method to model the boundary layer [239]:

$$V_{H,t} = V_{H_0,t} \left(\frac{H}{H_0}\right)^{1/7} \tag{4}$$

where $V_{H,t}$ and $V_{H_0,t}$ are, respectively, the estimated wind speed at height H and the measured one at height $H_0 = 6\ m$ at time interval t.

The solar irradiation data series provided by [229] is measured on a horizontal surface, so a horizontal-to-tilted plane conversion (Eq (5)–(7)) was performed to obtain the solar irradiation SI on a plane tilted 37º, which is the optimum angle for the latitude of the sample. This can be done as follows [240]:

$$SI_{tilt} = SI_{horizontal} \cdot \frac{\sin(\alpha + \beta)}{\sin(\alpha)} \tag{5}$$

where α is the elevation angle and is the tilt angle measured from the horizontal, in the sample selected β= 37º. The elevation angle can be calculated as follows:

$$\alpha = 90 - \phi + \delta \tag{6}$$

$$\delta = 23.45 \cdot \sin\left(\frac{360}{365} \cdot (284 + d)\right) \tag{7}$$

Φ being the latitude and the day of the year and dϵ(1,365) the day of the year.

3.3.1.2. *Electricity demand data collection and Thermal energy demand calculation*

The electricity demand data series were provided by the local utility companies of Santa Coloma de Queralt [236] and Caldes de Montbui [237], which provided a measure of the entire township electricity consumption in an hourly basis. It is worth noting that these households have an annual electricity consumption close to the average household electricity consumption for the Mediterranean region of [241], although the total demand also included all the consumers of the township, including services, industry, streetlight, to name but a few.

An example for a random day of [237] is shown in Fig. 8:

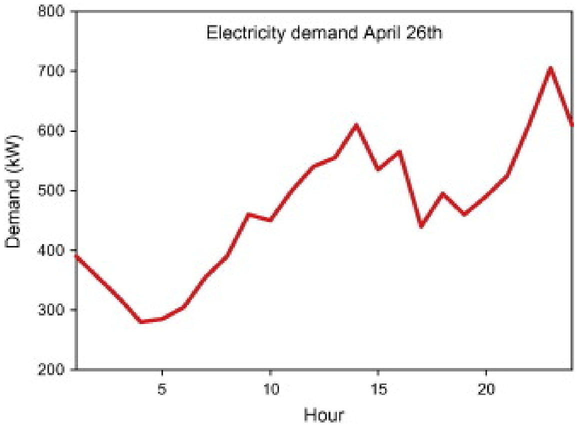


Fig. 8 Hourly series of a random day for electricity demand

In addition, Spain has electricity prices close to the Euro area electricity average price [242] so the results derived from this case study will be significantly representative for any other European country in the Mediterranean area, for instance Greece, Southern France or Italy. Despite the applicability of the results of the proposed case study to similar climate regions, the methodology is designed to be as universal as possible allowing to be applied wherever is desired provided that the location-dependent input variables, that is solar irradiation, wind speed and electricity demand hourly patterns, are known. The methodology proposed is not only intended to be useful for Mediterranean regions, and changes in the input variables, including weather-related, load demand, and economic data, would lead to trustworthy results in regions with other idiosyncrasies.

The thermal demand for each type of household included in the DH network was obtained using the procedure from the Spanish Institute for energy diversification and saving (IDAE in its Spanish acronym) [243], which establishes that the thermal demand for heating purposes can be calculated as follows:

$$Q_{total} = \phi + Q_v + Q_{SHW} \tag{8}$$

where ϕ is the heat transfer flow in Watts, Q_v the ventilation heat losses and Q_{SHW} the thermal demand for sanitary hot water. These terms were calculated for each type of household with an hourly accuracy for heat transfer and ventilation heat losses and with homogenous demand throughout the year for sanitary hot water.

The annual heat transfer needs are calculated as

$$\phi = U \cdot A \cdot \left(T_{in} - T_{out,i}\right) \tag{9}$$

where U is the thermal transmittance of the contact surface of each household type, in W/(m^{2}K), A is the contact area in m^2 and T_{in} and T_{out} are the temperature setting inside households and the outside temperature. The thermal transmittances for each type were obtained using the building energy certification software CE3X [244], which provides their values according to the type of contact surface (façade, party wall, window, roof, ground), the materials used and year of construction.

$$Q_v = \sum_{i=1}^{8760} c_{p,a} \cdot \rho_a \cdot q_v \cdot \left(T_{in} - T_{out,i}\right) \tag{10}$$

$$Q_{SHW} = 365 \cdot c_{p,w} \cdot \rho_w \cdot q_{SHW} \cdot \left(T_{ref} - T_{cw}\right)/(A \cdot \eta_{SHW}) \tag{11}$$

where $c_{p,a} = 1.005\ kJ/kgK$ and $\rho_a = 1.2\ kg/m^3$ are the specific heat and the density of air, $c_{p,w} = 4.18\ kJ/kgK$ and $\rho_w = 1000\ kg/m^3$ are the specific heat and the density of water, A is the household area, η_{SHW} is the efficiency of sanitary hot water distribution inside the house of 0.75 according to [243]; and q_v and q_{SHW} are the ventilation air flow in m^3/s and the sanitary hot water volumetric demand, obtained according to:

$$q_v = \frac{\dot{m}_v \cdot A \cdot h}{3.6} \tag{12}$$

$$q_{SHW} = \frac{c \cdot average\ inh.}{3.6} \tag{13}$$

where $\dot{m}_v$ is the ventilation flow of 0.8 renovations per hour, A is the household area in m^2, h is the average floor height, set at 2.7 m, c is the water consumption per inhabitant of 30 liters per day and $average\ inh$ is the average number of inhabitants per household, of 2.6340 according to 2011 housing census [232].

For the temperature setting inside households, a daily pattern similar to electricity demand pattern was established, with two temperature settings, 16 ºC at night and no-occupancy periods and 20.5 ºC during occupancy hours (see Fig. 9).

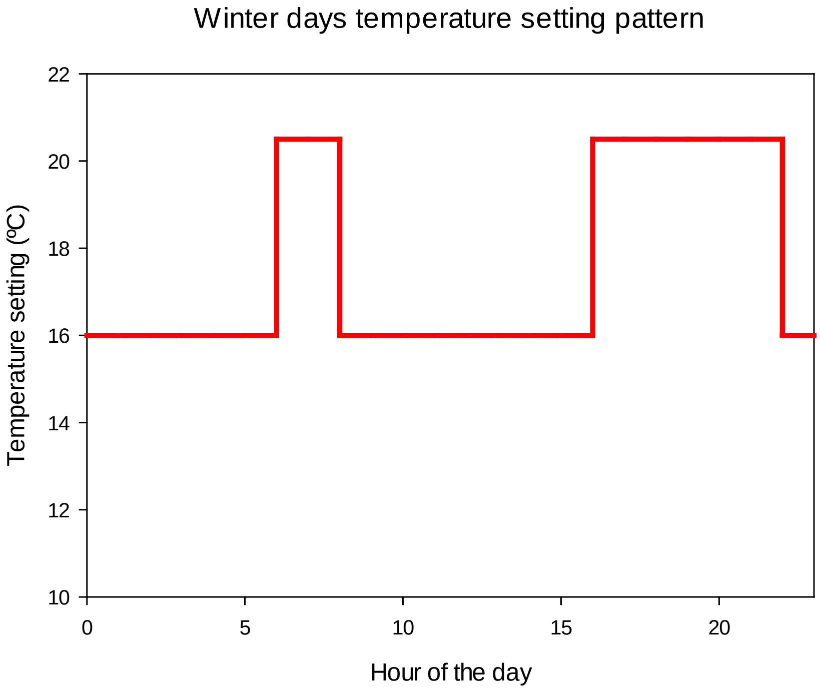


Fig. 9 Hourly temperature setting of winter days

In addition, the DH was supposed to work only in winter days, from November, 15th to April 15th, as presented in Fig. 10:

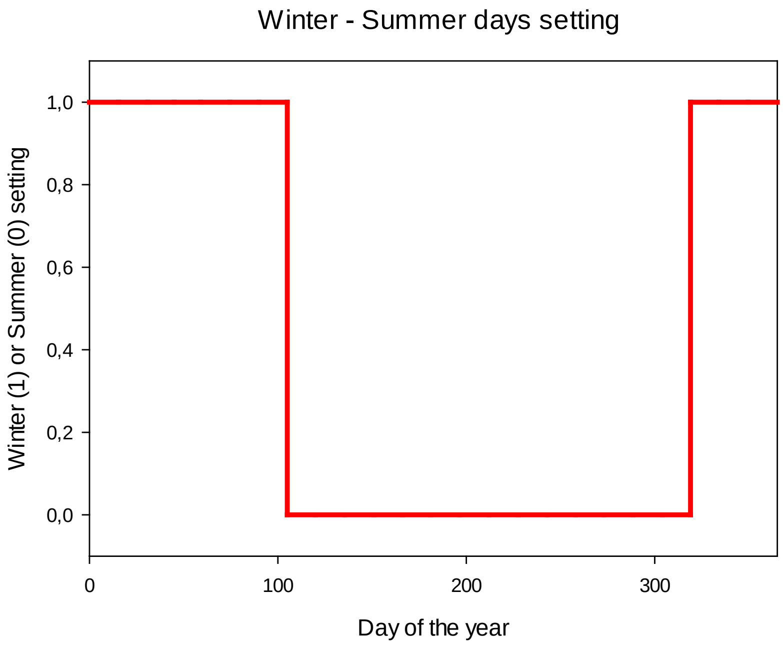


Fig. 10 Annual setting of central heating: winter days (1) with temperature setting shown in Fig. 9 and summer days (0) without temperature setting

With all these parameters set, the last step was to multiply the unitary household thermal demand by the number of households of each type. A vector of 8760 points, as in the case of electricity demand, was obtained as input data for the optimization model. Again, as it happened with the electricity demand, the average thermal demand of a household obtained for the proposed DH neighborhood of 17.54 MWh/year is close to average consumption for a Spanish continental climate household of 15.53 MWh/year, according to [241].

This thermal demand, however, has to be increased to account for the distribution losses, i.e. the energy losses due to dissipation throughout the ducts of hot water distribution system. According to technical manuals from DH pipe manufacturer Danfoss [245], the distribution losses, expressed in Watts per meter of pipe, are 18.08 W/m for a circular twin pipe and 26.53 W/m for a pair of single duct pipes. Similar values are given by the pipe manufacturer Rehau [246]: with working temperatures of 80ºC for heat flow and 60ºC for return circuit losses are 24.6 W/m with a pair of single duct pipes of 90 mm; whereas for smaller pipelines of 75mm and slightly lower working temperatures for heat and return flow of 75ºC and 55ºC respectively, the losses equal 16.2 W/m.

Taking the most limitative value of 26.53 W/m, and multiplying this value by the total length of the DH system of 1100m approximately, total heat losses due to distribution equal:

$$DH\ heat\ losses_{max} = 26.53\ W/m \cdot 1100m = 29183W \approx 30kW \tag{14}$$

When considering a system of 500 kWe and 1014.6 kWth (see conversion efficiencies in the following section), (14) represent approximately 3% power losses. However, since the township under study has not severe cold weather, it was assumed that working temperatures are not required to be particularly high, and distribution losses were calculated taking the heat losses per meter of pipeline of 16.2 W/m, obtaining the following total distribution losses:

$$DH\ heat\ losses = 16.2\ W/m \cdot 1100m = 17820W \approx 20kW \tag{15}$$

which represents 1.9% of thermal energy produced by a gasifier – ICE group of 500 kWe. Therefore, the distribution losses were assumed to be a 2% of thermal energy produced, and thermal demand was increased by this factor.

3.3.1.3. *Efficiency and performance data collection*

This set of data includes all the variables required to implement the performance calculation into the model. That includes all the efficiencies of a solar PV installation, of a wind turbine installation and a biomass gasification – ICE installation. For solar PV power, these data include the module efficiency itself but also the ancillary equipment including the wiring, converter and de-rating efficiencies among others [247]; whereas for wind power that is acquired in the form of the characteristic curve of the wind turbine provided by the manufacturer that includes all the efficiencies of the entire wind turbine [248]. The biomass heating value has also been classified in this group.

Table VI shows the values used in the algorithm for all the variables that take a fixed value.

Table VI Efficiency and performance variables

Data	*Value*	*Source*
Module reference efficiency	15.0%	[249]
Model nameplate de-rate	95.0%	[250]
Inverter efficiency	92.0%	[250]
Module mismatch factor	98.0%	[250]
Connections efficiency	99.5%	[250]
DC wiring losses factor	98.0%	[250]
AC wiring losses factor	99.0%	[250]
Soiling de-rate factor	95.0%	[250]
System availability O&M	98.0%	[250]
Gasifier ideal efficiency	71.0%	[251]
Gasifier operation efficiency	95.0%	[234]
Biomass syngas-fired ICE	37.0%	[227,234]

Biomass lower heating value (LHV)	15.5 GJ/t	[234,252]

In addition to such information, it is also important to introduce the PV power warranted by the manufacturer curve, obtained from [249,253] depending on the modules used, which diminishes over time as a result of aging (see Fig. 12) and the wind power characteristic curve [238] (see Fig. 11) that shows the output of the wind turbine, including the wiring, generator, transformer and power and control cabinet efficiencies.

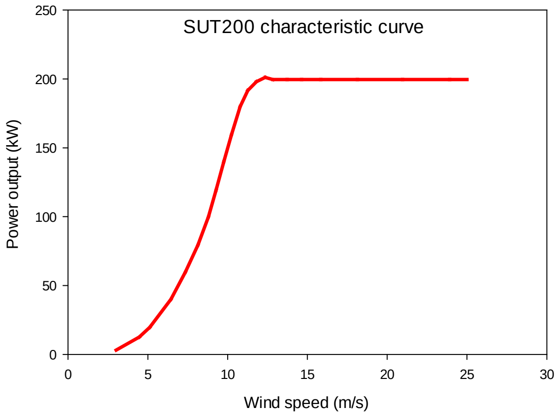


Fig. 11 SUT200 characteristic curve, representing output power (kW) over wind speed (m/s).

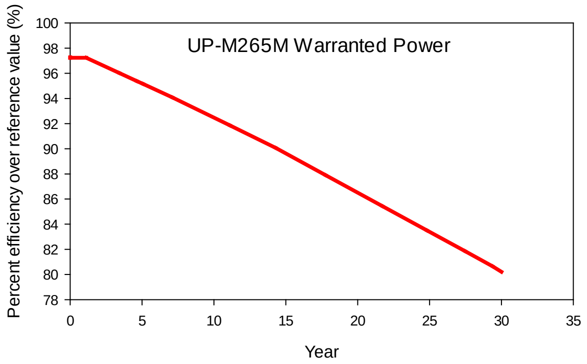


Fig. 12 Warranted power (%) over lifetime of UP-M265M PV module

The warranted power refers to the module reference efficiency, so the manufacturer warrants 97% of the reference efficiency for the first two years and then the warranted power experiences a linear decline until reaching 80% of the reference efficiency by the 30th year of module usage.

The entire biomass-to-electricity conversion system efficiency is calculated by multiplying all the involved efficiencies (see Equation (16))

$$\eta_{bio\ system} = \eta_{gasif\_ideal} \cdot \eta_{gasifier\_op} \cdot \eta_{engine-generator} = 24.9 \quad (16)$$

A conservative value of 25% was selected.

The LHV of biomass can be calculated from the higher heating value (HHV) of biomass, as follows [252]:

$$LHV_w = \left(HHV_{daf} - 20.3 \cdot H_{daf}\right) \cdot (1 - AC_w - MC_w) \tag{17}$$

where HHV_{daf} is the higher heating value of dry ash free biomass, H_{daf} is hydrogen ash free content, AC_w is the ash content and MC_w is the moisture content. They are 20.4 GJ/t, 6.2%, and 3% according to [254], respectively.

Regarding the moisture content, according to a manufacturer of the biomass gasification equipment [234], biomass is usually supplied at 30% of moisture content, however, after an atmospheric pre-drying over four to six months, it easily reaches a moisture content of 15%. Hence, the expected LHV of biomass at intake of the gasifier is calculated with Equation (18):

$$LHV_{15\%} = (20.4 - 20.3 \cdot 0.062) \cdot (1 - 0.03 - 0.15) = 15.70\ GJ/t \tag{18}$$

In this case, a value of 15.5 GJ/t was selected, corresponding to 16% moisture content. Considering that the selected biomass-to-electricity system efficiency was a conservative value, it seemed a reasonable value to choose.

3.3.1.4. Cost and financial data collection

The cost variables to be considered range from the equipment acquisition costs to the operation and maintenance (O&M) expenditures, including the equipment replacement costs whenever required throughout the lifetime of the system.

There are also some financial variables that are important to be considered to effectively perform the cost optimization under the perspective of the lifecycle analysis. For instance, the lifetime of the entire system and the different components of it, whenever different, must be included to account for inflation of electricity and obsolete equipment selling prices. The interest rate must also be included because it is necessary to discount all the future costs and revenues as if they took place at the moment of initial investment, according to the Net Present Value metric.

The values of all these variables are listed in Table VII.

Table VII Cost and financial variables

Data	*Variable name*	*Value*	*Source*
System lifetime	N	25 years	[180,255,256]
Wind turbine lifetime	Y_{wt}	20 years	[256]

Solar PV DC – DC inverter lifetime	Y_{inv}	15 years	[223,256]
Interest rate	IR	3.5%	[257]
Spain’s Value Added Tax (VAT) rate	TR	21%	[258]
General inflation rate	g	3%	[256]
Electricity selling price inflation rate	$g_{electricity}$	3%	[256]
Wind turbines selling price inflation rate	g_{wt}	-5%	[256]
Inverter selling price inflation rate	g_{inv}	-5%	[256]
Cost reduction limit due to technological maturity for wind turbines	L_{g_wt}	-25%	[256]
Cost reduction limit due to technological maturity for inverters	L_{g_inv}	-25%	[256]
PV capital cost	C_{PV}	3800 $/kW (2011) 2930 $/kW (2014)	[247] [259]
Wind capital cost	C_{WT}	2700 $/kW	[248]
Inverter capital cost	C_{INV}	250 $/kWPV	[256]
PV fixed O&M costs	$C_{PV_{fixed}O\&M}$	32.64 $/kW	[260]
Wind fixed O&M costs	$C_{WT_{fixed}O\&M}$	32.15 $/kW	[260]
PV variable O&M costs	$C_{PV_{var}O\&M}$	0 $/kW	[260]
Wind variable O&M costs	$C_{WT_{var}O\&M}$	0.01475 $/kW	[260]
Electricity market price	C_{pool}	Vector of 8760 points; 24 hours per 365 days	[261]
Electricity retail price	C_{electr}	Peak – 0.101406 €/kWh Flat – 0.078289 €/kWh Off-peak – 0.052683 €/kWh	[262]
Time periods		Peak: 17-23 winter/10-16 summer Flat: 8-17, 23-24 winter /8-10,16-24 summer Off-peak: 0-8 winter time / summer time	[263]

According to [247,259], PV system costs decrease exponentially as the size of installation increases, reaching an average value of $3.8 per Watt for utility-scale installations in 2011 [247] that are those relevant for the scale of the proposed case study. Such price decreased to $2.93 per Watt in 2014 [259]. The values provided account for the cost of all the components of an installed system: PV modules, converter, installation materials, labor costs, supply chain and even land acquisition and taxes, commissioning and permitting costs. For residential or commercial scale equipment this value should be changed to take into account the higher costs of the technology. In the first three stages of the research (single objective PV-wind HRES optimization, single objective PV-wind-biomass HRES optimization and multi-objective PV-wind-biomass HRES optimization) the price of 2011 [247] was used as it was the most recent one available. In the last stage of the research (multi-objective PV-wind-biomass CHP HRES optimization) the PV price was updated to the price of 2014 [259], as a new PV prices report was available.

Regarding the wind power systems price, the data given in [248] also show an exponential decrease in price with increasing project size. In this case, the entire cost of the system is also provided.

Furthermore, the electricity retail prices [262] were introduced only taking into account the price of the energy consumed, i.e. the cost of the kWh, and considering the different prices at different time discrimination periods that the electrical bill has. The fixed costs derived from the contract like the cost of the power contracted, are not introduced as the system is designed as grid-connected so they will be paid regardless of the consumption that is what is expected to be reduced. For the market price of electricity, the data of a whole year has been retrieved from the Iberian market operator OMIE [261], which provides the clearing price in the pool of electricity with hourly accuracy that is the time period at which the auctions take place. With these two datasets, it is possible to account for the benefits of selling electricity and costs of purchasing according to the positive production (surplus) or negative production (lack) of electricity at each hour of the day.

These prices were considered to suffer an annual inflation of 3%, a conservative value according to last years' price change that doubled that value [264].

The last renewable energy generation subsystem to be considered is the biomass-to-electricity conversion technology. In this case, equipment cost data have been obtained from Environmental Protection Agency (EPA) [251] and from the Swedish Linnaeus University [265], which are in accordance with a validation made through a personal communication with a professional engaged in the manufacturing of this type of equipment at a small scale (up to 1 MWe) [234]. The cost of wood chips that serve as fuel of the biomass subsystem has been calculated according to data provided in [30], of 12.8 €/GJ for wood chips obtained in a scenario of sustainable forest management based on cow grazing, a representative value among those provided in the article:

$$fuel\ cost = 12.8\ €/GJ \cdot 13.5 GJ/t_{30\%} = 173 €/t_{30\%} \tag{19}$$

It is worth mentioning that such a result is far above the current market price of wood chips, reported between 56 €/t and 136 €/t in different European countries [266]. Such a difference is due to the fact that wood chips currently found in market are not collected and processed using sustainable practices, as the authors suggest doing.

3.3.1.5. Environmental impact data collection

The last group of input variables, and only required in the third and fourth stage of the research, namely the multi-objective optimization, includes the life-cycle CO_2 emissions for all electricity supply alternatives, that is PV modules, wind turbines, forest wood biomass gasification and the Spanish electricity grid. The values are presented in Table VIII.

Table VIII Life-cycle CO_2 emissions values

Data	*Value*	*Source*
PV life-cycle CO_2 emissions ($kgCO_2$/kWp)	439.9	[267]
Wind turbine life-cycle CO_2 emissions (gCO_2/kWh)	30	[268]
Forest wood biomass-based life-cycle CO_2 emissions (gCO_2/kWh)	60	[269]
Spanish grid electricity supply CO_2 emissions (gCO_2/kWh)	428.6	[270]

In the case of PV system life-cycle CO_2 emissions, it was chosen as representative the impact of a system by UPSolar with 439.9 $kgCO_2$/kWp [267]. This datum corresponds to about 48 gCO_2/kWh in a region with an average solar irradiation of 1650 kWh/(m^2·year) as the one under study, a figure in accordance with other accessed sources, such as 40-45 gCO_2/kWh reported by the NREL [271] and 46 gCO_2/kWh reported as median value by the IPCC and Eurelectric [272,273]:

$$\frac{439.9\ gCO_2}{Wp\ year}\cdot\frac{m^2 year}{1650\ kWh}\cdot\frac{265\ Wp}{1.46\ m^2}=48.4\ \frac{gCO_2}{kWh} \tag{20}$$

For wind power, the value of 30 gCO_2/kWh for an average 300 kW wind turbine [268] was used as representative of life-cycle CO_2 emissions.

With biomass gasification and combustion in a gas engine – generator group, the chosen value was 60 gCO_2/kWh, obtained from [269], a value in accordance with the range of 40-60 gCO_2/kWh given by NREL [274]. In this case, the value accounts for the logging, chipping, transport and other processes associated with biomass gathering and preparation. The emissions from syngas combustion were not accounted since biomass has a carbon neutral balance due to its carbon capture throughout lifetime before logging. It is claimed that this neutral balance is not accurate because the logging of forest wood biomass means a decrease in carbon stock that is equivalent to carbon emissions [275]. However, in this study this effect can be dodged because its impact is small compared with the environmental impact from logging, chipping and transport of forest wood biomass [230].

3.3.2. Optimization algorithm(s) design

The first important step performed when designing the optimization model was to choose the most suitable optimization algorithm for the problem at hand.

For HRESs optimization, as a result of the inherently non-linear variables found in this kind of problems involving stochastic variables such as weather patterns [4,207] or electricity demand patterns, the most preferred methodologies are genetic algorithms (GAs) and particle swarm optimization (PSO) algorithms [222], both heuristic approaches. Among the advantages of iterative algorithms highlight their low computational requirements that allow them to obtain the desired solutions without requiring huge amounts of computational resources [176]. In particular, GAs have been identified and used as one of the best alternatives for those cases where non-linear systems are involved as HRES cost optimization problems are [199] even in cases with only few variables involved because this method is very good attaining optimal solutions with non-linear relationships between variables [207].

According to [276], the concept of GA dates back to 1960s, and it is named after its use of the evolutionist theory of the survival of the most suitable individuals [277]. As in nature occurs, the weak and unfit species become extinct by natural selection, whereas the strongest ones reproduce themselves by crossing over between them. Therefore, the GA is based on the idea that the species carrying the better combination become dominant in their population, and this concept is extrapolated to a population of possible solutions in which the best-fit individuals are selected and crossed over in successive populations of individuals [276] so the least fitted solutions have small probability of reproduction whereas the best fitted solutions have high probability of reproduction [277].

This evolutionary process is usually started randomly, and the mechanism of elite individuals' selection gradually adjusts the population to the optimum solutions in successive iterations to eventually converge [276] into a single solution or a set of solutions, depending on whether the problem is single objective or multi-objective. GAs imitate genetic reproduction through the usage of mathematical operations that imitate best individuals' selection, crossover between the individuals and mutations.

The parameters that are usually analyzed for HRES optimization include not only the cost, which is the topic at hand, but also the lifetime environmental impact of the system, the reliability of supply or a combination of two or more of these parameters [168,176,180,199], obtaining in such multi-objective case a set of possible solutions called Pareto front.

The software used to run the optimization procedure is MATLAB R2013b and R2014a, in which GAs are already implemented in the ‘‘Optimization Toolbox’’.

3.3.2.1. Variables

The variables chosen to represent the different potential alternative systems are the area covered by PV modules pvArea, which is proportional to the number of PV modules pvNumber, and the number of wind turbines wtNumber. With these variables, the GA will treat the objective function as dependent of the system sizing and will provide as outputs the minimum Net Present Value and the values of both variables that lead to an optimal HRES sizing with a minimum NPV.

Wind turbine number variable is treated as an integer by the optimization algorithm for single objective optimization, whereas for multi-objective could not be done. Conversely, the PV area allows using decimal values thus reducing the computational requirements to run the GA. That is why the area is selected as the variable rather than the number of PV modules.

3.3.2.2. Fitness functions

The parameters that were sought to optimize in are the cost of the system in all four case studies and environmental impact in the 3rd and 4th case studies of multi-objective optimization. Therefore, two fitness functions have been defined, that is the Net Present Value (NPV), a cost metric obtained by adding and subtracting the discounted present values of all lifetime incomes and expenses (see Eq. (21)), respectively; and the life-cycle system CO_2 emissions, an environmental impact metric that accounts for all life-cycle greenhouse gas (see Eq. (34)).

Cost fitness function

Considering that lifecycle perspective is currently gaining importance in HRES’ optimization methodologies [223], the lifecycle cost has been chosen as the metric to optimize for cost. To do so, the chosen objective function is the Net Present Value (NPV) cost metric that is calculated by adding the discounted present values of all lifetime incomes and subtracting the discounted present costs along lifetime of the system, i.e. considering the expenses and revenues 25 years ahead. Therefore, this cost metric is accounting for the future cash-flows’ present value by converting them to the value of money at the time of investment after applying inflation and discount rate to all of them. Hence, the system lifetime costs can be analyzed discounting external effects like the financial volatility or oscillations inherent to the free market economy that affect the value of money.

To appropriately compute all the costs throughout the entire lifetime of the system, the initial investment, operation and maintenance, equipment replacement and electricity purchase costs have been taken into account, similarly as done in [223]. On the other hand, the benefits from selling the electricity to the grid and the profit from equipment sale at the end of the lifetime have been considered on the benefits side:

$$NPV = C_{investment} + NPV_{O\&M} + NPV_{biofuel} + NPV_{repl} - NPV_{electricity} - NPV_{endlife} = f(pvArea, wtNumber) \tag{21}$$

(21) being the fitness function. In the following paragraphs, the five terms in (21), namely cost of initial investment $C_{investment}$, NPV of Operation and Maintenance of equipment $NPV_{O\&M}$, NPV of biofuel purchase $NPV_{biofuel}$, only included whenever required, NPV of components' replacement throughout lifetime NPV_{repl}, NPV of electricity acquisition and sale $NPV_{electricity}$ and NPV of equipment sale at system end of life $NPV_{endlife}$, are detailed.

The initial investment cost refers to the initial expense required for equipment purchase. It has been implemented as a function of the number of modules and the number of wind turbines installed:

$$C_{investment} = C_{PV} \cdot pvNumber \cdot P_{module} + C_{WT} \cdot wtNumber \cdot P_{turbine} + C_{BIO} \cdot P_{ICE} \tag{22}$$

where C_{PV} is the capital cost of PV panels in $/kW, P_{module} is the nominal power of each module; C_{WT} is the capital cost of wind turbines in $/kW and $P_{turbine}$ is the wind turbine nominal power; C_{BIO} is the capital cost of biomass conversion equipment in $/kW – including gasifier, syngas cooling and cleaning system and ICE-generator group – and P_{ICE} is the nominal power of the ICE. As the input variable is pvArea, the number of PV modules is expressed as follows:

$$pvNumber = pvArea/panelArea \tag{23}$$

where pvArea is the independent variable and panelArea is the area covered by a single PV module, in the first three case studies 1.277 m2 and in the fourth one 1.460 m2.

The second term of the NPV definition are the discounted operation and maintenance (O&M) costs, which are calculated taking into account the annual inflation rate [256]:

$$NPV_{O\&M} = \sum_{i=1}^{N} C_{O\&M,k} \frac{(1+g)^i}{(1+IR)^i} \tag{24}$$

where $C_{O\&M\_k}$ refers to the cost of operation and maintenance of component k, g is the general inflation rate, IR is the interest rate, and N is the system lifetime.

$NPV_{biofuel}$ term refers to the cost of biomass fuel acquisition. Such a term is obtained by multiplying the amount of biomass burnt in kg by its cost, adjusted for inflation:

$$NPV_{biofuel} = \sum_{i=1}^{N} \frac{P_{BIO}}{LHV \cdot \eta_{BIO}} C_{Wood} \frac{(1+g)^{i}}{(1+IR)^{i}} \tag{25}$$

where P_{BIO} is the power produced at each hour of the 365 days of a year by the biomass unit, LHV is the lower heating value of the biofuel used, C_{Wood} is the cost of wood fuel, and η_{BIO} is the total efficiency of the gasifier-ICE equipment.

The next term in the NPV definition are the discounted present costs of equipment replacement that are also calculated considering the annual inflation rate [256]:

$$NPV_{repl\_k} = \sum_{i=1}^{N\_first_{repl\_k}} C_k \frac{(1+g_k)^{i \cdot N_k}}{(1+IR)^{i \cdot N_k}} + \sum_{i=N_{first_{repl}}+1}^{N\_repl\_k} C_k \frac{(1+g_k)^{Y_k}(1+g)^{i \cdot N_k - Y_k}}{(1+IR)^{i \cdot N_k}} \tag{26}$$

where C_k is the acquisition cost of component k, g_k is the expected inflation rate of the acquisition cost of component k and N_k is the lifetime of such a component. N_{repl_k} and $N_{firstrepl\_k}$ are the total number of replacements during the system lifetime and during the years that the price of the component is changing at g_k inflation rate, respectively, and are calculated as follows [256]:

$$N_{\_repl\_k} = int\left[\frac{N}{Y_k}\right] \tag{27}$$

$$N_{\_first_{repl}\_k} = int\left[\frac{Yg\_k}{Y_k}\right] \tag{28}$$

where Y_{g_k} is the number of years required for technology k to reach the technological maturity with a cost reduction of L_{g_k} [256]:

$$Y_{g\_k} = \frac{\log\left(1+L_{g\_k}\right)}{\log(1+g_k)} \tag{29}$$

The only components of the system that have to be replaced during the system lifetime, which is 25 years, are wind turbines and solar PV converters. PV modules' performance is warranted up to 25 years, which has been selected as the system lifetime. Regarding the biomass-to-electricity equipment, it is expected to last 25 years or more with appropriate maintenance [234].

On the revenue side of the equation, there are benefits or cost of electricity sale or purchase. To effectively account for this, the hourly net power production has been calculated for each hour:

$$NPP = P_{PV} + P_{WT} - demand \tag{30}$$

where P_{PV} and P_{WT} are the PV and wind power produced at each hour of the 365 days of a year, and demand is the electricity demand of the location under study.

Whenever Equation (30) yields a negative value, the PV-wind system is not producing enough power to match the demand. In these cases, the system is designed to turn on the biomass engine at a full load. If the result of doing so still yields a negative net power production, then electricity is purchased from the grid at retail price. Conversely, if it yields a positive value, the surplus is sold to the electricity pool at market price. The same is done whenever Equation (30) yields a positive value, meaning that more power is produced than demanded.

The benefits of electricity sale are calculated as follows:

$$NPV_{electricity} = \sum_{i=1}^{N} \sum_{j=1}^{8760} C_{electr\_j} \cdot NPP_j \cdot \frac{\left(1 + g_{electricity}\right)^i}{(1 + IR)^i} \tag{31}$$

Additionally, for positive net power production, the discounted present incomes from purchasing the electricity are:

$$NPV_{electricity} = \sum_{i=1}^{N} \sum_{j=1}^{8760} C_{pool\_j} \cdot NPP_j \cdot \frac{\left(1 + g_{electricity}\right)^i}{(1 + IR)^i} \tag{32}$$

It should be pointed out that, in the first case, NPP < 0 or lack of electricity, the $\text{NPV}_{\text{electricity}}$ will take negative values, whereas, in the second case, NPP > 0 or surplus of electricity, the $\text{NPV}_{\text{electricity}}$ will take positive values. As a result, this term of $\text{NPV}_{\text{electricity}}$ is computed in the benefits side, as previously mentioned.

Additionally on the revenue side of the NPV Equation (X), the discounted present values of income derived from equipment sale at the end of system lifetime are found. They are calculated as follows [234]:

$$NPV_{endLife\_k} = C_k \left[1 - \frac{N_{repl\_k} Y_k}{N}\right] \left(\frac{(1 + g_k)^{Y_{g\_k}} (1 + g)^{N - Y_{g\_k}}}{(1 + IR)^N}\right) \tag{33}$$

Environmental Impact fitness function

Regarding the measure of environmental impact, the life-cycle CO_2 emissions have been selected as a representative metric. It is important to highlight the relevance of the life-cycle perspective, accounting the entire life-cycle emissions rather than the use-phase emissions alone. It is calculated as follows:

$$EI = EI_{PV} + EI_{W} + EI_{BIO} + EI_{GRID} = f(pvArea, wtNumber) \qquad (34)$$

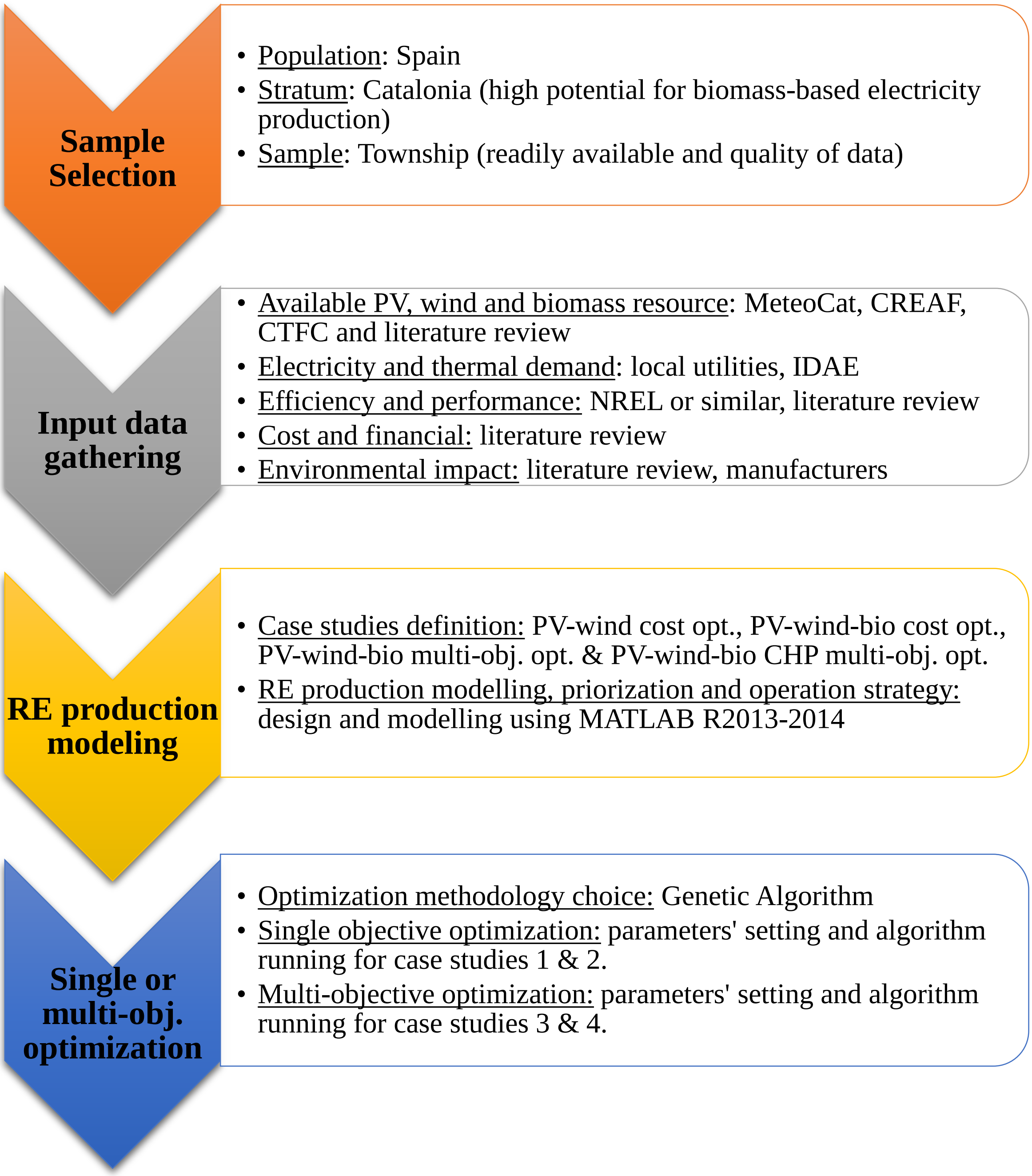
(34) being the fitness function. EI_{PV}, EI_{W} and EI_{BIO} are the environmental impact of the electricity produced by the PV, wind and biomass subsystems, respectively; and EI_{GRID} is the environmental impact of the electricity purchased to the electricity grid, calculated with the actual grid emissions.

The environmental impact of the PV subsystem is proportional to the size of the installation, as given in [267], whereas the impact of wind and biomass subsystems are proportional to the amount of electricity generated with these technologies [268,269], similarly as calculated for the grid using the data in [270].

3.4. Summary (methodology overview)

With the described methodology, it was sought to obtain a useful HRES sizing tool that provides the minimum cost solution or a set of optimal solutions given the electricity demand or the combined electricity and thermal demand of a particular location.

The methodology described in this section and further developed in the following section detailing the particularities of the different case studies can be summarized with the following flow chart (see Fig. 13):



Sample Selection

- Population: Spain
- Stratum: Catalonia (high potential for biomass-based electricity production)
- Sample: Township (readily available and quality of data)

Input data gathering

- Available PV, wind and biomass resource: MeteoCat, CREAF, CTFC and literature review
- Electricity and thermal demand: local utilities, IDAE
- Efficiency and performance: NREL or similar, literature review
- Cost and financial: literature review
- Environmental impact: literature review, manufacturers

RE production modeling

- Case studies definition: PV-wind cost opt., PV-wind-bio cost opt., PV-wind-bio multi-obj. opt. & PV-wind-bio CHP multi-obj. opt.
- RE production modelling, priorization and operation strategy: design and modelling using MATLAB R2013-2014

Single or multi-obj. optimization

- Optimization methodology choice: Genetic Algorithm
- Single objective optimization: parameters' setting and algorithm running for case studies 1 & 2.
- Multi-objective optimization: parameters' setting and algorithm running for case studies 3 & 4.

Fig. 13 Flow chart summarizing the designed methodology

4. Case studies

As previously claimed, the system layout has been continuously modified during the development of the research, in order to assess different alternatives or to optimize the system sizing according to different criteria. To do so, four case studies were performed in order to assess different possibilities. However, all the case studies share certain characteristics: the grid connection and the hybridization of, at least, solar PV and wind power technologies. Throughout the following subsections, these different case studies are deeply detailed.

There are also presented the main findings of the research. To provide a useful interpretation of the results, a sensitivity analysis has been performed in all the four case studies. For the single objective optimization, they are referenced to a base case which is the one obtained by implementing the described methodology with the values for the input variables provided in the previous chapters. For the multi-objective optimization, no single solution is obtained, but a set of optimums are presented in the so-called Pareto front. The sensitivity analysis was done with respect to a base case, and comparing the optimum that is obtained when giving the same relative importance to both criteria, although multiple other solutions could be also optimal with different weighing of the criteria.

Many conclusions can be extracted from the gathered results and findings detailed in the previous chapter. These have been classified according to each case study in the following sections.

4.1. Grid-connected solar PV-wind HRES

This case study consisted in a cost optimization of a grid-connected PV-wind HRES to supply the electricity demand of the township under study under a supply condition of net balance, meaning that the total amount of electricity produced equals or surpasses the total amount of electricity demanded during an entire year, regardless of the supply – demand matching hour to hour.

4.1.1. System description

The first system layout consisted in a grid-connected PV – wind system without any kind of storage units as represented in Fig. 14. Therefore, the system is more flexible than a stand-alone one due to its ability to supply the surplus of energy produced in low-demand and/or high-generation periods and to consume the lack of energy when the demand is higher than the production of the system. In addition, a grid-connected system requires a lower initial investment as a result of its fewer components because it does not require battery banks that otherwise would be necessary [206] and that can mean as much as 50% of the total life cycle cost of the installation [32]. The system was designed as modular since it allows obtaining appropriate installed capacity by only increasing or decreasing the number of PV modules or wind turbines installed.

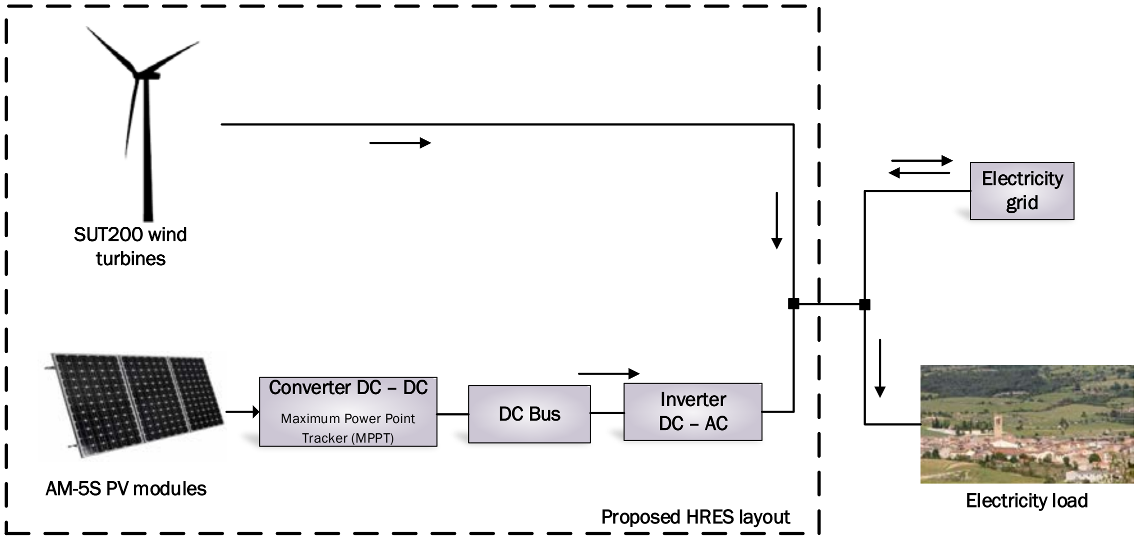


Fig. 14 Grid-connected PV-wind HRES for cost optimization

The chosen components were the AmeriSolar AS-5M PV module with a nominal power of 210W and 1.277 m2 per module [249] and the SUT200 wind turbine with a nominal power of 200 kW [238]. The power supply-related variables used to optimize the system were the area covered by the PV modules, which is proportional to the number of PV modules, and the number of wind turbines installed.

The design condition of net annual balance was selected as the constraint for supply – demand match. By annual net balance it is understood a design constraint that stablishes that the total amount of electricity generated by the HRES matches the total demand of the location under study throughout the year, but not necessarily hour by hour, but in global terms. Therefore, the lack of electricity generation at those hours with low availability of solar and wind resources can be counteracted by the excess of electricity production at other times when the system can produce more electricity that is being demanded.

The entire methodology of the proposed grid-connected HRES power balance approach is detailed in Fig. 15:

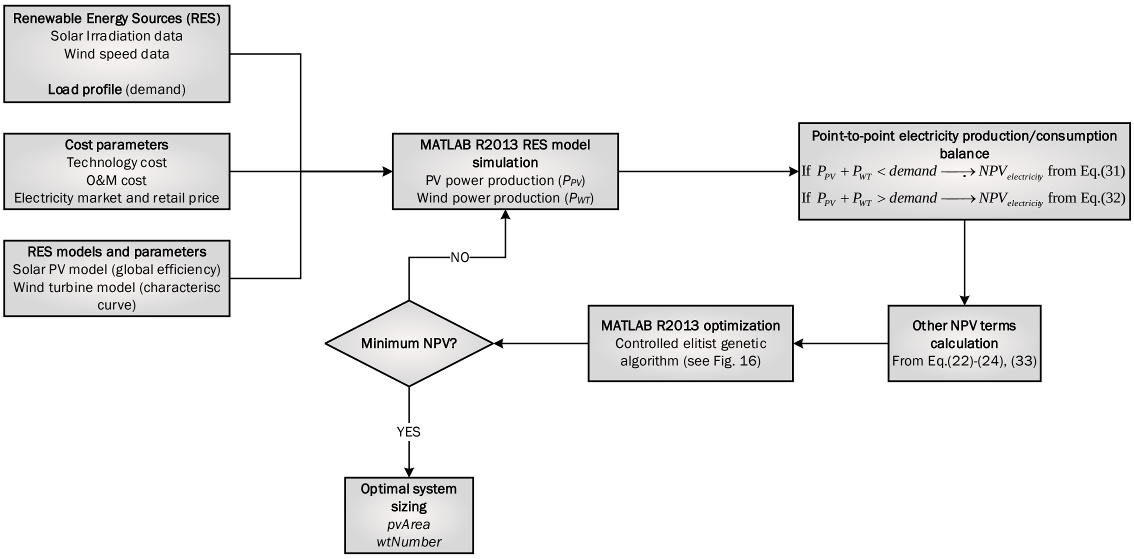


Fig. 15 Proposed HRES cost optimization approach for grid-connected PV-wind HRES

4.1.2. Optimization process

Once the objective function is properly defined (see 3.3.2.2) and all the input variables introduced, the optimization algorithm can be run. From all the available alternatives, the GA optimization methodology has been selected for its easiness to tackle multiple solution problems using a random population of potential solutions and evolutionary methods to narrow down the possibilities according to the fitness of each possible solution until finding the optimum. The methodology starts with the generation of a random population with a size of:

$$PopulationSize = \max(\min(10 \cdot numberOfVars, 100), 40) \tag{34}$$

From this population the best individuals are selected according to the fitness function that is sought to optimize. The individuals are scaled by a ‘‘Rank’’ criterion meaning that the top individuals are selected; in this case, 5% is selected:

$$EliteCount = 0.05 \cdot \max(\min(10 \cdot numberOfVars, 100), 40) \tag{35}$$

Once they are selected, a new generation of ‘‘offspring’’ individuals is created via the crossover operation, that is the creation of a new individual or child from two existent individuals or parents, of existent specimens. The crossover fraction is set to 80% and the method to ‘‘Scattered’’. Mutation does not occur when one or more variables are integer variables. Migration is another process that allows movement of individuals within the space of solutions. In this case, 20% of individuals migrate in ‘‘forward’’ direction every 20 generations.

From the old set of individuals, the ‘‘least-fit’’ individuals are rejected and replaced by the new generation and this process is repeated many times until the minimum value of the fitness function is found. The stopping criterion is the condition of having an average change in the fitness function value below the function tolerance, in this case $1{\cdot}10^6$ once the stall generation, in this case 50, is reached.

Input variables upper and lower bounds are used to introduce restrictions in the potential solutions, so the lower bounds are 0 m^2 of area covered by PV modules and 0 wind turbines, the case of no system installed. The upper bounds set are the maximum allowable installed capacity of each renewable energy source. They have been assumed to be higher enough to not introduce any limitation but they could be set to a certain value if there were limitations in terms of maximum initial investment or available land useful to install the equipment, for instance.

Fig. 16 schematizes the single objective optimization process by means of GA and specifies the selected parameters, also shown in Table IX.

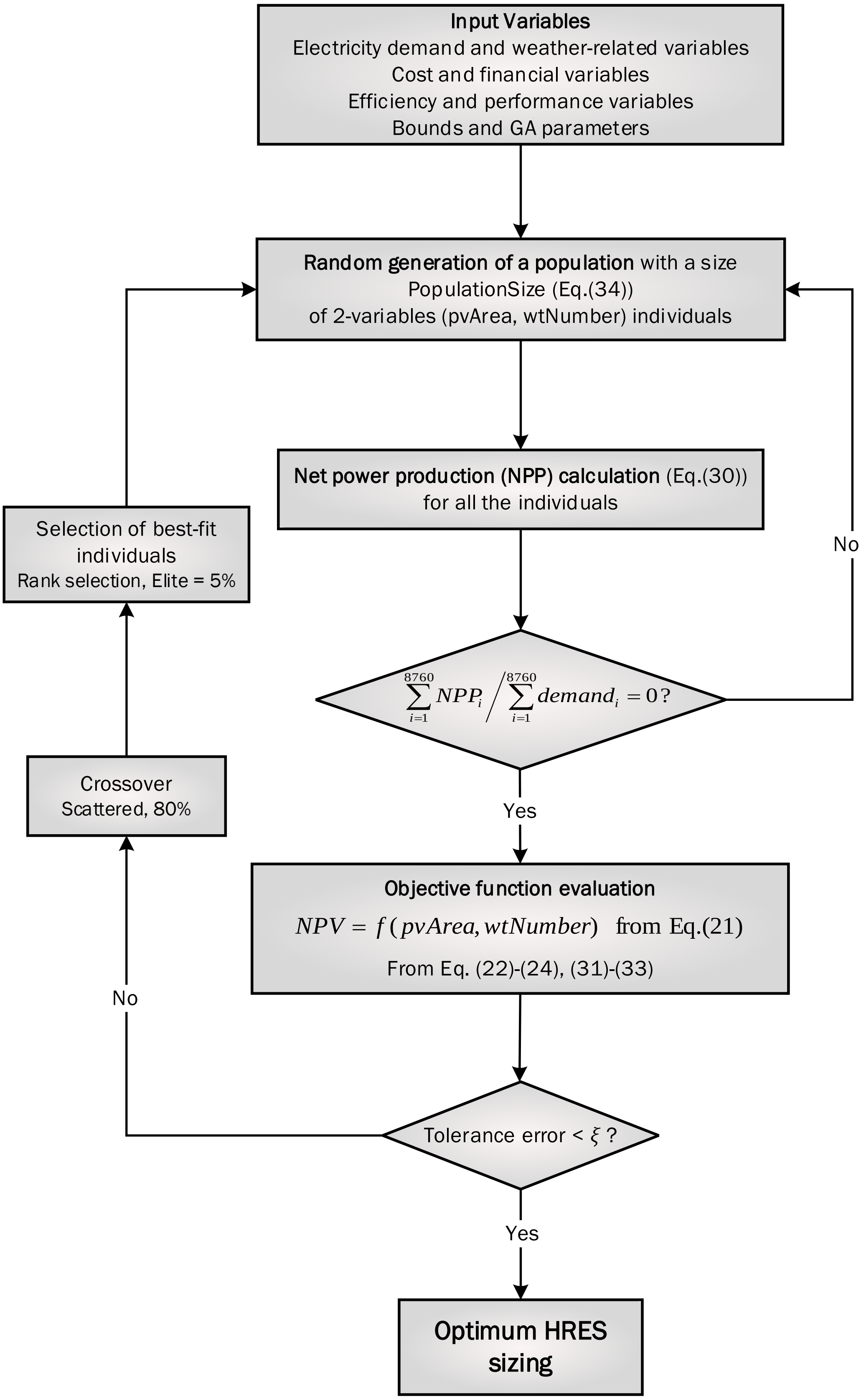


Fig. 16 Optimization model and parameters for single objective HRES cost optimization

Table IX GA parameters for single objective HRES cost optimization

Data	Value
Population size	Eq. (34)
Elite count	5% best individuals
Crossover fraction and method	80%, scattered
Tolerance function value	10^6
Stopping criteria	50 generations or tolerance function
Lower bounds	[0 m^2; 0 WTs]
Upper bounds	[25000 m^2; 25 WTs]

4.1.3. Results and findings

With this first case study, and with aim to contextualize the values obtained, all the simulated cases were compared with the no-HRES case, i.e. the case of a system with no solar nor wind renewable sources. This is a reduction of the general case used to estimate the cost of supplying the demand according to the actual situation in which the electricity is purchased from the local utility at the market retail price.

4.1.3.1. No-HRES scenario

The no-HRES case was obtained by running the algorithm with zero solar PV power and zero wind power production. The total electricity demand in one year, obtained from the data in [237], equals 4657.97 MWh. The cost of supplying this demand during the 25 years that a HRES would last, and considering the actual demand at each hour is purchased at the price established in the tariff with hourly discrimination is:

$$no - HRES\ NPV = \$2.3446 \cdot 10^7 = \$23.446M \tag{36}$$

That would be the total cost of supplying the present demand considering that electricity price suffers an annual inflation of 3% (see Table VII).

4.1.3.2. HRES base case scenario

The base-case is the case simulated using all the variables as previously defined in Table V, Table VI and Table VII. The wind data used were extrapolated to 35 m of rotor height, found at the middle between 30 and 40 m, the minimum and maximum values provided by the manufacturer [238]. The optimization procedure provides the following result:

$$base - case\ NPV = \$1.5353 \cdot 10^7 = \$15.353M \tag{37}$$

This result is reached with a system with 621.61 m^2 of PV installation and 18 wind turbines, equivalent to 102.22 kW of PV power and 3.6MW of wind power, a HRES that would require an initial investment of $\$1.0108 \cdot 10^7 = \$10.108M$.

For comparison purposes, the evolution of NPV of No-HRES and base case scenarios during the system lifetime are shown in Fig. 17.

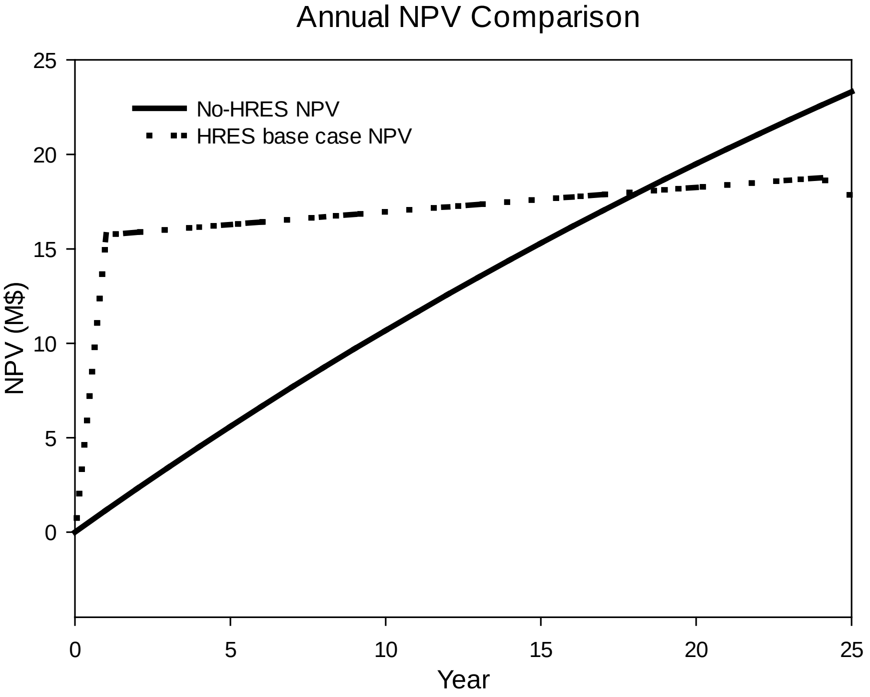


Fig. 17 Comparison of NPV evolution throughout 25 years of system lifetime for No-HRES and HRES base case scenarios in the first case study

4.1.3.3. Sensitivity analysis

The sensitivity analysis was performed introducing percent variations in the most relevant parameters of the system to observer how these variations vary the output of the system.

The variables chosen to be studied in this sensitivity analysis were: PV technology capital cost, wind technology capital cost, electricity price, general inflation rate, module and wind turbine reference efficiencies and interest rate. The change introduced in the values of these variables induces variations in the result of different magnitude. The results are shown in Table X.

Table X Sensitivity analysis of Grid-connected PV-wind HRES for cost optimization

Variable	Variation	NPV change
PV capital cost	+10%	+0.2606%
Wind capital cost	+10%	+9.3811%
Electricity price	+10%	+0.0000%
General inflation rate (g)	+10%	+1.2378%
Interest rate	+10%	-2.0020%
Module reference efficiency	+10%	-0.2606%
Wind turbine reference efficiency	+10%	-8.5993%

4.1.4. Conclusions

In this first case study, the HRES combined solar PV and wind power technologies at the most appropriate scales to supply the existent demand with a minimum life cycle cost that was measured using the Net Present Value, an economic metric that discounts the future costs and revenues at the time of investment. The designed optimization algorithm performs an analysis with one hour accuracy in order to capture the daily and seasonal patterns of both weather-dependent renewable energies and electricity demand. Moreover, it performs a meticulous calculation of the renewable electricity generation patterns and thus the profits and revenues derived from it, not only because of the different amount of energy produced at each hour but also because of the consideration of the different market and retail prices at each hour of the day. A sensitivity analysis was performed through the simulation of slight variations of a base case that served to understand the behavior of the results given by the algorithm in front of changes in the most important input variables. Such analysis also included a comparison with the no-HRES scenario that helps understanding how significant are the cost savings compared with the present situation costs.

Another aspect to highlight is that the algorithm responds well to positive and negative changes in the analyzed variables. For instance, the NPV obtained from the algorithm increases when cost variables increase, whereas decreases when efficiency of RE technologies improves. Again, wind turbine efficiency improvements have greater impacts on the result than PV panel efficiency improvements due to the greater importance of wind installation in the case under study.

The results, therefore, showed that in the location under study wind power is the renewable resource with greater impact but that it is well complemented by solar resource. Such HRES also proves its appropriateness to replace the present scenario in which electricity consumption is only supplied by the electrical grid, with potential savings amounting up to 40% of present cost structure throughout the next 25 years.

4.2. Grid-connected solar PV-wind-biomass HRES single objective optimization

This second case study consisted in a cost minimization of a grid-connected PV-wind-biomass HRES under a supply condition in which PV and wind are the first RES to supply, followed by the biomass working at full load to maximize the efficiency. Only at those times when PV, nor wind nor biomass are enough to supply the demand the system takes advantage of the grid.

4.2.1. System description

In this case, the layout of the system consisted in a grid-connected PV–wind–forest wood biomass hybrid energy system. Therefore, the system allows limiting or reducing initial investments as both grid connection and biomass energy, which has a short response time so it can be used to backup stochastic renewable energy sources whenever required, provide flexibility and the possibility of dispatching energy on demand instead of requiring a battery as with stand-alone systems [206]. In contrast, grid-connection allows the supplying of surplus energy generated in low-demand or high-renewable energy generation periods, while consuming the electricity required when demand exceeds production. The layout of the analyzed HRES is represented in Fig. 18.

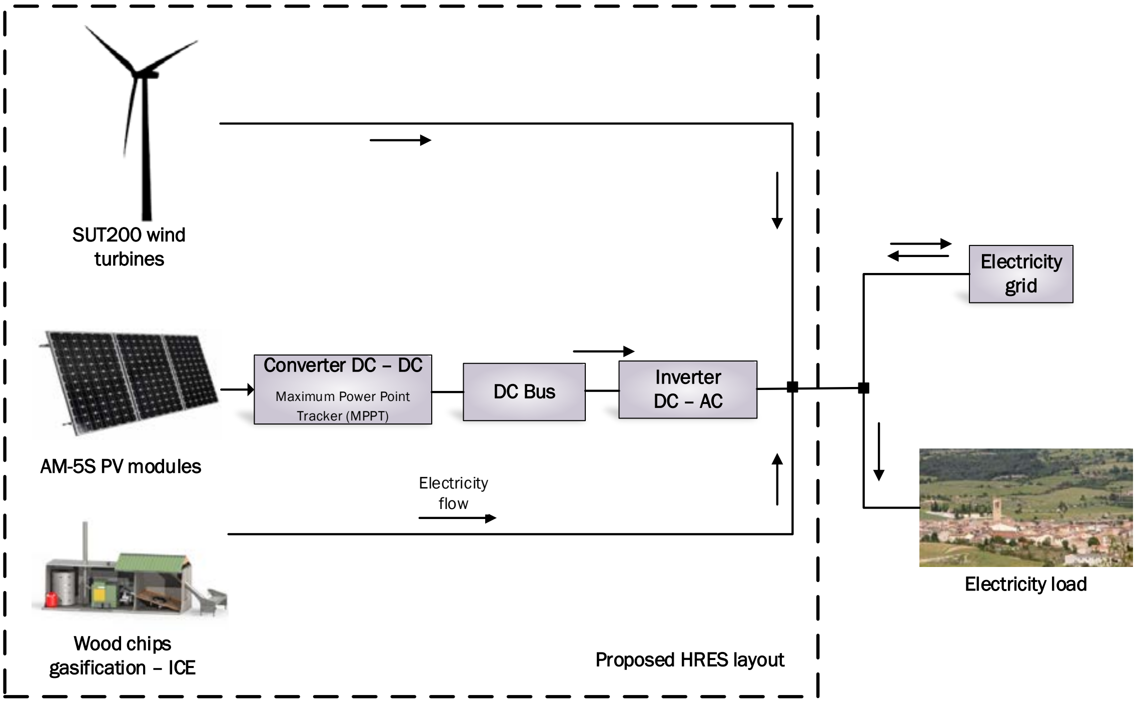


Fig. 18 Grid-connected PV-wind-biomass HRES for cost optimization

The proposed model deals with PV and wind systems as modular systems, thus allowing to obtain the appropriate installed capacity by increasing or decreasing the number of PV modules and wind turbines installed. As in the previous layout, PV modules were AmeriSolar AS-5Ms, a module with 210 W and 1.277 m^2 [249], and wind turbines are SUT200 turbines with a nominal power of 200 kW [238]. The system size is optimized through the determination of the optimum area covered by the PV modules and the number of wind turbines.

On the other hand, the considered biomass subsystem includes an installed single gasifier coupled with an ICE – generator of 500 kWe. The choice of scale comes from the average value of hourly demand in the location under study. In order to have the best commercially available efficiency, the option of a single ICE has been selected. In biomass-based electricity generation equipment, unlike in the previously mentioned PV and wind subsystems, system scale has significant impact on the efficiency, being preferable to select a single ICE. The conversion technology consists in forest wood chip gasification in a downdraft gasifier, with subsequent combustion of the obtained syngas in a gas engine after gas cleaning and cooling. This is the most efficient conversion path at the scale of 100-1000 kW [84,227] and it also beneficial in terms of maintenance and equipment lifetime [87]. The biomass subsystem is thought to work always at full load in order to maximize generator efficiency that otherwise would rapidly decay [88].

Another important aspect of the system layout is how to establish the priorities of using one source of another whenever there are one or more available, and the design condition of supply-demand match. For environmental reasons, this work proposes prioritizing PV and wind power usage ahead of biomass power generation, which is used at its full load to backup PV and wind whenever they are not available. Therefore, when demand exceeds the available supply from solar PV and wind power sources, the biomass engine is turned on at its full load, and the surplus energy—if any—is supplied to the grid and sold to the market. Only in those cases when PV, wind, and biomass power are not enough to match existent demand, the system will purchase electricity from the grid.

Furthermore, it is important to stress the importance of using forest wood biomass as a source of energy to back up the stochastic renewable energy sources. Its exploitation would not only stimulate the socio-economic progress of rural areas, as previously mentioned, but it also would encourage the improvement of forest management [235], thus counteracting the current tendency towards the abandonment of many forests in Mediterranean regions [30]. Evidence shows that, in those places where the overall fuel load is reduced, the risk of forest fires is also reduced [48]. Therefore, active forest management seems to be a goal worth pursuing, considering its potential to reduce wildfire’s risk [164] at which that Mediterranean forests are exposed to [45], Spain being one of the most vulnerable countries [166], and the negative economic and environmental impacts that they cause [165]. However, it is important to use the forest wood biomass at a rate that does not exceed the self-growth rate of the forest to not put the available resource at stake, thus ensuring long-term ecosystem functionality [50] and increasing forest productivity as the forest age is decreased [30].

The entire methodology of the proposed grid-connected HRES power balance approach is detailed in Fig. 19.

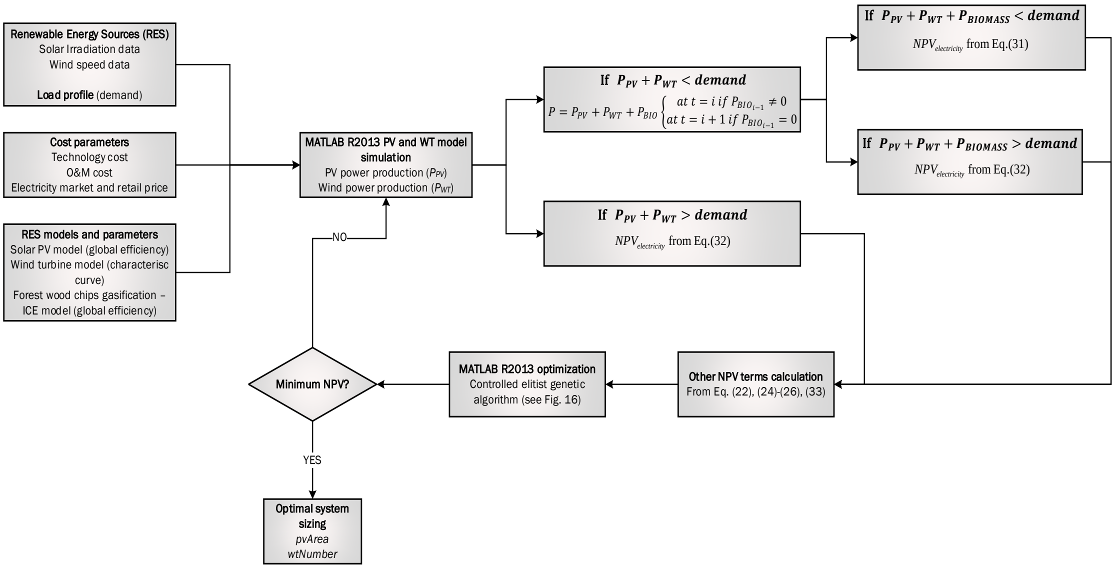


Fig. 19 Proposed HRES cost optimization approach for grid-connected PV-wind-biomass HRES

4.2.2. Optimization process

The optimization process was performed according to the same strategy and GA parameters as the first case study. Please refer to 4.1.2, specifically to Fig. 16 and Table IX for further detail regarding the operations performed by the algorithm and the driving parameters of such process.

4.2.3. Results and findings

In this second case study, the same outputs as in the 1st one were sought. The scenario obtained using the suggested values for all the input variables and in the sample location has been taken as the base-case scenario. The electricity demand data in this case was provided by [236]. Additionally, a sensitivity analysis was performed to better acknowledge the influence of the most important variables of the model in the result.

4.2.3.1. HRES base case scenario

Under the assumptions presented in the previous sections, the following result was provided by the optimization model:

$$base - case\ NPV = \$3.0697 \cdot 10^{7} = \$30.697M \qquad (38)$$

As shown in Fig. 20, the result was reached by convergence of results in less than 60 iterations.

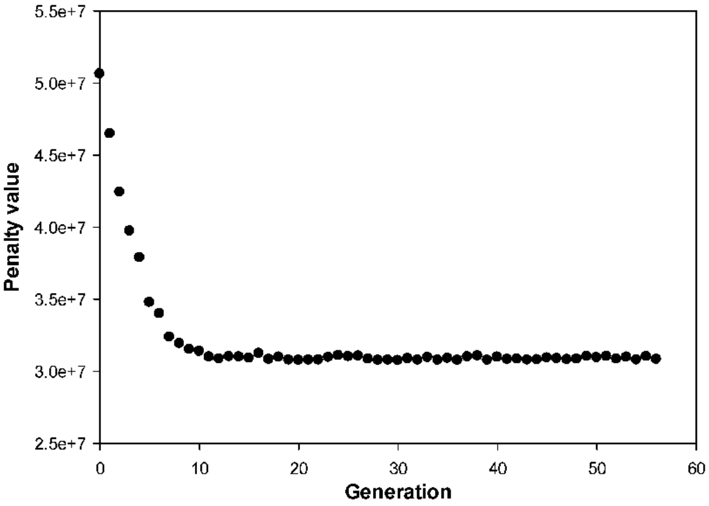


Fig. 20 MATLAB iterations penalty values

This NPV is the life-cycle cost of a HRES consisting of 6044.23 m^2 of PV installation, three wind turbines, and the biomass subsystem of 500 kWe. These values mean an installation of 993.96 kW of PV power, 600 kW of wind power, and 500 kW of biomass electrical power from forest wood chips.

The upfront investment required to install such a HRES is $\$7.3971 \cdot 10^{6} = \$7.397M$. This figure is significantly lower, approximately 25% less than the one obtained in [226], with a PV-wind HRES backed up only with a grid. However, the NPV approximately doubles the one obtained in [226] due to fuel consumption costs, which are around $220,000–230,000 per year, and electricity purchasing costs, because, in this case, the system does not produce the same amount of electricity that is demanded on an annual basis.

The fuel consumption ranges from 1017 metric tons per year at year one to 1050 metric tons per year at year 25. The consumption increase is due to the PV power decrease, caused by the aging of modules. At this point, the authors considered it relevant to compare such values with biomass availability—given that the available biomass is limited by forest self-growth rate—from local forests to ensure that the system can run autonomously only using local resources. According to [230,233] the growth rate of Mediterranean pine and oak forests is 1.6 metric tons of dry wood, per hectare, each year. This means two metric tons of wood at 20% of moisture content per hectare.

Considering that the region where the sample location is found has approximately 2200 hectares of forested area, the available amount of wood chips, without putting the survival of local forests at stake, is 4400 metric tons of wood at 20% moisture content each year. Therefore, the proposed HRES would require only one fourth of available sustainable forest wood chips.

For comparison purposes, Fig. 21 summarizes the annual accumulated costs of the system against the current annual costs from electricity purchase to the utility.

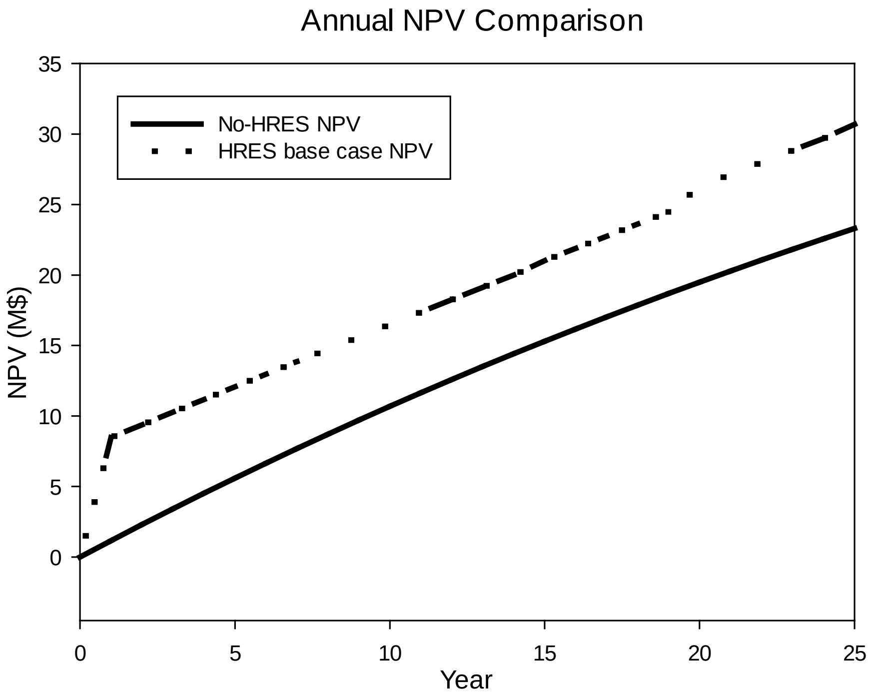


Fig. 21 Comparison of NPV evolution throughout 25 years of system life time for No-HRES and HRES base case scenarios in the second case study

4.2.3.2. Sensitivity Analysis

The sensitivity analysis was done setting a 10% variation in the values of the following variables: PV technology capital cost, wind technology capital cost, biomass gasifier-ICE technology cost, wood chips (fuel) cost, electricity price, general inflation rate, interest rate, PV modules, wind turbines, and biomass equipment reference efficiencies and wood chip LHV, which is inversely proportional to moisture content. These changes induce variations in the results of the optimization process, the NPV. The results are shown in Table XI.

In some cases, changes in system sizing were observed. Particularly, increases in PV capital cost lead to readjustments of system sizing, decreasing the PV subsystem size and increasing the number of wind turbines from three to four. Similar behavior is shown for fuel cost increases, resizing the system to a similar PV subsystem size and four wind turbines as well. The same occurs if electricity prices increase, in which case an additional wind turbine is desirable.

Regarding technology efficiencies, PV efficiency improvement does not lead to system size changes, but, on the other hand, biomass and wind turbine efficiency improvements imply relevant HRES size changes. Under the hypothesis of improved wind turbine efficiency, a system with one more wind turbine and 600 m^2 of solar installation less proves to be the best alternative, whereas under the hypothesis of biomass conversion efficiency and LHV improvements a reduction of 300 m^2 of PV subsystem leads to the minimum NPV system, with more biomass capacity factor.

Table XI Sensitivity analysis of Grid-connected PV-wind-biomass HRES for cost optimization

Variable	Variation	NPV change
PV capital cost	+10%	+1.055%
Wind capital cost	+10%	+0.773%
Fuel cost	+10%	+1.629%
Biomass capital cost	+10%	+0.652%
Electricity price	+10%	+3.808%
General inflation rate (g)	+10%	+0.764%
Interest rate	+10%	-3.264%
Module reference efficiency	+10%	-1.457%
Wind turbine reference efficiency	+10%	-1.075%
Biomass gasifier – ICE efficiency	+10%	-1.557%
Biomass LHV	+10%	-1.531%

4.2.4. Conclusions

The work performed in this second case study consisted on the design and validation of an optimization methodology for minimum life-cycle cost grid-connected HRES, based on the usage of solar, wind, and forest wood chips energy sources. The methodology has proved to be effective and helpful for decision-makers, as it provides a system sizing that minimizes life-cycle costs, expressed as Net Present Value (NPV). The results provided are based on the treatment of data with an accuracy of one hour, for both renewable energy generation and electricity demand patterns, thus, giving a trustworthy result.

The proposed HRES prioritizes solar PV and wind power technologies and uses biomass power in cases where solar and wind resources are not enough to fulfill the load demand. Biomass power is used at a full load to maximize the technology efficiency, and, if this leads to excess energy production, the surplus is sold in the electricity pool. Conversely, if the sum of biomass, solar and wind power is still not enough to fulfill the demand, electricity is purchased from the utility company.

The results obtained for the proposed validation case show that a system consisting of 6044 m^2 (994 kW) of PV power, three wind turbines (600 kW) of wind power, and 500 kW of biomass power with a yearly consumption of 1000–1050 metric tons would be the best option in terms of life-cycle cost. Such system would require an initial investment of 7.4 million US Dollars, and would suppose a 30.7 million US Dollar cost throughout its lifetime. From the comparison with the life time costs of electricity purchase from the utility company, it can be seen that the system would have similar annual costs to electricity purchase, but that the difference in life-cycle cost is roughly the initial investment required to install the system (see Fig. 21).

4.3. Grid-connected solar PV-wind-biomass HRES multi-objective optimization

This third case study consisted in a multi-objective optimization of a grid-connected PV-wind-biomass HRES according to both environmental impact and cost criteria. The strategy of operation was the same as in the previous case, prioritizing the usage of PV and wind sources of energy, then biomass and finally the grid.

4.3.1. System description

This third case study consists in the same layout as the second case study, described in the previous section. The difference is found in the optimization methodology, in which a second criterion was introduced to perform a multi-objective optimization. Hence, the reader is referred to Fig. 19 for a system layout and mode of operation description. In this multi-objective optimization case, however, the PV modules were substituted by the UP-M265M, a model with a peak power of 265 Wp and 1.46 m^2 [253], to improve the accuracy of PV subsystem life-cycle environmental impact, which is provided by the manufacturer [267].

The resulting layout of the analyzed HRES is represented in Fig. 22.

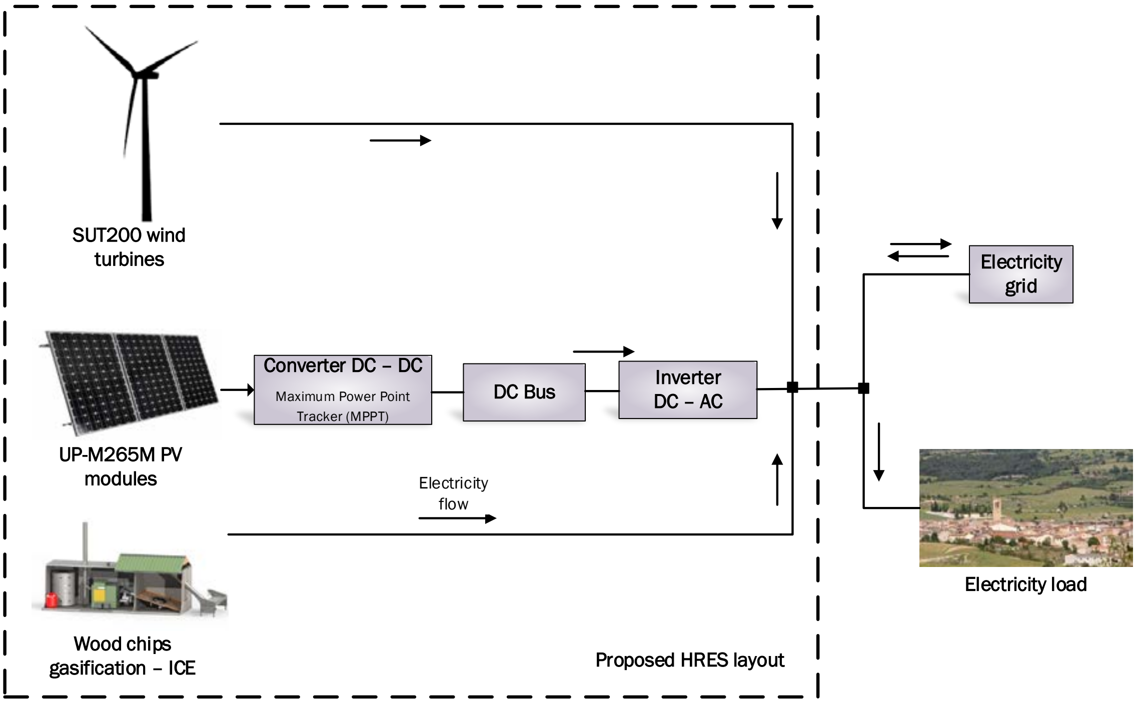


Fig. 22 Grid-connected PV-wind-biomass HRES for multi-objective life-cycle cost and environmental impact optimization

4.3.2. Optimization process

With multi-objective optimization, the affecting parameters are slightly different with respect to single objective optimization. The ones worth highlighting for their influence on algorithm performance and its ability to tackle the set of optimum solutions in the Pareto front are presented in Table XII and shown in Fig. 23 together with the optimization model.

Table XII GA parameters for multi-objective HRES cost-EI optimization

Data	Value
Population size	100 individuals
Pareto fraction	35%
Maximum number of generations	500 generations
Tolerance function value	$1 \cdot 10^{-4}$
Lower bounds	[0 m^2; 0 WTs]
Upper bounds	[25000 m^2; 25 WTs]

The population size has been set to 100, 50 times the number of variables, to ensure a diverse potential of solutions when running the GA.

The Pareto fraction is the percentage of possible solutions that are forced to be maintained as optimums, the rest would be object of reproductions, migrations and mutations, which were established at their default rates, 80% for reproduction with an intermediate cross-over function that gives the same weight to both “parents” and 20% for forward migration. Mutation was set to be “constraint dependent” so slight changes in the individuals do not lead to a constraint violation.

The stopping criterion was set through the maximum number of generations and the tolerance function value. The latter is set to 10^{-4}, and the former is set to 500. The maximum number of generations is required because in some cases the algorithm may reach a point where it starts fluctuating in a region of optimums within the space solutions, but without stopping if the tolerance function value is too small, as it was set in this case.

The last settings are the bounds, which define the thresholds of the space of solutions. In this case, the lower bounds were set to 0 for both variables, meaning inexistent installation of each subsystem, and the upper bounds were set to values corresponding to a huge installation size, thus considering it not to be limited by available area. If there were constraints in terms of available area to be covered by PV panels it could be introduced in this part of the model.

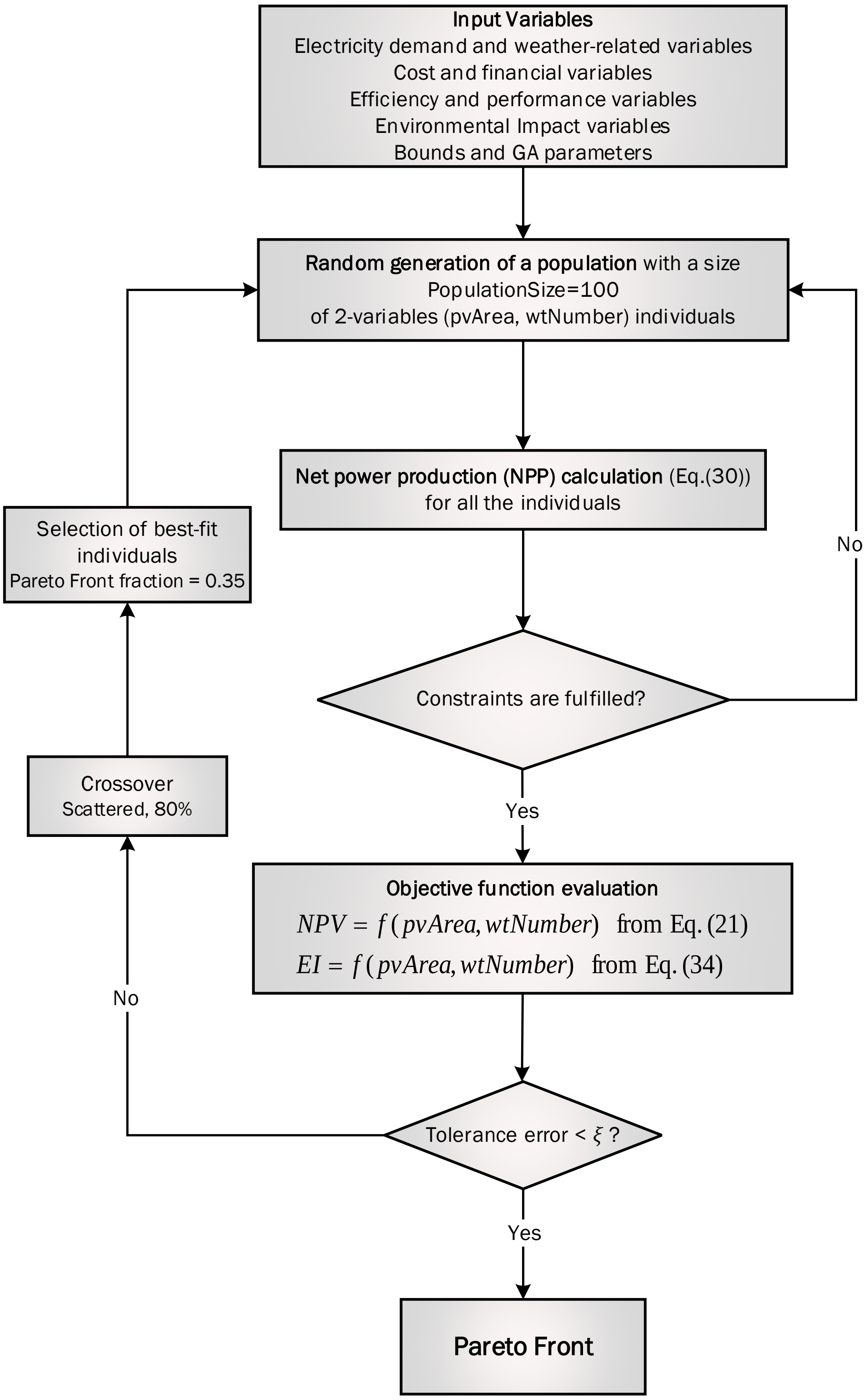


Fig. 23 Optimization model and parameters for multi-objective HRES cost-EI optimization

4.3.3. Results and findings

In this case study, the multi-objective perspective was added, so instead of obtaining a single optimal solution, a Pareto front is presented. Again, a base case with all the variables set at the values provided in the previous sections is presented by then analyze the behavior of the model through a sensitivity analysis. The electricity demand was provided by [236].

4.3.3.1. HRES base case scenario

Under the assumptions presented in Table V, Table VI, Table VII and Table VIII, the base-case scenario is defined. The model provides the Pareto front as a solution (see Fig. 24a), from which a range of different solutions can be chosen by applying different weights to the two criteria analyzed, that is cost and environmental impact.

As can be seen, when applying contradicting criteria, there is not a single optimum solution. Instead, there are multiple optimum solutions, and the choice of one or another depends on the weighing of these criteria that the decision-maker does.

However, the scale of the values and the variation of them observed in the Pareto front makes it difficult to analyze de results in terms of weighing the two criteria. For instance, the life-cycle NPV of the system varies within the range of 54 to 64 million US dollars whereas the life-cycle CO_2 emissions vary between 1 million tons and ten million tons CO_2 emitted. To overcome this issue, results were normalized according to [278], so relative variations were observed instead of magnitude variations:

$$\widetilde{x_i} = \frac{(x_i - \bar{x})}{s} \tag{39}$$

where $\widetilde{x_i}$ is the normalized value and $\bar{x}$ and s are the average and standard deviation of the set of values, calculated as follows

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{40}$$

$$s = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N}} \tag{41}$$

With aim to provide an insight on the required system size for the scale of generation of the sample township, a compromise solution giving equal importance to both criteria, i.e. weighing each criterion 50%, has been selected (see Fig. 24a and Fig. 24b the highlighted dot):

$$base - case\ NPV = 58.645M\$ \tag{42}$$

$$base - case\ EI = 0.3515MtnCO_2 \tag{43}$$

These results are reached with an installation of 3900 square meters of UP-M265M PV panels and 9 SUT200 wind turbines.

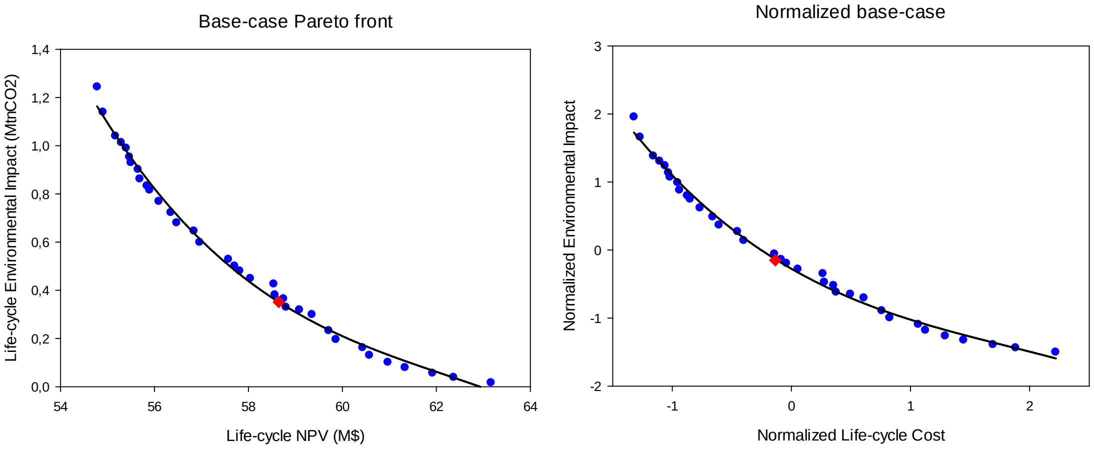


Fig. 24 Base-case Pareto front: (a) raw data and (b) normalized data obtained in the third case of study

4.3.3.2. *Sensitivity analysis*

To facilitate results interpretation as well as the behavior of the proposed model to changes in input variables, a sensitivity analysis was conducted. Such analysis consists in creating 10% increase changes in the input variables identified as relevant and to observe the difference in the result yielded by the algorithm. The results are shown in Table XIII.

Table XIII Sensitivity analysis of Grid-connected PV-wind-biomass HRES for multi-objective life-cycle cost and environmental impact optimization

	Variable	Variation	NPV change	EI change
COST	PV capital cost	+10%	+0.60%	-13.66%
	Wind capital cost	+10%	+0.48%	+6.77%
	Biomass capital cost	+10%	+0.22%	-3.33%
	Fuel cost	+10%	+0.78%	-0.94%
FIN.	Electricity price	+10%	+6.40%	-2.85%
	General inflation rate (g)	+10%	+0.37%	-2.71%
	Interest rate	+10%	-3.69%	-5.83%
EFFICIENCY	Module reference efficiency	+10%	-1.01%	+0.17%
	Wind turbine reference efficiency	+10%	-1.10%	-3.58%
	Biomass gasifier – ICE efficiency	+10%	-0.97%	-1.31%
	Biomass LHV	+10%	-0.83%	-3.07%
ENV. IMPACT	PV life-cycle CO_2 emissions	+10%	-0.13%	+0.12%
	Wind life-cycle CO_2 emissions	+10%	-0.10%	+1.14%
	Biomass life-cycle CO_2 emissions	+10%	-0.06%	-1.31%
	Grid life-cycle CO_2 emissions	+10%	-0.06%	-2.13%

The results show that the technology with higher impact on the results is wind power. Increases in wind turbine cost lead to increases in both cost and environmental impact and efficiency improvements also have significant cost and environmental impact reductions. It is also noteworthy to mention that efficiency improvements lead to both cost and environmental impact reductions, aside from PV efficiency improvements that only have the positive outcome of cost reduction but with environmental impact increase. That is due to the higher environmental impact of this RE source compared with wind power which share is reduced under the assumption of PV efficiency increases.

Regarding RE environmental impact variations, it can be observed that increases in these variables lead to lower costs because the share of electricity grid, which is the energy source with lower cost but higher environmental impact. However, when looking at how environmental impact increases affect system global environmental impact, it is observed that increases in PV and wind power lead to system increases whereas with biomass and grid power the global environmental impact is reduced. This could be expected because the formers are the two energy sources with less impact, so increases in their impact lead to global system impact increases; while the latter are the two sources with higher impact so the system can shift to less harmful energy sources when their impact is increased.

Regarding cost variations, the sensitivity analysis show that increases in all energy sources' costs lead to higher system life-cycle costs, without exceptions. However, the outcomes in terms of system environmental impact show different behavior. On the one hand, when PV, biomass capital investment and forest biomass fuel costs increase, the entire system EI decrease, as a result of wind power share increase, which is the most harmless of the RE sources. On the other hand, wind power cost increases lead to system EI increases as there is no alternative with less life-cycle CO_2 emissions.

Regarding financial variables, the greatest impacts are observed with the interest rate, which dramatically changes the life-cycle cost as an increase makes capital investments more profitable, which is the most important weakness of RE-based electricity generation systems. Electricity price has also a remarkable impact on system outcomes, increasing life-cycle costs as well as reducing life-cycle environmental impact. This is because as the cost of electricity from the grid increases, it is more profitable to install renewable energy systems with less environmental impact.

4.3.4. Conclusions

The work carried out in this third case study proposes an optimization of a grid-connected PV-wind-biomass HRES methodology based on economic and environmental criteria, in a so-called multi-objective optimization based on the use of genetic algorithm. This methodology, instead of providing a single optimum result, which, on the other hand, does not exist because of the contradicting criteria chosen, provides a set of optimum results. The results are plotted in a Pareto front, a useful tool for decision-makers because it shows the trade-off between the contradicting criteria.

The proposed HRES layout combines the advantages of using the low-carbon energy sources PV, wind and biomass with the reliability of supply of grid. The system is thought to prioritize RE sources over grid supply. In particular, it prioritizes solar PV and wind power over biomass which, in turn, is used when the formers cannot match the existent demand. Only when the three sources of energy are not able to supply the load, electricity is purchased from the grid.

4.4. Grid-connected solar PV-wind-biomass combined heat and power HRES

The fourth case study consisted in the multi-objective optimization of a grid-connected PV-wind-biomass HRES for combined heat and power (CHP) production. In this case, the system prioritizes the use of biomass during winter days to supply the existent thermal demand so PV and wind RES are only used if the excess electricity produced is not enough to supply the electricity demand. Conversely, during summer days, the system mode of operation is the same as in the second and third case studies.

4.4.1. System description

At this last stage of the research, the system was improved to include the exploitation of the thermal energy produced in the forest biomass gasification – ICE subsystem for electricity production, using a so-called combined heat and power (CHP) layout.

In this case, the system consisted in a grid-connected PV – wind – biomass HRES. Similarly as the system described in the previous section, the system takes advantage of the flexibility and availability of biomass power and its short response time that allows it to behave as a backup of the stochastic renewable energy sources, namely wind and solar PV power. Besides, the biomass subsystem is also used to supply a certain heating demand during winter days. The HRES layout is shown in Fig. 25.

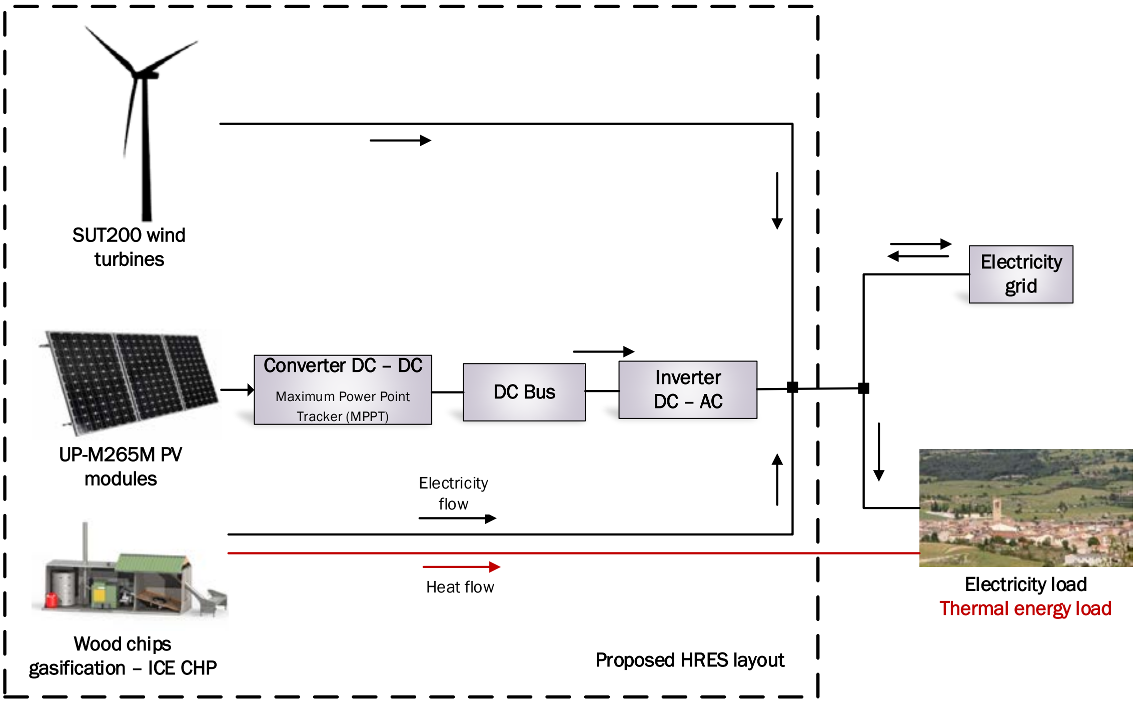


Fig. 25 Grid-connected PV-wind-biomass CHP HRES for multi-objective life-cycle cost and environmental impact optimization

The proposed layout consisted in UpSolar modules UP265M, PV modules with 265 Wp of nominal power and 1.629 m^2 of area [253], and wind turbines are SUT200 turbines with a nominal power of 200 kW [238]. As had been done in the previous cases, the system size was optimized through the variation of area covered by PV modules and the number of wind turbines installed. These two subsystems were combined with a CHP biomass gasification equipment of 500 kWe. Such equipment produces a surplus of approximately 1000 kWth. Again, the choice of scale come from the average value of hourly demand in the location under study, and the thermal demand associated has been escalated to a number of households that can be supplied, provided that the district heating (DH) installation is viable.

To determine the number of households that can be included in the DH network, a first estimation of the thermal demand of the different typologies of household in the township (see Table XIV) under study was performed according to the methodology proposed by the Spanish Institute for energy diversification and saving (IDAE in its Spanish acronym) [243]. After that, it was estimated the number of households that could be supplied respecting by considering a diversity factor of 60% and choosing a neighborhood in which it would be technically feasible to install a DH network without exceeding installation lengths of 500 meters in order to keep the distribution network efficient and, consequently, reduce losses. The resulting DH proposal is shown in Fig. 26 and Table XV. The procedure used to calculate the thermal energy demand

and the ratio of coverage is shown in the methodology section for this HRES layout, and the results obtained are presented in the results Chapter.

Table XIV Types of households in the sample township

Type	# of households	Year of construction	Typology	Area (m^2)	# of floors	Doors and Windows
Old town	250	Prev. s.XVI	Single family, attached	70	3	5 of 1 m^2 (wood, old)
Suburbs and walls	350	s.XVIII-XX	Single family, attached	90	3	9 of 1.5 m^2 (wood)
Out of walls 1	150	1950	Single family, attached	120	2	9 of 1.5 m^2 (wood, aluminum)
Out of walls 2	50	1990 or later	Single family, attached	90	2	7 of 1.5 m^2 (aluminum, PVC)
Apartment building	100	1980 or later	Multi-family housing unit	80	4	5 of 2 m^2 (aluminum, PVC)
Detached house	100	1980 or later	Single family, detached	180	2	10 of 2 m^2 (aluminum, PVC)

Fig. 26 Households included in the DH

Table XV Households included in the DH

Type	# of households
Out of walls 1	135
Out of walls 2	45
Detached house	40

Regarding the prioritization of energy sources, the following strategy was set up: on the one hand, the PV and wind power systems are the first option for electricity generation, whereas the biomass subsystem supplies electricity working at engine full load whenever those stochastic RES are insufficient to match the existent demand. On the other hand, the biomass gasification – ICE system is the only provider of thermal energy, so whenever exists a thermal demand, the system produces at full load. The generated electricity is used if there is enough electricity demand, otherwise, it is sold to the grid at market price. By operating in this way, the system sometimes produces excess electricity, which is sold to the grid, and sometimes produces excess heat, which is evacuated by the refrigeration system. The overall performance is better than when the system was only oriented to electricity generation, because in winter days the equipment is operating at efficiencies around 75% from the addition of both electricity and heat exploitation. Besides, the system is completely independent almost year-round, being only required to purchase electricity from the grid at those times when the combination of PV, wind and biomass power systems are not enough to supply the electric demand; and being only required to use gas oil or natural gas (current sources of thermal energy) during days specially cold.

4.4.2. Optimization process

The optimization process was performed according to the same strategy and GA parameters as the third case study. Please refer to 4.3.2, specifically to Fig. 23 and Table XII for further detail regarding the operations performed by the algorithm and the driving parameters of such process.

4.4.3. Results and findings

This fourth and last case study was again a multi-objective optimization approach to understand the tradeoffs between cost and environmental impact. Therefore, the solution obtained was a Pareto front.

4.4.3.1. HRES base case scenario

The base-case scenario is obtained by setting the variables to the values presented in Table V, Table VI, Table VII and Table VIII. The result provided by the optimization model is a Pareto front (see Fig. 27a).

Because of the nonexistence of a single optimal solution, the normalization process performed in the case study above (see Eq. (39)–(41)) was also used in this case to then calculate the compromise solution obtained by equally weighing both criteria (see highlighted solution in Fig. 27a-b).

$$base - case\ NPV = 55.459M\$ \tag{44}$$

$$base - case\ EI = 1.3672MtnCO_2 \tag{45}$$

These results are reached with an installation of 8421 square meters of UP-M265M PV panels and 1 SUT200 wind turbine.

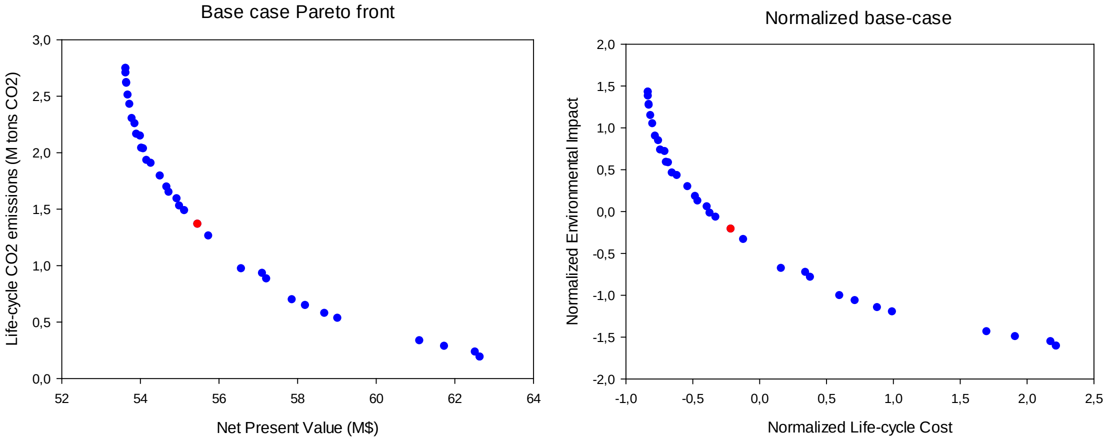


Fig. 27 Base-case Pareto front: (a) raw data and (b) normalized data obtained in the fourth case of study

To contextualize these results, a comparison with the current costs of supplying the entire township electricity demand and the DH neighborhood thermal demand was made. It is graphically represented in Fig. 28.

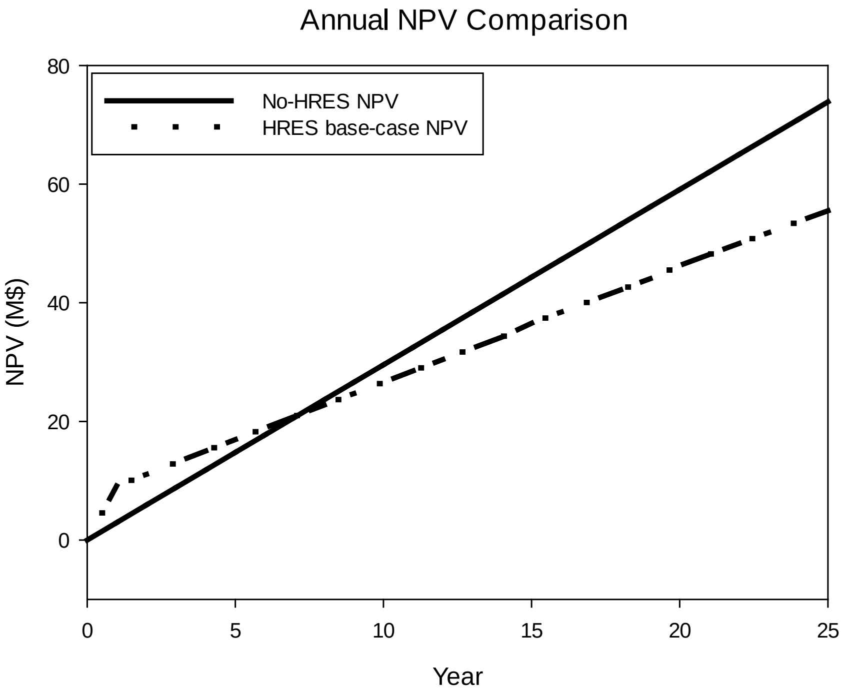


Fig. 28 Comparison of NPV evolution throughout 25 years of system life time for No-HRES and HRES base case scenarios in the fourth case study

4.4.3.2. Sensitivity analysis

To perform the sensitivity analysis that helps interpreting the results provided by the model, 10% increases in relevant input parameters were made to observe the variations induced in the results provided by the model. The observed changes are presented in Table XVI.

Table XVI Sensitivity analysis of Grid-connected PV-wind-biomass CHP HRES for multi-objective life-cycle cost and environmental impact optimization

	Variable	Variation	NPV change	EI change
COST	PV capital cost	+10%	1.63%	-10.04%
	Wind capital cost	+10%	0.92%	-13.60%
	Fuel cost	+10%	1.32%	4.50%
FIN.	Electricity price	+10%	7.31%	-10.46%
	General inflation rate (g)	+10%	1.79%	-19.69%
	Interest rate	+10%	-3.11%	-8.33%
EFFICIENCY	Module reference efficiency	+10%	0.31%	-18.91%
	Wind turbine reference efficiency	+10%	0.82%	-7.84%
	Biomass gasifier – ICE efficiency	+10%	-0.41%	-14.43%
	Biomass LHV	+10%	-2.34%	13.67%
ENV. IMPACT	PV life-cycle CO_2 emissions	+10%	1.38%	-9.27%
	Wind life-cycle CO_2 emissions	+10%	0.12%	-2.08%
	Biomass life-cycle CO_2 emissions	+10%	1.47%	-17.72%
	Grid life-cycle CO_2 emissions	+10%	0.86%	-4.42%

The results show that the technology with higher impact on the results is solar power, followed by biomass. This is because their importance in the system sizing. Focusing on cost changes, all of them except in the case of fuel cost, lead to increased life-cycle costs and decreased life-cycle environmental impact as a result of system sizing changes.

Looking at the efficiency improvements, they lead to increases in NPV and decreases of EI aside from the biomass efficiency increases. This can be explained because this RES is the one with higher environmental impact so efficiency improvements reduce PV and wind power shares thus increasing the use of biomass.

Regarding the EI increases, for each of energy production technologies ceteris paribus, they lead to NPV increases and EI decreases. This, which appears as a contradiction, is due to system sizing changes.

4.4.4. Conclusions

The work carried out in the fourth case study consisted in the design and validation of an optimization model for life-cycle cost and environmental impact assessment of a grid-connected CHP HRES. Such system has two different modes of operation depending on whether exists a thermal demand, i.e. in winter days, or does not exist such thermal demand, as occurs in summer days.

During winter days, the system uses the biomass subsystem to produce thermal energy for a neighborhood in a DH scheme. During this period, the additional electricity produced is used to supply the existent demand in the township and, if necessary, sells the surplus to market. In those cases when additional electricity generated is not enough, the system uses solar PV and wind energy sources. Only whenever all the three RES are not enough to supply the electricity demand, the system would purchase it from the grid. Conversely, during summer days the system is electricity demand driven, which means that PV and wind energy sources are the first to produce electricity and biomass operates as a backup for these sources. Analogously to previous case studies, only whenever PV, wind and biomass power sources are not enough to supply the electricity demand the system would purchase electricity from the grid.

The results obtained are a so-called Pareto front, a set of optimal solutions that has the ability to show the trade-offs between the contradicting criteria analyzed. Specifically, it showed cost increases with environmental impact decreases and vice versa, meaning that RES that have lower environmental impacts are more expensive than current grid mix with fossil fuel prevalence.

Focusing the attention to a compromise solution consisting on equal weighing of both criteria, it was observed that the system would have a life-cycle cost of more than 55 million dollars with a life-cycle environmental impact of 1.37 million tons of CO_2 emitted, a result reached with a system of 8421 square meters of 265 Wp PV panels and one 200 kW wind turbine.

It is also important to highlight that the addition of thermal energy exploitation to the system reduces the payback time, being profitable the HRES at 10th year of lifetime.

5. Discussion

The main purpose of this research was to provide a grid-connected hybrid renewable energy system sizing tool. For cost optimization cases, this tool is a model that, given the electricity demand and the renewable energy sources availability patterns, provides the minimum cost layout. Such model was developed for a PV-wind HRES and for a PV-wind-biomass HRES. For multi-objective optimization cases, this tool is a model that, given the electricity demand or the combined electricity and thermal demand of a particular location and knowing the solar, wind and biomass availability of such location, provides a set of possible layouts to better inform the tradeoffs between life-cycle cost and life-cycle EI when performing a decision making process. This process was carried out in the form of four different case studies that served as model development and validation stages.

In the first case study [226], it could be observed that the main hurdle to be overcome by renewable energy technologies is the significant upfront investment required. For example, although the Net Present Value of the HRES base case is \$15.535, 65.26% of the no-HRES NPV, the system requires an initial investment of \$10.108 M, a very important amount that makes difficult to engage in investing most of the small companies or particular investors. However, when the evolution of NPV during system lifetime for both base case and no-HRES scenarios are compared, it emerges that the installation of a HRES implies higher accumulated costs during first years, a tendency that is inverted approximately after two thirds of system life time. In particular, with the proposed case study the system would imply less accumulated costs from 18th year onwards (see Fig. 17). Therefore, even though the required investment is a significant amount that is never paid off, the system proves to be worthwhile once the current situation costs are taken into consideration. Besides, the NPV evolution throughout system lifetime also shows that policies that would improve RES profitability could act either on the slope of the curve or in the huge jump that is observed in the first year. To influence on the former, one could subsidize the renewable electricity sale, for instance introducing a feed-in tariff that would increase the electricity selling price and thus invert the slope of the curve; whereas to influence on the latter, one should subsidize the installation of renewable energy systems. The first solution has been adopted in countries like Germany, Spain or Australia, whereas the second is the alternative proposed in some US States like California.

From the sensitivity analysis results, it is shown that the most significant parameter analyzed was the wind capital cost. That is because the optimal sizing found by the algorithm consists on a 3.6MW wind installation for the 0.1MW of solar PV power, so changes in the cost of the component that represents more than 95% of the total installation are expected to affect more the final NPV than changes in the cost of the component that represents less than 5% of installation size.

Furthermore, it was also observed that the electricity price did not significantly affect the result, so the installation was expected to have the reported profitability regardless of the inflation of electricity price. This effect is caused by the low impact of electricity purchasing prices on the system as it is based on the reduction of electricity consumption from the grid. Conversely, the inflation in the retail electricity prices would affect the break-even point as the no-HRES scenario would see its costs surge, making the installation of the HRES system more worthwhile compared with the business-as-usual alternative.

The last analyzed variable was the interest rate. Increases in this variable result in decreases in the NPV as they mean more monetary value discount in future years. That is why in the NPV definition itself the interest rate is dividing several terms (see (2)–(26), (31)–(33)). This behavior shows the effect of time value of money, which means that a certain amount of money is worth more at present time that in the future, and that this discounted present value is lower as higher is the discount rate. The chosen value in the base case of 3.5% is a reasonable approach considering the current interest rates for loans to non-financial corporations in Spain that averaged 3.5% in the last 10 years [257].

It is also worth mentioning that the system sizing did not suffer changes with the first five cases, PV and wind capital cost, electricity price, general inflation rate and interest rate; but with the other two cases, PV module and wind turbine efficiency improvements, the system sizing is changed. On the one hand, with 10% improvement in the PV module reference efficiency, the new HRES consisted of 18 wind turbines and 565.13 m2 of PV installation, being the total installed capacity the same as in the base case scenario but with 10% less land usage for the PV installation. On the other hand, with 10% improvement in the wind turbine reference efficiency, the new HRES consisted of 17 wind turbines and PV installation reduced to a marginal size, the total installed capacity remaining again unchanged at roughly 3.7MW but with different share of each RE technology.

In the second case study [225], it is of interest to compare the results with those shown in the first case study [226] for a grid-connected PV-wind HRES, designed under the condition of annual electricity net balance. It is worth noting that less initial investment is required when a biomass subsystem is added, but that it leads to a greater life-cycle cost than that obtained for a PV solar-wind HRES, as a result of using biomass power at full load when PV and wind power do not match the existent demand, even if such a difference is only a few kilowatts.

At this point, it is relevant to highlight that forest wood chip costs have been computed under the assumption of sustainable forest management, i.e., using less biomass than the self-growth rate of local forests and sustainable clearing and harvesting practices, as proposed in [30]. Such a hypothesis not only ensures that the proposed system is realistic and effectively deployable, but also makes the proposed model generally applicable in other townships and regions with a similar latitude and climate, e.g., Southern France, Italy, or the Balkans Peninsula, including Greece. The proposed methodology is suitable to design a small-scale system that would not have high biomass resource requirements and, therefore, could be easily replicable in other rural locations.

It is also worth mentioning that the use of this source of energy would also have environmental benefits compared to the current fossil fuel intensive electricity production pattern, and in terms of job opportunity creation. These benefits would also induce economic earnings. For instance, forest resources would be revaluated as a result of active and sustainable management and unemployment could be reduced with jobs in the fields of O&M of the system and wood chip harvesting and processing. Another important benefit that has not been accounted for is the potential sale of heat power produced. Biomass Combined Heat and Power (CHP) produces twice the thermal energy compared to electricity, an aspect that was evaluated later on the fourth case study [279]. Although thermal energy is sold at slightly lower prices, taking advantage of it could improve system efficiency up to 70%–80% [227] from the actual value of 24%. Therefore, there is still a great deal of potential for the improvement of economic results.

In addition, such a system adds energy autonomy and also lays the groundwork for the expected transition from a centralized electricity generation scheme to a distributed energy model, also known as “Smart Grid”.

From the sensitivity analysis, it was observed that the proposed model responded well to positive and negative changes in the most important input variables, for instance, showing increases in the NPV for technology cost increases, and showing decreases in the NPV when technology efficiencies are improved.

With the third case study [280], the results showed that the system with a lower cost is the one with higher CO_2 emissions whereas the most expensive layout is the one that would have less environmental impact. This explains why, at present time, REs are not the preferred alternative for massive electricity generation. However, the results also showed that relatively small investment increases could have a high impact on CO_2 emissions reduction, especially in the lower range of cost. Taking as a reference the solution with higher environmental impact and minimum cost, it is shown that a slight increase in investment in the magnitude of 5%, leads important savings in emissions, close to 50% reduction. On the contrary, after reaching this 50% of emissions savings, further emission reductions require increasing amounts of investment, thus being less attractive.

From the sensitivity analysis performed, it was proven that wind power is the RE source with higher impact on the system, as it is the cheapest of the RE sources and the energy source with less environmental impact. Cost reductions or performance increases from this source would lead also to positive outcomes for the system. It also was observed that interest rate increases has significant positive outcomes in both life-cycle cost and life-cycle environmental impact. Hence, considering that interest rate expresses the rate of return on the analyzed investment, it seems that improving this financial issue in HRES seems to be an interesting measure to encourage RE implementation.

With the fourth and last case study [279], the results show, analogously as the previous case study did, that the system with a lower cost is the one with higher CO_2 emissions whereas the most expensive layout is the one that would have less environmental impact. Again, it should be noted that these results support the justification of the small prevalence of RES in electricity mixes throughout the world. However, the results also showed that relatively small investment increases could have a big impact on CO_2 emissions reduction, especially in the lower range of cost.

It is worth noting that the compromise solution reached with equal weighing of both criteria is close to the compromise solution obtained in the previous case study, despite the fact that the PV system cost was reduced from $3800 per kilowatt installed in 2011 [247] to $2930 per kilowatt installed in 2014 [259] with its subsequent increase in PV share that should significantly reduce total system cost. Although this result may appear to be extremely disproportionate next to previous case studies, it cannot be compared since the system is supplying the entire winter thermal demand of a neighborhood of 180 attached houses and 40 detached houses. Therefore, the cost of thermal energy purchase at current energy costs must be added when calculating the return on investment. When doing so, it is proven that system amortization is significantly reduced, being the installation of the proposed CHP HRES from 10th year onwards. Compared with previous cases, with payback periods of 17 or even more years, it is well proven the suitability of CHP layouts so greater shares of biomass energy potential are taken advantage of.

What is comparable is the system sizing obtained. Whereas in the three previous case studies wind power was the prevalent RES, in the fourth case study the system sizing shifts to a system chiefly based on solar PV power. There are two reasons behind this change. On the one hand, PV system cost was decreased by almost 23%, making its installation much more worth it compared with wind power with systems costs stabilized that do not suffer relevant decreases. On the other hand, the new operation strategy dramatically affects the system layout. Since biomass is mandatorily used in winter days due to the heat-driven strategy, the rest of subsystems are scarcely required during this period. Conversely, in summer days, the operation strategy is electricity-driven and is in these days when other sources of energy are prioritized over the biomass. Therefore, PV power has greater impact since its energy generation pattern precisely peaks during summer days whereas wind power has an opposite seasonal energy generation pattern that peaks during winter days.

The sensitivity analysis showed that PV power is the RES with higher relevance in the system due to an increased installation sizing with regards to previous cases.

6. List of papers and other publications from the author in this field

In this chapter the journal and conference papers that this research has led to are presented. Three journal papers have been accepted and already published in Renewable and Sustainable Energy Reviews, Applied Energy and Sustainability journals, as well as a conference paper presented at the World Renewable Energy Congress XIII from 2014, in London.

Additionally, two more papers are currently in the process of revision by Applied Energy and to be submitted to Energy Conversion and Management.

6.1. Papers from the author published

González A, Riba J-R, Puig R, Navarro P. Review of micro- and small-scale technologies to produce electricity and heat from Mediterranean forests′ wood chips. Renew Sustain Energy Rev 2015;43:143–55. doi:10.1016/j.rser.2014.11.013.

González A, Riba J-R, Rius A, Puig R. Optimal sizing of a hybrid grid-connected photovoltaic and wind power system. Appl Energy 2015;154:752–62. doi:10.1016/j.apenergy.2015.04.105.

González A, Riba J-R, Rius A. Optimal Sizing of a Hybrid Grid-Connected Photovoltaic–Wind–Biomass Power System. Sustainability 2015;7:12787–806. doi:10.3390/su70912787.

6.2. Conference papers from the author published

González A, Rius A, Puig R, Esteban B. Cost-effective design for electricity generation from a Hybrid wind – solar system in a rural township in Catalonia. Proc. World Renew. Energy Congr. XIII, London, UK: Springer New York; 2014.

6.3. Papers and other publications from the author submitted and under review

González A, Riba J-R, Esteban B, Rius A. Multi-objective Optimal Sizing of a Hybrid Grid-connected Photovoltaic - Wind - Biomass Power System. Appl Energy 2016; Under Review.

González A, Riba J-R, Rius A. Combined Heat and Power HRES design based on environmental and cost criteria. Energy Convers Manag 2016; Expected Submission: May 2016.

6.4. Collaborations

Esteban B, González A, Gibert M, Baquero G. Water in vegetable/diesel oil emulsions to be used as biofuels. Proc. World Renew. Energy Congr. XIII, London, UK: Springer New York; 2014.

7. Recommendations for future work

Some areas to be explored in future work include, but are not limited to the topics detailed below.

7.1. Recommendations for practice

An important area of future work is to use this decision-making support tool developed to better inform HRES sizing and to implement the installation of this kind of systems. Since the required upfront investments for a HRES in a small township scale are considerable, it would be interesting and advantageous to test the developed methodology at different scales of generation and consumption. For instance, the use of the developed tool to size systems at a neighborhood, industrial parks or household's scales would be also beneficial and the required initial investments would result much more affordable. In addition, it would help to inform decision-makers about the suitability and feasibility to install micro-grid schemes in rural areas where the renewable energy availability is high relative to existent energy demand.

This usage of the proposed methodology at different scales is also in line with the testing in other locations with different RES availability pattern and energy needs. For example, rural villages in the Pyrenees could benefit from adopting the installation of HRES since these townships have significant forest wood biomass resource available and higher wind patterns that, combined with the greater slopes of the mountains could make interesting to explore the possibility of adding hydro energy source to the system. This is a possibility that would require further research as explained in the section below.

7.2. Recommendations for further research

Future research expanding the work performed during the development of this thesis includes the usage of different optimization algorithms. In this work, GA was used for its ability to tackle non-linear problems and multi-objective optimizations without requiring much computing power. However, there are other optimization algorithms that could be successfully used for the purpose of HRES single and multi-objective optimization. For instance, particle swarm optimization (PSO) [281] and fuzzy logic methodologies [282] from the field of artificial intelligence methodologies are proven to be useful as well. Placing the focus on another methodologies family, those based on iterative approaches, hill climbing or dynamic and linear programming have also been used in other HRES optimization researches [282].

Another important research area to be explored is the inclusion of storage technologies to the proposed layout of the system. Although biomass gasification – ICE group and grid-connection provide flexibility and increase demand coverage up to a hundred percent, the inclusion of storage technologies would increase system autonomy and would make feasible the design of stand-alone systems that can be useful in remote locations. Even though the proposed optimization methodology was developed in the context of an industrialized region, namely central Catalonia in Spain, the model could be used in other contexts, for example small islands without grid connection, i.e. Greek islands, small islands in the Balearic or Canary archipelagos; or in rural villages in developing countries that currently lack grid connection. Some of the storage technologies that could be explored, without limitation to, are battery storage for household-scale HRES or pumped hydro storage (PHS) for township or greater scales.

Finally, another interesting field to be explored in further research is the inclusion of other RES to the analysis. This last future research path proposed is in line with the storage technologies as long as one of the technologies to explore should be clearly hydro power because of its good energy return on investment, efficiency and available resource. Other RE technologies to introduce could be the use of solar thermal energy for heating purposes, which could be hybridized with the proposed biomass CHP system to provide thermal energy in a DH scheme.

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