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# POTENTIAL FOR ELECTRICAL POWER GENERATION USING FOREST WOOD BIOMASS IN RURAL AREAS OF CATALONIA

A Thesis

Submitted to the Faculty

of

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by

Arnau González Juncà

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To my wife, Noelia – she is there whenever my mood wavers

*Your love drives me to get the best of me*

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| | |
|---|---|
| $\eta_e$ | electrical efficiency |
| $\eta_{th}$ | thermal efficiency |
| $\eta_{tot}$ | overall efficiency |
| $AC_w$ | ash content of wet biomass |
| $CO_2$ | carbon dioxide |
| GJ | GigaJoules |
| $H_{daf}$ | hydrogen content of dry ash free biomass |
| $HHV_{daf}$ | HHV of dry ash free biomass |
| kg | kilogram |
| kWe | kiloWatts of electric power |
| kWth | kiloWatts of thermal power |
| kWhe | kiloWatts hour of electric energy |
| kWhth | kiloWatts hour of thermal energy |
| $LHV_{ar}$ | LHV of biomass “as received”, i.e. with moisture and ash content. |
| $LHV_{daf}$ | LHV of dry ash free biomass |
| $LHV_w$ | LHV of wet biomass |
| $MC_w$ | moisture content of wet biomass |

| | |
|---|---|
| MJ | megaJoules |
| MWe | megaWatts of electric power |
| MWth | megaWatts of thermal power |
| MWhe | megaWatts hour of electric energy |
| MWhth | megaWatts hour of thermal energy |
| tn | metric tons |

# ABSTRACT

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Biomass is a renewable energy source that has been used for many years. However, its usage as an electricity source in Spain is not well developed due to many causes, among which highlights the lack of knowledge about the available technical potential. This research sought to close this gap assessing the technical potential for electricity generation using forest wood biomass in rural areas of Catalonia. The study characterizes the amount and type of biomass available in Catalonian forests that can be used to produce electricity without going beyond the capacity of regeneration of the forest, as well as the state-of-the-art efficiencies for commercially available biomass conversion to electricity technologies. The main outcomes of this research include the choice of a suitable technology and the evaluation of the technical potential for electricity generation in a sample of a rural Catalonian township. In particular, it was found that the forests of rural Catalonia yearly produce about 1.6 metric tons of biomass per hectare, with a heating value of 12.8 GJ per ton at 30% of moisture content.

To take advantage from such resource it was found that, given the amount of available resource, nowadays the most efficient technology is the internal combustion engine (ICE) coupled to a biomass gasification unit, with an electrical efficiency around 25%. However it was observed that this choice is linked to the scale of generation and, thereby, for larger amounts of biomass other technologies such as gas or steam turbines could perform better. To improve the efficiency of biomass usage, combined heat and power opportunities should be sought. Therefore, it is strongly recommended to study the possibilities of cogeneration in rural areas of Catalonia, looking for potential applications for the excess heat produced during the electricity generation process. Another aspect that requires additional work is the environmental and economic evaluation of the technologies to support a more informed choice of technology.

In addition to these relevant outcomes, applicable to similar regions in terms of area and type of forests, this research also ended up with the development of a methodology that can be used to find out the best option to take advantage of forest wood biomass resources in other regions.

# CHAPTER 1. INTRODUCTION

Electricity is one of the most essential commodities in our society. Its advantages are widely known, but so are its drawbacks. Among them, stands the CO2 emissions caused by fossil fuel burning that are the main cause of climate change (Prentice, et al., 2001) as 70% of all greenhouse gas emissions are caused by the energy sector (Höök & Tang, 2013).

In order to reduce the rate of CO2 emissions, the electricity generation industry has turned to renewable energy technologies for electricity production. There are many different alternatives such as solar and wind among others. However, the main disadvantage of these technologies is that their supply can only be predicted rather than controlled, so these energy sources required backup generation plants to counteract those hours when the resource is not available.

In contrast, biomass is a storable renewable source that permits a controllable supply, making it a key alternative for the future electricity generation scheme. In addition, biomass conversion technologies using forest woods could help to improve the forest management strategies and reduce the risk of forest wild fires.

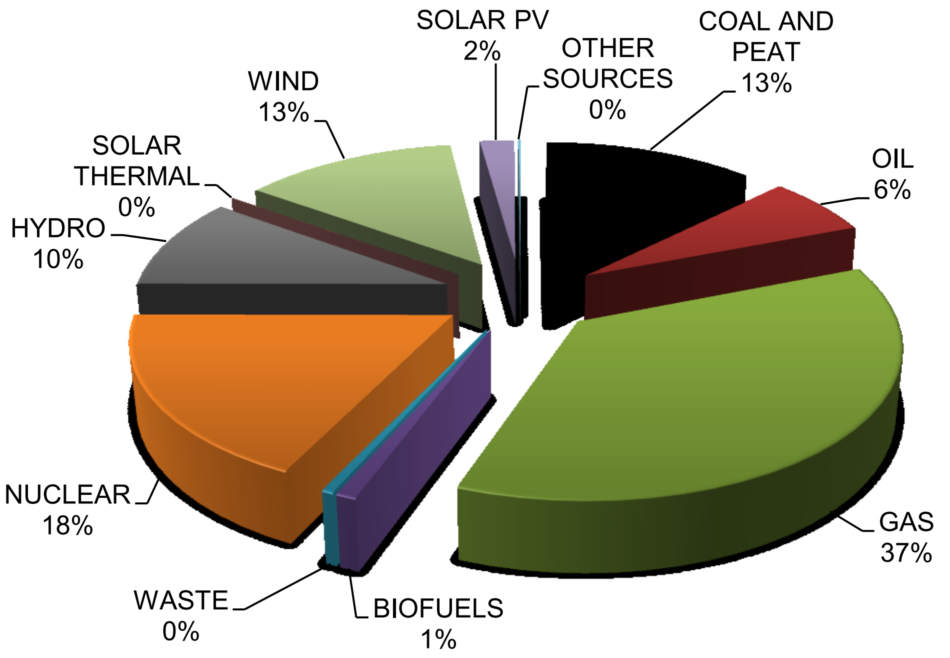
However, due to the lack of technical and feasibility studies of implementation of these technologies, biomass is only accounting for a very small share of the electricity supply distribution of developed countries.

The purpose of this thesis is to help to address that lack of technical studies focusing on the evaluation of the potential capacity, not considering the economic side, for electrical power generation using biomass-based conversion technologies in the particular context of rural areas in Catalonia, Spain. The main goal sought with the research is to evaluate the amount of electricity potentially producible in a sample township from rural Catalonia using the amount of biomass resource available within the township in a sustainable way, i.e., not consuming more fuel than the quantity that the forest produces by itself.

An assessment of the available wood biomass in a sample township in rural Catalonia will be performed based on information published in different databases and articles. Then, a selection of an appropriate technology will be made in terms of relative efficiency to later calculate how much electricity can be generated using the available resource and the selected technology.

## 1.1 Statement of the Problem

Spain is one of Europe's biggest emitters of $CO_2$ due to its high energy consumption and the use of mainly fossil fuels for electricity generation (International Energy Agency, 2011), as represented in Figure 1.1. In addition, the generalized use of fossil fuels, which are not available in Spain, increases the energy dependency on other countries.



Source: Personal compilation based on International Energy Agency (2011)

Figure 1.1 Electricity generation in Spain by source, 2009

In the present context of increasing prices of energy due to volatility and rising of fossil fuel prices caused by their current depletion, and with the global concern about CO2 emissions that result in international treaties such as the Kyoto protocol (United Nations, 1998), more attention is being placed, not only in Spain but also in Europe and Western countries, on the development of cleaner alternatives to conventional energy sources. Among these alternatives, one that is very promising is the use of biomass-based technologies to generate both electricity and heat, due to its flexibility of use and storage, which are the main weaknesses of renewable energy sources (Passey, Spooner, MacGill, Watt, & Syngellakis, 2011). In addition, electricity generation plants fed with biomass can serve as a backup to complement generation from renewable sources inherently variable and unpredictable.

Among all the regions of Spain, Catalonia is one of the autonomous communities that have more wood biomass resource available for electrical power production within its territory (Gómez, Rodrigues, Montañés, Dopazo, & Fueyo, 2010).

In rural areas of Catalonia, there is a missed latent potential for generating electricity from biomass obtained from agricultural and forest waste. The lack of studies that evaluate the technical, economic and environmental feasibility constitutes an obstacle to the use of this energy, which would improve the energy supply in Catalonia reducing its environmental impact and increasing the security of supply through the use of indigenous sources.

In addition, in many rural areas of Catalonia there is a lack of forest management as they are mainly privately-owned. This entails a high risk of wild fires during the dry summer season in the Mediterranean area.

There are several major issues to consider when assessing whether or not it is feasible to generate power through biomass-based technologies in Catalonia. For example, the scale of generation, which in rural areas of Catalonia is likely to be confined in the small- or micro-scale range due to low forest production, is an important factor affecting the efficiency of the system. Another example is the conversion mechanisms, because there is a wide range of different efficiencies according to the type of technology used. Then, it is worth mention the environmental impact of the whole process, from production to consumption including transport and pre-treatment. Furthermore, the price of electricity generated should be compared with existing prices and to assess if it is economically viable at present times, if it will be viable in the near future or, conversely, if the definitive deployment of this technology requires financial support as feed-in tariffs or dedicated grants.

These issues are not the only ones that have to be considered to analyze the feasibility of deployment of a renewable energy technology, but they are the primary ones, and several technical and feasibility studies could help in these fields to encourage renewable electricity production deployment.

## 1.2 Significance of the Problem

Addressing the high-carbon emission and extremely dependent from foreign resources electricity supply is one of the major challenges of Western developed countries such as Spain, but there are still some technical and economic hurdles to overcome.

Knowing the available potential that Catalonia has for electricity generation using biomass sources and the environmental and, if any, economic benefits derived from the switch to the usage of these sources, will encourage the installation of new electricity generation power plants as well as cogeneration facilities for small buildings and households. The small-scale generation deployment is a key element in the transition to the distributed generation model that will help the implementation of the Smart Grid and the own-consumption scheme (Monteiro, Moreira, & Ferreira, 2009).

Furthermore, through the promotion of the use of forest biomass as an energy source, it may be given economic value to forest residues and, consequently, improve forest management and reduce the risk of forest fires that are very likely to happen in the dry summer season of Mediterranean areas.

## 1.3 Statement of Purpose

The purpose of this thesis was to establish the potential, not considering economic and long-term maintenance, for small-scale electrical power generation from biomass-based conversion technologies in a rural Catalonia sample township.

## 1.4 Research Questions

To achieve the purpose, the researcher addressed the following research questions:

- How much forest wood biomass is available in a sample township in rural Catalonia?
- What is the most suitable commercially available technology for small-scale electricity generation using forest biomass?
- How much electricity can be generated using the available forest wood biomass in the township under study and the selected technology?

## 1.5 Scope

This thesis was focused on a rural Catalonian sample township.

Regarding the availability of biomass in a rural township placed in Catalonia, data from existing databases such as the *Forest Inventory of Catalonia* provided by the Centre for Ecological Research and Forestry Applications (Centre de Recerca Ecològica i Aplicacions Forestals, CREAF), and specialized journals such as *Biomass and Bioenergy*, were sought to estimate the amount of metric tons of wood biomass produced each year per hectare in forests. The study was focused on forest wood biomass among all biomass types available for electricity generation purposes.

Regarding the election of the most suitable technology, those technologies already commercially available or at a point close to commercialization were considered. The choice was made in terms of relative efficiencies obtained at small-scale and their principles of operation, including the possibility of usage of the available biomass resource.

According to all the characteristics mentioned above, the research is designed as an ex post facto descriptive and analytical experiment.

## 1.6 Assumptions

The following assumptions were relevant to this study:

- The database *Forest Inventory of Catalonia* (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) is reliable
- Efficiency data coming from simulations are comparable to actual power plant data

- The mix of different biomass species available in the area of study has a unique heating value.
- The moisture of the wood biomass picked will be assumed to be homogeneous among different species and seasons

## 1.7 Delimitations

The delimitations of the research were:

- The research is limited to a sample township in rural Catalonia
- Biomass types other than forest wood biomass such as agricultural biomass, energy crops or municipal and industrial waste were not covered
- Large-scale biomass power plants, i.e., with more than 1 MW of electric output, were not covered
- The electric power generation and cogeneration technologies not fuelled with biomass were not covered
- Technologies that are not already commercially available were not considered when choosing the most suitable technology
- Co-firing technologies were not considered
- Economic feasibility and long-term maintenance were not studied

## 1.8 Limitations

The main limitations identified in this research were:

- The sample may not be fully representative of the whole population

- The biomass annual growth rate can vary among years due to weather changes and could override the amount of biomass that can be used sustainably.

## 1.9 Definitions

This section defines the main terminology related to the area of research:

(biomass) integrated gasification combined cycle ((B)IGCC) – power plant design consisting on the following layout: biomass dryer (if necessary), gasifier, gas cleanup system (if necessary), gas turbine-generator, heat recovery steam generator (HRSG) (Larson, Williams, & Leal, 2001)

Centre de Recerca Ecològica i Aplicacions Forestals (CREAF) – public-funded research centre aimed to production of new knowledge and tools for the terrestrial ecology field, improving rural and urban environment management (CREAF, 2013)

Centre Tecnològic Forestal de Catalunya (CTFC) – technological forestry center of Catalonia, governmental organization aimed at contribution to forestry industry modernization, rural development and sustainable management of environment (CTFC, 2013)

co-firing system – electricity production system fuelled using two or more fuels, for example producer gas and natural gas (Rodrigues, Faaij, & Walter, 2003) combined heat and power (CHP) – “also known as cogeneration, means that both electrical and thermal energy are generated simultaneously” (Monteiro, Moreira, & Ferreira, 2009, pp.290)

diesel engine – type of internal combustion engine in which the ignition occurs by compression of the fuel (Onovwiona & Ugursal, 2006)

European Union (EU) – “economic and political partnership between 27 European countries that together cover much of the continent” (Communication Department of the European Commission, 2013)

Food and Agriculture Organization of the United Nations (FAO) – governmental organization aimed to food security achievement among other goals (FAO, 2013)

heat recovery steam generator (HRSG) – heat cycle designed to generate steam from the excess heat at the exhaust of a gas turbine and circulate the steam through a steam turbine to produce additional electricity (Larson, Williams, & Leal, 2001)

high heating value (HHV) – it “is the total heat generated by the combustion of a fuel” (Onovwiona & Ugursal, 2006: p. 393). It also receives the name of gross calorific value, or GCV (Obernberger, 1998)

internal combustion engine (ICE) – engine with combustion chamber inside which the fuel ignites, comprising two main types according to their method of ignition: spark-ignition engine and Diesel engine (Onovwiona & Ugursal, 2006)

International Energy Agency (IEA) – “autonomous organisation which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond”. Its main focus areas are “energy security, economic development, environmental awareness, and engagement worldwide” (IEA, 2013)

Inventari Ecològic i Forestal de Catalunya (IEFC) – inventory of all forests found in Catalonia, considering “not only structural aspects (such as density or diameter), but also functional aspects (such as leaf area index, incident radiation, biomass and production of wood, bark, branches and leaves or growth series)

lower heating value (LHV) – also known as the net calorific value (NCV), the LHV is a thermodynamic property of a fuel giving the energy content of that fuel, expressed in MJ/kg. It “is defined as the higher heating value of the fuel (HHV) less the energy required to vaporize the water produced during combustion” (Onovwiona & Ugursal, 2006: p. 393). It is also called net calorific value, or NCV (Obernberger, 1998)

micro-scale cogeneration – different definitions of micro-scale cogeneration systems are found in the literature with regard to maximum power output of these systems. Among them, it has been chosen 50 kWe of maximum power output as the limit (Directive 2004/8/EC of the European Parliament and of the Council of the 11 February 2004 on the promotion of cogeneration based on the useful heat, 2004) micro-turbine – small-scale energy production gas turbine with an electrical power generation below 500 kWe (Invernizzi, Iora, & Silva, 2007), that typically mounts generator, compressor and turbine in a common shaft (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011)

Otto engine – type of internal combustion engine in which the ignition occurs by the effect of a spark (Onovwiona & Ugursal, 2006)

organic fluid – organic compound characterized by higher molecular mass and lower ebullition/critical temperature than water, consequently requiring less heat during evaporation (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011)

organic rankine cycle (ORC) – thermodynamic cycle operating under the same principle as the conventional Rankine cycle, but using as a working fluid an organic fluid such as toluene or propanol instead of water (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011)

Rankine cycle – thermodynamic cycle that uses a source of heat to produce high pressure steam that is later expanded in a turbine, also called condensing extraction steam turbine (Larson, Williams, & Leal, 2001)

small-scale cogeneration – different definitions of small-scale cogeneration systems are found in the literature with regard to the maximum installed capacity of these systems. Among them, a maximum power output of 1 MWe has been chosen as the limiting value (Directive 2004/8/EC of the European Parliament and of the Council of the 11 February 2004 on the promotion of cogeneration based on the useful heat, 2004) syngas – also called product gas or producer gas, is a gas obtained through gasification that “can be used by boilers, internal combustion engines or gas turbines to produce heat and power in CHP systems after proper cleaning and conditioning” (Dong, Liu, & Riffat, 2009, pp. 2121)

Stirling engine – engines that use an external heat source to produce power. Two main types exist: free-piston and kinematic (Monteiro, Moreira, & Ferreira, 2009)

## 1.10 Summary

Among all the renewable energy alternatives, electricity generation using biomass sources is a good opportunity to take advantage of a missed latent potential for using and giving economic value to forest wood biomass and improve the energy supply of both developing and developed countries. However, it is necessary to work on the technical and economic feasibility of these technologies in general and of biomass-based technologies in particular, with aim to encourage its usage at all levels.

This study was focused on the technical side of biomass-based electricity generation feasibility, and its purpose was to find out which is the current potential for electricity generation using forest wood biomass sources and current conversion technologies at small scale.

# CHAPTER 2. LITERATURE REVIEW

A comprehensive literature review was performed in order to achieve a good understanding of the state of the art in the field of study and the main reasons that underlie behind the growing interest and focus on the switch from traditional energy sources to renewable energy sources as biomass.

Main topics covered were the justifications for the use of renewable energy technologies and, particularly, biomass conversion technologies, as well as the availability and under development technologies including both biomass-based electricity generation and combined heat and power technologies.

These topics could be grouped into five main categories:

- Combustion technologies
- Gasification technologies
- Small- and micro-scale generation technologies
- Technology reviews
- Feasibility

## 2.1 Methodology for the review of the literature

Several sources were accessed to cover a wide range of all the available information in an attempt to discover what is the scientific community working with at present time.

The bulk of information was obtained by using electronic databases. Among them, the following ones should be emphasized:

- Google Scholar
- ScienceDirect
- Institute of Electrical and Electronics Engineers IEEEXplore
- Thomson Reuters Web of Knowledge

Although all of them are generic databases not focused on a particular topic, some screening was done in terms of limiting the search of specialized journals.

The first step performed was a brief search for terms such as *biomass*, *electricity*, *combined heat and power*, *CHP* and *small-/micro-scale*.

Once identified those journals related with the field of biomass conversion to electricity and, in particular, with small-scale and micro-scale technologies, searches were refined by journal. Particularly, *Renewable and Sustainable Energy Reviews*, *Renewable Energy*, Biomass and Bioenergy, *Energy for Sustainable Development*, *Applied Energy* and *Energy* were mostly used. References consulted could be classified between technology related sources and biomass related sources.

To delimit the breadth of the literature review and exemplify that the focus is placed on the overlapping of those concepts, a Venn diagram can be used:

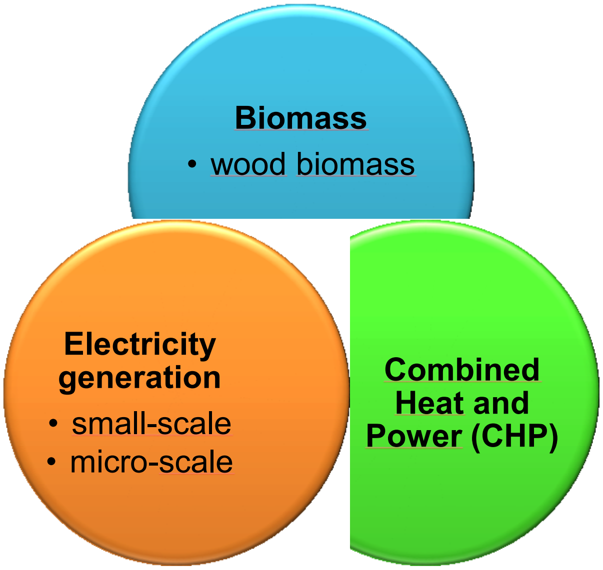


Figure 2.1 Venn diagram of studied concepts

Regarding the technologies, special attention was given to small- and micro-scale technologies. In regard to biomass availability, only the forest biomass was assessed due to their suitability for electricity generation, especially in Mediterranean areas.

## 2.2 Biomass as an energy source for the future

In the present context of increasing energy consumption throughout the world, the energy usage and sources have become a major issue with important implications in economics, public policy and environmental impacts.

Fossil fuels, which are the main energy source for the developed and developing nations, are starting to deplete in the last decade (Höök & Tang, 2013). In a free-market economy, that leads to increasing prices and thus decreased competitiveness of those countries highly dependent on these energy sources. In addition, in countries such as Spain with low or even no indigenous fossil fuel availability, the usage of fossil fuels results in energy dependency on foreign countries. Finally, the high level of greenhouse gas emissions derived from the combustion of fossil fuels is one of the biggest causes of climate change through the global warming that it entails (Höök & Tang, 2013).

Facing all mentioned odds, there are the renewable energy technologies, which are indigenous sources of virtually perpetual energy, scalable and carbon neutral (Buragohain, Mahanta, & Moholkar, 2010).

Furthermore, renewable energies could help to implement the distributed generation model that consists on energy production close to both renewable energy resources and consumption and, consequently, large production plants are substituted or complemented by small-scale and micro-scale plants (Monteiro, Moreira, & Ferreira, 2009). Distributed generation, in turn, is a key tool to address the problems of security of supply and CO2 emissions and to improve the efficiency of energy systems (Kuhn, Klemes, & Bulatov, 2008), as well as to overcome the problem of rising electricity costs and shortages (Buragohain, Mahanta, & Moholkar, 2010). Finally, 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 (Buragohain, Mahanta, & Moholkar, 2010) and by generating new income opportunities through revaluation of local resources (Herran & Nakata, 2012).

Among all the renewable sources, biomass is one of the most promising options. Particularly, the fact of being a proven technology, its flexibility of operation and installation (Buragohain, Mahanta, & Moholkar, 2010), its low (even null) and stable (especially when compared with fossil fuels) price because of being often a waste product, its flexibility to be converted to several forms of energy such as heat, gas or electricity and its easy and efficient scalability (Prasad, 1990) are strong reasons for it. In addition, biomass is, together with hydro, the unique renewable source that can be stored and continuously used to have a predictable output not dependent of weather (Passey, Spooner, MacGill, Watt, & Syngellakis, 2011).

Furthermore, biomass admits the usage of combined heat and power technologies, which have better efficiencies (Gustavsson, Biomass and district-heating systems, 1994) and lower consumption (Raj, Iniyan, & Goic, 2011) than heat and electricity production individually. Biomass-fuelled CHP systems can be used in both commercial buildings such as hospitals and schools (Dong, Liu, & Riffat, 2009), commercial centers, hypermarkets, and heated swimming pools (Monteiro, Moreira, & Ferreira, 2009) and residential dwellings due to their low operating and maintenance costs, high overall efficiencies and their low noise, vibration and emissions levels (Kuhn, Klemes, & Bulatov, 2008).

## 2.3 Biomass types and availability

Biomass is defined as “the organic material from recently living things, including plant matter from trees, grasses, and agricultural crops” (Ciferno &

Marano, 2002: p. 5). It includes all living and dead plants and residues derived from their processing (Osowski & Fahlenkamp, 2006), and can be classified in four main categories: woody materials, herbaceous and annual growth materials, forestry and agricultural residues and waste materials such as municipal solid waste (Franco & Giannini, 2005). Among them, those that can be used for electricity production are agricultural crop and residues such as bagasse, forest residues and wood wastes (bark, wood chips and sawdust) and dedicated energy crops (Evans, Strezov, & Evans, 2010; Salomón, Savola, Martin, Fogelholm, & Fransson, 2011).

Main characteristics affecting the quality of biomass resource are density, presence or lack of uniformity and moisture level (Prasad, 1990). It is noteworthy to mention that biomass for combustion and gasification purposes is required to have a low moisture level, within an appropriate range between 10% and 15% (Buragohain, Mahanta, & Moholkar, 2010). The types of biomass are summarized in Table 2.1:

Table 2.1 Existing types of biomass

| **Biomass type** | **Description** |
|---|---|
| Woody materials | Firewood, Wood |
| Herbaceous and annual growth materials (energy crops) | Mischantus, Switch grass, Wheat straw, Beechwood |
| Forestry and agricultural residues | Wood chips, Wood pellets, Bark, Sawdust, Bagasse, Corn cob, Rice husks, Pits |
| Waste materials | Dry sewage, Municipal solid waste |

Source: personal compilation based on (Vallios, Tsoutsos, & Papadakis, 2009) and (Yoshida, et al., 2003)

In the Mediterranean area, the main tree species is the maritime pine, followed by the eucalyptus (Viana, Cohen, Lopes, & Aranha, 2010).

The deep assessment of the biomass resource available in Portugal made by Viana, et al. (2010) ended up finding that the available biomass resource coming from those species is about 0.85 and 0.90 metric tons per year and hectare.

## 2.4 Biomass conversion technologies

Several sources summarize the main conversion technologies available and break them down into primary technologies and secondary technologies.

Primary technologies are those that perform the first conversion step. They are combustion, gasification and pyrolysis technologies (Evans, Strezov, & Evans, 2010; Dong, Liu, & Riffat, 2009; McKendry, 2002).

Secondary technologies are those coupled to a primary technology to use the end product (producer gas, fuel or heat from combustion) to generate electricity. They are internal combustion engine (ICE), steam engine, steam turbine, external combustion (commonly called Stirling) engine, organic Rankine cycle (ORC) applications, gas turbine, micro-gas turbine and fuel cells (Dong, Liu, & Riffat, 2009; Salomón, et al., 2011). In addition to them, there are some ideas under research such as evaporative gas turbines, externally fired gas turbines, pulverized-fired gas turbines, air bottoming cycles and powdered-fuelled ICEs (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011).

Some studies such as the review carried out by Dong, et al. (2009) state that primary and secondary technologies might be combined in multiple ways, while others provide only a few possible combinations. For example, Buragohain, et al. (2010) claim that there are actually seven conversion mechanisms available (gasifier with ICE, combustion and steam engine or turbine, biomass integrated gasification combined cycle (BIGCC) with steam or gas turbine, external combustion engines and biomethanation with ICE); and that only two of them are commercially viable and widely deployed at present. They are biomass gasification coupled with an ICE and biomass combustion coupled with a steam turbine.

Throughout the following sub-sections the main findings related to these existing technologies are summarized.

### 2.4.1 Primary conversion technologies

The primary conversion technologies are those that convert biomass into another form of energy, for example heat or a raw gas. There are three main primary conversion technologies, described in the following subsections.

Table 2.2 summarizes the different primary conversion technologies found in the literature and a brief description of the principles of operation:

Table 2.2 Biomass conversion primary technologies summary

| **Primary Technology** | **Principle of operation** |
|---|---|
| Pyrolysis | Chemical reaction that converts biomass into a liquid or gaseous fuel though indirect heating |
| Gasification | Chemical process that converts dry biomass into a gaseous combustible through partial oxidation |
| Combustion | Complete oxidation of dry biomass creating freeing energy in heat form |

Source: personal compilation based on Evans, Strezov, & Evans (2010) and McKendry (2002)

From these options, gasification and direct combustion have been pointed out as the most efficient processes to get the maximum advantage of dry biomass such as forestry residues (Yoshida, et al., 2003).

### 2.4.1.1 Pyrolisis

Pyrolosis is a chemical process consisting on the conversion of biomass to liquid, gases and condensable vapors through indirect heating (to around 500 ºC) applied in an anaerobic environment (Bain, Overend, & Craig, 1998; Evans, Strezov, & Evans, 2010; McKendry, 2002).

The obtained products can be used for both electricity and heat production and as a fuel for transport purposes (Murphy & McKeogh, 2004).

### 2.4.1.2 Gasification

Gasification is a chemical process consisting on the conversion of dried biomass into a combustible in a gaseous state through a partial oxidation, typically at around 800-900 ºC (Difs, Wetterlund, Trygg, & Söderström, 2010; Evans, Strezov, & Evans, 2010; McKendry, 2002). Gasification has been defined as a clean, efficient and versatile process that is suitable for heat and electricity generation purposes in both developed and developing countries (Kirkels & Verbong, 2011). For example, gasification has been proposed as the best technology for providing cooking and heating gas to a rural agricultural village while generating electricity for household and industry consumption (Shuying, Guocai, & DeLaquil, 2001).

Regarding the efficiency, biomass gasification is considered to have higher efficiencies than direct combustion, thus having fewer greenhouse gas emissions per kWh produced (Murphy & McKeogh, 2004).

The gasification process comprises several stages. Typically, a pre-treatment of the biomass is done before being introduced to the gasifier where the gasification reaction occurs. Then, a gas cleaning stage is required in most of the cases before fuelling the chosen secondary technology (Bain, Overend, & Craig, 1998; Kirkels & Verbong, 2011; Osowski & Fahlenkamp, 2006; Zhang, Chang, Guan, Chen, Yang, & Jiang, 2012), which typically is gas engines and gas turbines or combustion boilers (McKendry, 2002).

Among all the existing variables affecting the process, it is worth highlighting the tar formation or the gas cleanup (Difs, Wetterlund, Trygg, & Söderström, 2010), but the gasifier is probably the most important. The different types of gasifiers can be classified according to the fluid-biomass contact. Using this criterion, fixed bed, circulating-fluidized bed and entrained flow reactors exist (Bain, Overend, & Craig, 1998; Buragohain, Mahanta, & Moholkar, 2010; Ciferno & Marano, 2002; Osowski & Fahlenkamp, 2006; Zhang, et al., 2012).

Table 2.3 summarizes these three types of gasification reactors found in the literature and the different sub-types available:

Table 2.3 Gasification technologies summary

| Gasifiers | Principle of operation |
|---|---|
| **FIXED-BED REACTORS** | |
| Direct current | Gasification fluid flows in the same direction as biomass |
| Counter current | Gasification fluid flows in the opposite direction to biomass |
| Cross-flow | Gasification fluid is introduced from one side and exist from the opposite, while biomass moves up-down |
| **FLUIDIZED-BED REACTORS** | |
| Bubbling fluidized-bed | Frictional forces of fluidizing material reach equilibrium with biomass weight |
| Circulating fluidized-bed | Frictional forces are higher so the biomass particles are entrained by the fluid |
| **ENTRAINED FLOW REACTORS** | |
| Suspension flow or dust cloud | Used for coal and oil gasification. Small particles of fuel are entrained by the gasification fluid |

Source: personal compilation based on (Ciferno & Marano, 2002)

Fixed-bed gasifiers are more suitable for small-size projects while circulating-fluidized beds are widely used in small- and large-scale projects as Zhang, et al. (2012) inferred using actual data of gasification plants in China.

Regarding the accepted fuel, Zhang, et al., (2012) claimed that fixed-bed gasifiers should be used for large and dense fuels such as wood chips or densified biomass, while the fluidized bed reactors accept low density fuels such as sawdust.

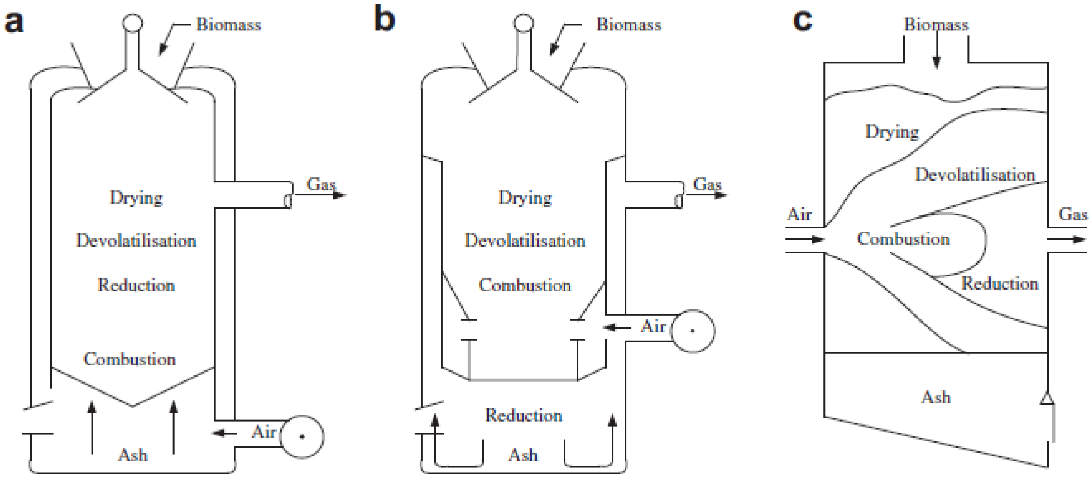
#### 2.4.1.2.1 Fixed bed reactors

In this kind of reactors the fluid, oxygen or air, passes through the biomass that is placed in a fixed position. This type of gasifier has low investment costs (Osowski & Fahlenkamp, 2006). Three different types exist: updraft, downdraft and cross-flow gasifiers (see Figure 2.2).

Downdraft gasifiers, i.e., direct current, have a fluid flow in the same direction as biomass, up-down. In these reactors, almost all tar formed is also consumed (Ciferno & Marano, 2002), so low-tar gas is produced even when the fuel is wood (FAO Forestry Department, 1986). According to Buragohain, et al. (2010), the tar present in the producer gas may condense in the engine shaft, which results in more cleaning tasks. Consequently, downdraft gasifiers have been identified as the most suitable type for rural village applications in developing countries due to their low operating and maintenance requirements (Henderick & Williams, 2000). However, it has some disadvantages such as the high temperature at which the producer gas exits the reactor and the low moisture content of biomass fuel required (Buragohain, Mahanta, & Moholkar, 2010; Ciferno & Marano, 2002).

Updraft gasifiers, i.e., counter current, have a fluid flow in the opposite direction than the biomass. In comparison with downdraft reactors, updraft gasifiers have high tar content, thus having higher operating and maintenance costs (Osowski & Fahlenkamp, 2006). However, as they are the oldest type of gasifiers, they constitute a proven and reliable technology that also accepts biomass with high moisture content as a fuel (Ciferno & Marano, 2002).

Last type of fixed bed reactors are the cross-flow gasifiers, where the fluid is introduced from one side and exiting from the other while the biomass has an up-to-down movement (Zhang, et al., 2013).



Source: (Zhang, et al., 2012: p.179)

Figure 2.2 Schematic diagram of the three types of fixed-bed gasifiers: a: updraft; b: downdraft; and c: cross-flow

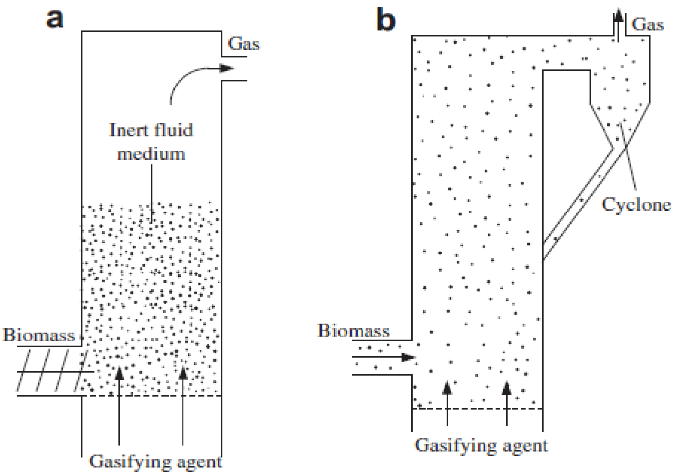
### 2.4.1.2.2 Fluidized bed reactors

The main principle that underlies the fluidized bed reactors is that a small amount of feedstock together with a large amount of fluidizing material such as sand or alumina can be gasified when a heated fluid (either oxygen or air) is introduced (Kirkels & Verbong, 2011). Two different types exist: bubbling and circulating fluidized bed gasifiers (Kirkels & Verbong, 2011; Onovwiona & Ugursal, 2006), represented in Figure 2.3. These are mainly applied at medium to large scales, from 5 to 10 MWth. Both of them have been proven reliable for wood-biomass burning, as they reduce the risk of slagging in heat transfer surfaces (Siewert, Niemelä, & Vilokki, 2004) and have better contact between solid and fluid leading to more adjustable and uniform temperature distribution (Osowski & Fahlenkamp, 2006; Zhang, et al., 2012). However, they admit only biomass with small particulate size, so the wood has to be crushed (Osowski & Fahlenkamp, 2006).

In bubbling fluidized bed gasifiers, equilibrium is reached between the frictional forces of the fluidizing material and the weight of the feedstock. At this point, biomass appears to be bubbling and the gasification reaction occurs (Ciferno & Marano, 2002) at a temperature that ranges between 700 and 900 ºC depending on the fuel/fluid ratio (Zhang, et al., 2013). The producer gas is uniformly generated and the gasifier accepts a wide range of particle size (Ciferno & Marano, 2002).

Circulating fluidized bed gasifiers operate at higher velocities so the particles are entrained by the fluid. These reactors achieve higher carbon conversion rates and thus the gasification reaction is faster even though the velocity is limited by the size of fuel particles (smaller particles allow to achieve higher velocities) and the heat exchange is less efficient than that obtained with a bubbling fluidized bed (Ciferno & Marano, 2002). These kinds of reactors require a quite higher investment than that for bubbling fluidized bed reactors due to increased complexity and size (Osowski & Fahlenkamp, 2006). In addition, they are more suitable for large scale and IGCC as they already work with pressurized gas so the pressurization is not done in vain (Kirkels & Verbong, 2011).

The research by Zhang, et al. (2012) also describes a third type of fluidized bed reactor: the dual fluidized bed gasifier, which still is under research.



Source: (Zhang, et al., 2012: p. 179)

Figure 2.3 Schematic diagram of the two types of fluidized-bed gasifiers: a: bubbling fluidized bed; b: circulating fluidized bed

#### 2.4.1.2.3 Entrained flow reactors

Entrained flow reactors, i.e., suspension flow or dust cloud reactors, have been applied for oil and coal gasification. In this design, small particles are entrained in a flow of the fluidizing medium (Kirkels & Verbong, 2011).

### 2.4.1.3 Combustion

Direct combustion consists on the complete oxidation of biomass in an aerobic environment (Evans, Strezov, & Evans, 2010).This process frees the chemical energy from the biomass and converts them into heat that can be used for both heating and electricity production purposes through the use of a suitable technology like boiler, steam turbine and others (McKendry, 2002). Although there are several possible uses of combustion, the most widely scattered option is the usage of heat from combustion to convert water to vapor and drive a turbine. The turbine is based on the thermodynamic Rankine cycle (Bain, Overend, & Craig, 1998).

According to Bain, et al. (1998), there are several combustors available, including pile burner, stoker grate, bubbling and circulating fluidized bed and suspension burners among other non-conventional options.

### 2.4.2 Secondary conversion technologies

The secondary conversion technologies are those that convert the intermediate form of energy, i.e., that obtained after the primary conversion technology, into electricity. There are three many secondary conversion technologies, described in the following subsections.

The table below (see Table 2.4) summarizes the different secondary conversion technologies found in the literature, split by whether or not being commercially available, along with the primary conversion technology to which each one can be coupled and a brief description of the principles of operation:

Table 2.4 Biomass conversion secondary technologies summary

| **Secondary Technology** | **May be coupled to… (Primary Technology)** | **Principle of operation** |
|---|---|---|
| **COMMERCIALLY AVAILABLE TECHNOLOGIES** | | |
| Internal Combustion Engines (ICE) (Otto, Diesel) | Gasification<br>Pyrolisis | Heat from combustion in an internal comb. chamber drives a piston through gas expansion |
| Stirling Engine (Free-piston, Kinematic) | Combustion | Heat from combustion in an external comb. chamber drives a piston through gas expansion |
| Steam Engine | Combustion | Steam generated through thermal |

| Secondary Technology | May be coupled to… (Primary Technology) | Principle of operation |
|---|---|---|
| | | evaporation of a fluid drives an engine |
| Steam Turbine | Combustion | Steam generated through thermal evaporation of a fluid is expanded in a turbine |
| Organic Rankine Cycle (ORC) | Combustion | Same as steam turbine but organic fluids are used as working fluids |
| Gas Turbine / Biomass Integrated Gasification Combined Cycle (BIGCC) | Gasification | Clean gas is compressed before burnt in a combustion chamber and then expanded in a turbine / Biomass gasification cycle is attached to a CHP application using a gas turbine |
| Microturbine | Gasification | Same as gas turbine but with power output < 500 kW |
| **TECHNOLOGIES UNDER R&D** | | |
| Externally-fired gas turbine | Gasification<br>Combustion | Combustion chamber of gas turbine substituted by a heat exchanger |
| Pulverized wood-fired gas turbine, ICE or Stirling engine | Combustion | Gas turbine, Diesel engine or Stirling engine fired with micro-particulates of pulverized wood |
| BIGCC with air-bottoming cycle | Gasification | Same as BIGCC but with a steam turbine added at the exhaust to use waste heat |
| Gas Turbine co-fired with fossil fuels | Gasification | Producer gas is burnt together with natural gas or coal |

Source: personal compilation based on Buragohain, Mahanta, & Moholkar (2010), Franco and Giannini (2005), Henderick and Williams (2000), Invernizzi, Iora, and Silva (2007), Larson, Williams, and Leal (2001), Monteiro, Moreira, and Ferreira (2009), and Salomón, Savola, Martin, Fogelholm, and Fransson (2011)

#### 2.4.2.1 Internal combustion engine (ICE)

Internal combustion engines are the widely-spread technologies of Otto engine (spark-ignition) and Diesel engine. They have been labeled as the only secondary technologies at a maturity level for the utilization of producer gas (Henderick & Williams, 2000).

In ICEs, producer gas obtained from biomass can be used together with diesel or other fossil fuels in a co-firing scheme as well as alone, but only with spark-ignition engines (Buragohain, Mahanta, & Moholkar, 2010; Henderick & Williams, 2000). However, ICEs do not admit the combination with direct combustion application, due to their requirement of a fluid fuel. Furthermore, ICEs are considered an interesting possibility to reach high efficiencies for small- and micro-scale plants (Ahrenfeldt, et al., 2006).

Several articles provide data about the efficiency of gasification technologies coupled with ICEs. Onovwiona and Ugursal (2006) and Monteiro, Moreira, & Ferreira (2009) summarized the technical characteristics of some micro-scale ICE-based CHP systems. Electrical efficiencies reported range from 21% to 30%, increasing with the power output, and overall efficiencies from 78% to 90% (Onovwiona & Ugursal, 2006) and from 50% to around 60% (Monteiro, Moreira, & Ferreira, 2009). Other authors reported electrical efficiencies ranging from 20 to 26% with overall efficiencies up to 90% (Barbieri, Spina, & Venturini, 2012), and electrical and overall efficiencies of 25% and 90% respectively, for an ICE-based small-scale CHP plant of 100 kWe of power output (Kimming, et al., 2011). The high variability in both size and efficiencies is shown in International

Energy Agency (2007), which reported efficiencies as low as 5% going up to 30%, for outputs from 200 kWe to 1 MWe.

The BERI project carried out in Karnataka, India, consisted on building a gasification plant coupled with a 120 kWe spark-ignited gas engine, and an electrical efficiency of 18% was obtained (Dasappa, Subbukrishna, Suresh, Paul, & Prabhu, 2011). The Viking gasification plant set up at the Technical University of Denmark used a 19 kWe engine generator and 25% of electrical efficiency was obtained (Ahrenfeldt, et al., 2006).

#### 2.4.2.2 Stirling engine

Stirling engines are external combustion engines. Both two types, free-piston and kinematic, are based on the Stirling cycle (Monteiro, Moreira, & Ferreira, 2009). That means that the combustion takes place outside the closed cylinder so these engines accept all kinds of fuel and have less maintenance requirements (Kuhn, Klemes, & Bulatov, 2008) making the process simpler when compared with ICE's requirements (Nishiyama, et al., 2007). Consequently, Stirling engines have been identified as one of the more suitable technologies for micro-scale applications (Monteiro, Moreira, & Ferreira, 2009).

As a result of their operating mode with external combustion, Stirling engines have low electrical efficiency and high overall efficiency due to a high thermal efficiency (Kuhn, Klemes, & Bulatov, 2008; Monteiro, Moreira, & Ferreira, 2009), which is theoretically higher than that for a Diesel engine (Obara, Tanno, Kito, Hoshi, & Sasaki, 2008). Some studies (Monteiro, Moreira, & Ferreira, 2009) have reported electrical efficiencies that vary between 10% and 33% and that approach 40% (Onovwiona & Ugursal, 2006), when using this technology. According to the same sources the overall efficiency ranges between 65% and 90%. Other researches showed that a small-scale CHP unit of 100 kWe of power output based on Stirling engine technology reaches 12% of electrical efficiency and 90% of overall efficiency (Kimming, et al., 2011).

#### 2.4.2.3 Steam engine

Steam engine technology uses steam generated through thermal evaporation of a working fluid, usually water, to drive an engine. Nowadays, this technology is being replaced by steam turbines because of the higher level of superheating reached by the latter (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011). Steam engines can be used with all primary technologies, but due to their capacity to take advantage of produced heat to generate electricity are more suitable for direct combustion applications.

Electrical efficiencies of about 16% have been reported for small-scale systems, i.e., 25 kWe of output, using steam generated with biomass direct combustion driving a steam engine (Prasad, 1990). In Hartberg, Styria (Austria), a 730 kWe screw-type steam engine was installed in 2003 as the prime mover of a CHP plant. The plant reached an electric efficiency of about 10% and an overall efficiency around 80% while fuelled with wood chips, bark and sawdust from nearby areas (Hammerschmid, Stallinger, Obernberger, & Piatkowski, 2004).

### 2.4.2.4 Steam turbine

The steam turbine is a technology based on the conventional Rankine thermodynamic cycle. It is a proven and mature technology widely used for biomass conversion to electricity, especially for large-scale plants, i.e., above 3 MW of electric output (Franco & Giannini, 2005; Salomón, et al. 2011). However, this maturity stage reached makes virtually impossible for this technology to achieve any relevant breakthrough (Buragohain, Mahanta, & Moholkar, 2010).

The most common layout for a steam turbine plant consists on a boiler fuelled with biomass coupled with a heat exchanger where the heat from combustion is used to vaporize a fluid, usually water, that is expanded thorough the steam turbine (Larson, Williams, & Leal, 2001). This mode of operation makes this technology especially useful for direct combustion applications although it can be used with all other primary technologies.

This technology admits the residual heat utilization so it can be used in conventional power plants and CHP plants. Existing experiences showed electrical efficiencies from 18% up to 34%, depending on the scale (Wahlund, Yan, & Westermark, 2001).

### 2.4.2.5 Organic Rankine cycle (ORC)

The ORC technology is based on the same principle that steam turbines, the Rankine cycle, but in this case organic fluids such as propanol, toluene and isobutane are used as a working fluid (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011). These fluids have lower vaporization temperature than water and therefore they allow the use of lowest temperature heat sources (Liu, Shao, & Li, 2011; Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011) and reach higher cycle efficiencies (Dong, Liu, & Riffat, 2009).

ORC applications have better performances in small- and micro-scale installations and reduce the risk of turbine damage due to partial vaporization of the working fluid. They also allow the use of single-stage turbines as they do not reach high temperature gradients between evaporation and condensation phases (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011).

The ORC technology can be virtually used with all primary technologies but, as in case of steam turbines, its characteristics make it more suitable for direct combustion applications. However, ORC applications are also interesting for using excess heat in bottoming cycles or for applications in the micro-scale range as claimed by Invernizzi, et al. (2007).

Several papers reported electrical efficiencies around 15% (Dong, Liu, & Riffat, 2009) and up to 20% (Liu, Shao, & Li, 2011). Dong et al. (2009) also stated that in the Lienz CHP plant, which has a 1000 kW of power output, an electrical efficiency of 18% have been achieved. Finally, Liu, et al. (2011) found that electrical efficiency between 7.5-13% could be reached in a 2 kW CHP systems using the ORC technology, depending on the fluid used.

#### 2.4.2.6 Gas turbines/Biomass integrated gasification combined cycle (BIGCC)

Gas turbines layouts almost always consist of a gasification unit, a producer gas cleaning unit, a gas turbine and a heat recovery steam generator (HRSG) in case of CHP plants (Corti & Lombardi, 2004; Jurado, Cano, & Carpio, 2003; Larson, Williams, & Leal, 2001). This layout is called biomass integrated gasification combined cycle (BIGCC) or biomass integrated gasification gas turbine (BIGGT) depending on the presence or absence of a heat recovery cycle.

Different combination of gasification technologies with gas turbines alone or combined with a HRSG are commercially available (Pellegrini, de Oliveira Júnior, & Burbano, 2010). Obviously, this technology can only be used with gasification as a primary technology because gas turbines need a gas fluid to work.

The efficiencies achieved with these technologies are higher than those obtained with a steam turbine under the same conditions (Larson, Williams, & Leal, 2001). Other studies also showed that they also perform better than other combustion technologies including not only steam turbines but also gas engines (Dornburg & Faaij, 2001).

Reported efficiencies are around 30-45% (Wahlund, Yan, & Westermark, 2001). These figures are supported by some demonstration plants as the

Värnamo demonstration plan that reached 32% of electrical efficiency (Stahl & Neergaard, 1998) or the simulations of the Termiska Processer that gave an electrical efficiency of 32.5% (Faaij, et al., 1997). For large-scale BIGCC power plants, efficiencies up to 43% have been reported (Uddin & Barreto, 2007).

#### 2.4.2.6.1 Microturbines

The main drawback of gas turbines is their scale of operation. Due to their large scale, they are not usable in places where there is a low availability of biomass resources, for example in Mediterranean areas. Microturbines solve this weakness, as they are commercially available in the range between 25 to 80 kW of power output and even smaller output turbines are under intensive research (Monteiro, Moreira, & Ferreira, 2009). Other sources claim can be considered microturbines all turbines under 500 kW of power output (Invernizzi, Iora, & Silva, 2007) or all turbines under 250 kW of thermal and electric output for CHP applications (Kuhn, Klemes, & Bulatov, 2008).

Microturbines-based power plants have a slightly different layout than gas turbine-based applications. In the case of microturbines, the gas turbine, the generator and the compressor share a common shaft (Kuhn, et al., 2008; Salomón, et al., 2011). The principle of operation is the same as that for aerospace turbines, and is described in depth by Henderick and Williams (2000) in their article.

Microturbines are a down-scaled version of conventional gas turbines and thus they are designed for working with a fluid fuel, so a biomass gasification stage is expected to be set up before the microturbine.

The efficiency of microturbines is stated to be around 30%, slightly lower than that obtained with an ICE, by Invernizzi, et al. (2007). Other studies reported efficiencies of commercial units from Capstone that range from 26 to 33% for 30 to 200 kW of power output (Basrawi, Yamada, Nakanishi, & Katsumata, 2012). Onovwiona and Ugursal (2006) demonstrated in their research that the efficiency for a Capstone microturbine is slightly lower when it is fuelled with biomass (26%) instead of natural gas (30%), but still higher than when it is fuelled with diesel (25%). Finally, Monteiro, et al. (2009) also summarized the efficiencies achieved by some commercial units and found that they are comprised between 24-30%.

#### 2.4.2.7 Other designs

Other designs based on gas turbine technology are available. Salomón, et al. (2011) and Invernizzi, et al. (2007) described in their article the air bottoming cycle alternative, consisting on adding another turbine for using the waste heat at the exhaust of the gas turbine. With this system an increase of 10%, from 30% to 40% in efficiency is obtained. It is also stated that this variation of the gas turbine design admits not only electricity production increases but also cooling and heating production.

Another available variation of the gas turbine design is the co-firing of producer gas with coal or natural gas. With this option, an increased efficiency can be obtained (Franco & Giannini, 2005). According to the authors, two different alternatives are implementable: mix of both fuels in the gas turbine or a topping cycle fuelled with the fossil fuel and a bottoming cycle fuelled with producer gas obtained from biomass.

Externally-fired gas turbines are the last modification that can be found in the existing literature. These designs substitute the combustion chamber by a heat exchanger so the combustion can take place outside the gas turbine (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) and thus not only gasification can be used as a primary technology but also direct combustion is admitted. Two different options are available, open cycle, where the working fluid is discharged to the environment, and closed cycle, where the working fluid is confined in a closed circuit (Al-attab & Zainal, 2010). This layout also ensures that the working fluid in the turbine is completely clean so lower maintenance costs are expected (Al-attab & Zainal, 2010). Al-attab and Zainal (2010), Franco and Giannini (2005) and Wahlund, Yan, and Westermark (2001) claimed that the efficiency obtained with these systems is around 30%.

## 2.5 Summary

Existing literature available focused on the biomass conversion to electricity topic was accessed in order to achieve a solid knowledge about the state of the art at present time.

Regarding the energy usage and its environmental, social and economic potential problems, several sources suggest that renewable energies will help to overcome them providing cheaper and indigenous energy for both developed and developing countries. Biomass has been identified as a key renewable source because it is based on proven technologies that admit both electricity and combined heat and power production. Furthermore, its price is expected to remain low and stable, especially when comparing with that of fossil fuels.

Several types of biomass can be used in electricity production and cogeneration facilities, among which stand out the forest residues for their availability in the Mediterranean areas such as Catalonia where a lack of forest management leads to wildfires from time to time so there is a potentially available resource.

From all reviewed sources, it was found that the conversion of biomass to electricity can be made using several mechanisms which can be classified as primary or secondary technologies and supporting multiple combinations among them. The most widely used layouts are those that combine combustion with steam turbines and gasification with internal combustion engines, but there are other promising alternatives such as biomas integrated gasification combined cycle (with either gas turbines or microturbines) or Stirling engines at diverse levels of development.

In case of small-scale and micro-scale alternatives, the review showed that the best available options are combustion paired with an organic rankine cycle using steam turbines and gasification coupled with either ICEs or microturbines.

# CHAPTER 3. FRAMEWORK AND METHODOLOGY

The main outcome sought from this research was the potential for electricity production from biomass sources. The research was approached from a point of view of a non-experimental quantitative analysis of existent data; consequently the research design was an ex post facto descriptive analysis.

The methodology of the study involved four main steps. The first one consisted of the sample selection that will be described in the next section (see §3.1.1), while the other three were aimed to address the research questions and will be deeply explained in the following section (see §3.2).

- Selection of an appropriate area where the study was focused.
- Available forest wood biomass resource assessment.
- Selection of the most suitable biomass conversion technology based on relative efficiencies and principles of operation.
- Calculation of the electricity that can be produced using the chosen technology and with the available biomass in the sample township.

## 3.1 Study Context

Due to the research design, two variables were considered. The amount of forest wood biomass available in sustainable basis, i.e., naturally produced per year, had to be estimated, and the relative efficiencies of biomass conversion to electricity technologies must be determined in order to select the most suitable one in the context of the research.

The selection of these variables was determined by the location of the study and by the selection of technologies to be assessed in terms of performance. The criteria for this selection are presented in the following two sub-sections.

### 3.1.1 Population, Stratum and Sample

As stated above, the selection of the study location was an important step of the research, because the amount of forest wood biomass resource available is constrained by the forest surface in the township under study and the tree species found there.

The population for the study was the country of Spain. It is noteworthy to mention that the forest wood biomass resources available in the country are very heterogeneously distributed due to differences in climate and tree species within the different regions, so differences in the technical and economic viability of biomass-based electricity production technologies were likely to be expected.

Among all the autonomous regions of Spain, Catalonia was selected as a stratum to study because it is claimed to be one of those with higher technical potential for electricity production using biomass (Gómez, Rodrigues, Montañés, Dopazo, & Fueyo, 2010). In addition, the researcher has deep knowledge of its geography, political organization and distribution of the territory as it is his birthplace and location of his professional education.

However, the study of potential for electricity generation of all Catalonia would be excessively extensive for the purpose of this thesis so in order to narrow down the scope, only a sample township in rural Catalonia was selected. The reason behind the condition of a township from rural Catalonia is that rural areas are where the amount of biomass produced is most likely to be large enough to produce a significant portion of the electricity required.

Nevertheless, there are many rural townships in Catalonia that could be appropriate for the purpose of this research in terms of resource available and potential for electricity generation. The criterion for selecting one or another was the quality and readiness of information about the amount of usable biomass and the electricity consumption of public buildings among others.

### 3.1.2 Technologies to assess

Regarding the technologies considered for the election of the most suitable one, only those technologies that were already commercially available for biomass conversion to electricity were considered. That is because these technologies have more efficiency data available as well as it will be less expensive to implement them, making the project more achievable, and move it away from the purely academic sphere.

The judgment of whether or not a technology can be labeled as available at commercial level was made according to the existing literature. For example, some studies such as the research carried out by Salomón, et al. (2011) have already classified which technologies are at present at point of commercialization. Other criteria to figure out which are these available technologies was whether there is or not data of actual power plants using a technology in the literature.

## 3.2 Methodology description

After the sample selection was done, the research consisted of three steps, one for each of the three research questions. The conceptual framework and tasks required to be carried out in order to do so are presented in the following subsections.

### 3.2.1 Biomass resource availability

The first step was aimed to address the first research question, what is the amount of forest wood biomass available in the selected township in rural Catalonia.

When assessing the amount of biomass available in a certain region, the rate of annual growth, i.e., the amount of biomass that a forest produces by itself during a year, was used to estimate that. This resource estimate is used to maintain the vegetation of the area. The units for the annual growth rate are metric tons per hectare and year ($tn/(ha \cdot year)$).

Another important aspect of forest biomass estimation is the different existent types and their annual growth. On the one hand, there is the biomass from forest waste, corresponding to the amount of biomass produced by a forest in form of residues. On the other hand, there is the biomass from whole trees, corresponding to the amount of trees that could be cut without reducing the vegetation density of a certain forest. Both quantities are potentially useful for electricity generation purposes.

Hence, the assessment of biomass resource availability was developed through the execution of two tasks:

- The calculation of the biomass resource available in the area under study was done using the following database: *Forest Inventory of Catalonia* (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) provided by the Centre for Ecological Research and Forestry Applications (CREAF in its Catalan acronym).

  The relevant output from this step was the quantity of biomass in metric tons produced in sustainable basis, i.e., by the forest itself each year, in the forest area comprised in the area of study.
- As a checking step, the data provided by the literature focused on forest production for Mediterranean species was sought, with aim to verify that the data provided by the databases are reliable and in line with what the scientific community has found in recent studies.

As a secondary output, the total area populated by woods was sought, a datum useful for the estimation of the net mass of biomass available within the township.

### 3.2.2 Selection of most suitable conversion technology

The second step was focused on addressing the second research question, what is the most suitable technology for electricity production of small scale using forest wood biomass.

When addressing which is the best technology, the amount of biomass that can be used becomes a critical issue because it determines the scale of generation, as well as the performance of each technology that determines how much of the chemical energy stored in the biomass is effectively converted into electricity. It is also noteworthy to mention that the efficiency of an electricity production plant is closely related to the size of the plant, in form of a non-linear positive association.

Consequently, the selection of the most appropriate technology according to the singularities of the region of study was done carrying out the following tasks:

- Using performance data from both actual power plants and simulation of plants using existing technologies, a plot of efficiency against power plant size (in kW of electrical output) was made.
- From all commercially available technologies for biomass conversion to electricity, only those that may be used with the forest biomass fuel available in the area of study were selected as possible alternatives. This

task involved the selection of an appropriate electrical output for the fuel supply and thus discarding those technologies that are not implementable at that scale.

- Finally, a single technology was picked among all the feasible solutions. The selection emphasized the efficiency of the system but without ignoring other important aspects such as facility of installation, maintenance and operation or its reliability. The average efficiency of such technology was also calculated.

### 3.2.3 Potential for electricity production in the area of study

The last step of the research attempted to address the third research question, how much electricity can be generated using the selected technology and with the available biomass resource.

The estimation of potentially producible electricity requires the approach of how much chemical energy is stored in the biomass. Once having this value, the electrical energy that can be produced is obtained applying the efficiency of the conversion system to the total amount of energy released from the available forest wood biomass.

Accordingly, the estimation of potentially producible electricity was obtained following the tasks presented below:

- The heating value of the biomass was approached from the figures published in the existing literature. It is reasonable to assume that the mix of different tree species have a unique heating value because the differences between the species in the Mediterranean area are small enough.

- The total amount of energy that could be obtained from the biomass was obtained multiplying the quantity of biomass obtained in the first step of the study (see §3.2.1) by the heating value of such biomass:

$$Energy(MJ/year\ ) = LHV(MJ/tn) \cdot m(tn/year)$$

- The electrical energy producible during a year from the chemical energy stored in the biomass could be calculated using the average efficiency obtained in the second step of the study (see §3.2.2):

$$Electricity\ (MWh/year) = Energy\ (MWh/year) \cdot\ \eta$$

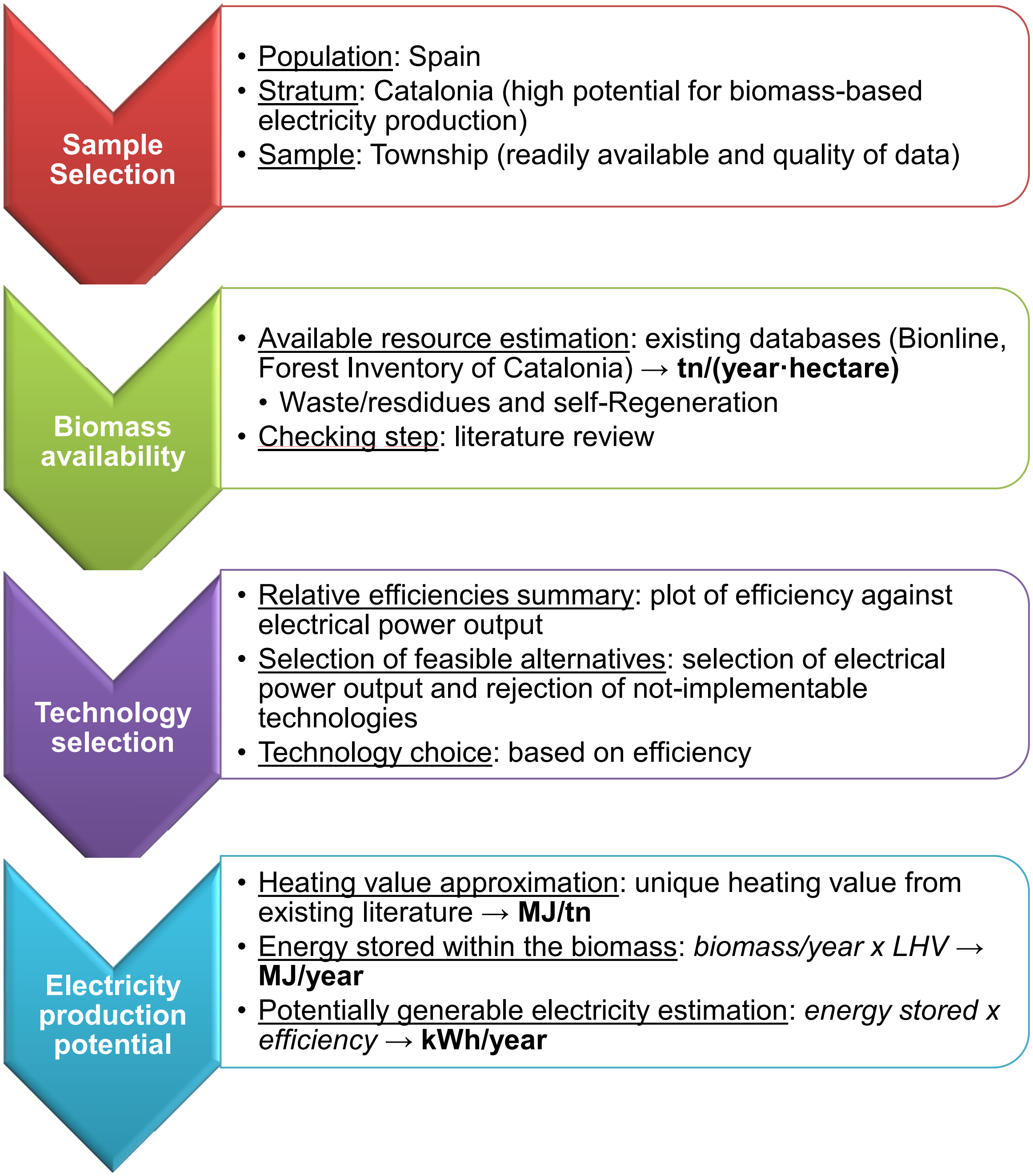
## 3.3 Methodology overview

With the described methodology, the researcher sought to obtain an approximate figure of the electricity that could be produced in the sample township using its own biomass resources in a sustainable manner during one year.

Indirectly, the study intended to demonstrate whether or not it is technically feasible the use of forest wood biomass as an energy source for electricity production.

The achievement of reliability and validity of the different parameters of the study will be explained in the corresponding section for each datum in Chapter 4.

This whole methodology can be summarized with the following flow chart (see Figure 3.1):



**Sample Selection**

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

**Biomass availability**

- Available resource estimation: existing databases (Bionline, Forest Inventory of Catalonia) → **tn/(year·hectare)**
  - Waste/resdidues and self-Regeneration
- Checking step: literature review

**Technology selection**

- Relative efficiencies summary: plot of efficiency against electrical power output
- Selection of feasible alternatives: selection of electrical power output and rejection of not-implementable technologies
- Technology choice: based on efficiency

**Electricity production potential**

- Heating value approximation: unique heating value from existing literature → **MJ/tn**
- Energy stored within the biomass: *biomass/year x LHV* → **MJ/year**
- Potentially generable electricity estimation: *energy stored x efficiency* → **kWh/year**

Figure 3.1 Flow chart summarizing the methodology

# CHAPTER 4. DATA ANALYSIS, CALCULATIONS AND FINDINGS

To address each of the research questions, a quantitative analysis of existent data was performed. In the first section, the population of the study and the criteria underlying the choice of the sample are explained. Then, the main data analyzed to address each research question is presented along with the outcomes of each step.

## 4.1 Population and Sample

Because the design of this research is essentially developmental, the selection of the sample, while determining the results, is not critical in that other values can easily substitutable. The overall methodology as a whole can be extrapolated to other situations.

In the following subsections, the territorial organization of Spain is explained with the aim to determine the most appropriate sample. The criteria used to select the sample are then explained by characteristics, such as population, surface, population density and climate region.

### 4.1.1 Territorial organization of Spain

The country of Spain is politically organized into Autonomous Communities, which would be tantamount to US States. Each Autonomy is constituted by one or more provinces (see Figure 4.1). In total, Spain is constituted by 17 Autonomous Communities and two Autonomous Cities (Ceuta and Melilla) (IDESCAT, 2013).

Source: http://2.bp.blogspot.com/-NGv3QJuxInw/T4htyPCXFMI/AAAAAAAAAMU/xjRcbZBMTGk/s1600/MAPA%2BPOLITICO053.jpg

Figure 4.1 Political organization of Spain

In terms of sampling design, these Autonomous Communities could be seen as the strata while the whole country would be the population. Among the 17 existing divisions, Catalonia has been already pointed as one of those with considerable technical potential for electricity production using both agricultural and forest wood biomass (Gómez, Rodrigues, Montañés, Dopazo, & Fueyo, 2010). Because of this it has been selected as the general target for the study. In addition, this selection is not only motivated by its technical potential, but also by being the birthplace and location of professional education and training of the researcher, who consequently has a deeper knowledge of its geography and distribution of the territory than he would have for other areas.

Each of the 17 Autonomous Communities in Spain are, in turn, divided in several *comarques*, which would be tantamount to a county in using English terminology. In the case of the selected Autonomy, Catalonia, the Community consists of 41 *comarques* (IDESCAT, 2013) (see Figure 4.2). Each *comarca* is formed by several *municipis*, equivalent to townships, which are the smallest political divisions in Spain. A total of 947 townships exist in Catalonia (IDESCAT, 2013).

The *comarca* where the study will be focused is Anoia, which is found in the central area of Catalonia (see Figure 4.2) and which enjoys a significant area covered by forests. In particular, Anoia has 47196 ha of its 118817 ha of total surface covered by forests, from which 27478 ha correspond to wooded area and the other 19718 are scrublands. Main data relevant for this project of the *comarca* of Anoia is summarized in Table 4.1:

Table 4.1 Forest area data for the *comarca* of Anoia

| | |
|---|---|
| **Region surface (ha)** | 118,817 |
| **Forested area, CREAF (ha)** | 47196 |
| Wooded area (ha) | 27478 (58.22%) |
| Scrubland (ha) | 19718 (41.78%) |

Source: personal compilation based on IDESCAT (IDESCAT, 2012) and IEFC (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

The reason behind the choice of Anoia is that the workplace of the researcher is the Engineering School of Igualada, the capital city of that region, where research teams are working together with local organizations to enhance the deployment of renewable energies within the region.

Source: Edu365 educational website (Saló Fontdevila, 2012)

Figure 4.2 Regions constituting Catalonia

From the sample and region selected, and for simplification purposes, the target of analysis was reduced to a single township from Anoia, in rural Catalonia. It was very important to select a rural township; because that guarantees that a significant amount of forest will be located within its territory. Accordingly, it is likely that the available amount of forest wood biomass will be enough to supply biomass-fuelled power plants while minimizing transportation costs and environmental impacts.

According to the atlas of rural townships from Catalonia, a township is considered rural according to its population and population density. There are three different definitions that apply in the context of Spain (Generalitat de Catalunya, 2010):

- According to the National Statistics Institute from Spain, a rural township is that with less than 2000 inhabitants
- According to the Directorate-General of the European Commission (EUROSTAT), a rural township have less than 100 inhabitants per square kilometer
- According to the Organization of the Economic Co-operation and Development (OECD), a rural township is that with less than 150 inhabitants per square kilometer.

For the purpose of this study, the condition of population was narrowed to a maximum of 1000 inhabitants within the township. In the region of Anoia, there are many townships that fulfill these requirements, and they are represented in yellow in Figure 4.3.

Source: Federació Anoienca de Comerç i Serveis (FACS, 2013)

Figure 4.3 Rural, semi-urban and urban townships in Anoia

Therefore, there are 20 out of Anoia's 33 townships that can be considered rural. From these 20 possibilities, the *municipi* of Argençola is the one with the best information available, as the Technological Forestry Centre from Catalonia (Centre Tecnològic Forestal de Catalunya, CTFC), made available the report of Biomass Availability at the *municipi* of Argençola in 2009 (Codina & Rodríguez, 2009), and it also stands out for having almost half of its surface covered by forests. These forests are mainly privately-owned. In particular, more than 96% of them are private while less than 4% are publicly-owned (Codina & Rodríguez, 2009), what means that giving economic value to the biomass available there would help to improve the lack of forest management present in the region.

It is also worth mention that Argençola is one of the townships declared as high fire-risk township by the Catalonia government (Codina & Rodríguez, 2009).

Better management practices would help to reduce that high risk of wildfires by reducing the excess of biomass that the forests may have.

According to the Forest Protection Association of the region, Argençola has 2974 hectares of forested area, representing 63% of the 4710 hectares occupied by the township (Federació ADF Anoia, 2011), while according to the Centre for Ecological Research and Forestry Applications, the land covered by forest equals to 2811.40 hectares meaning almost 60% of the whole land covered by the township (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000). From these 2811.40 hectares, only 2191.56 hectares correspond to wooded area while the other 619.84 hectares are scrubland, as summarized in Table 4.2:

Table 4.2 Forest area data for the *municipi* of Argençola

| | |
|---|---|
| **Township surface (ha)** | 4710 |
| **Forested area, ADF Anoia (ha)** | 2974 |
| **Forested area, CREAF (ha)** | 2811.40 |
| Wooded area (ha) | 2191.56 |
| Scrubland (ha) | 619.84 |

Source: personal compilation based on IDESCAT (IDESCAT, 2012), IEFC (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) and Federació ADF Anoia (Federació ADF Anoia, 2011)

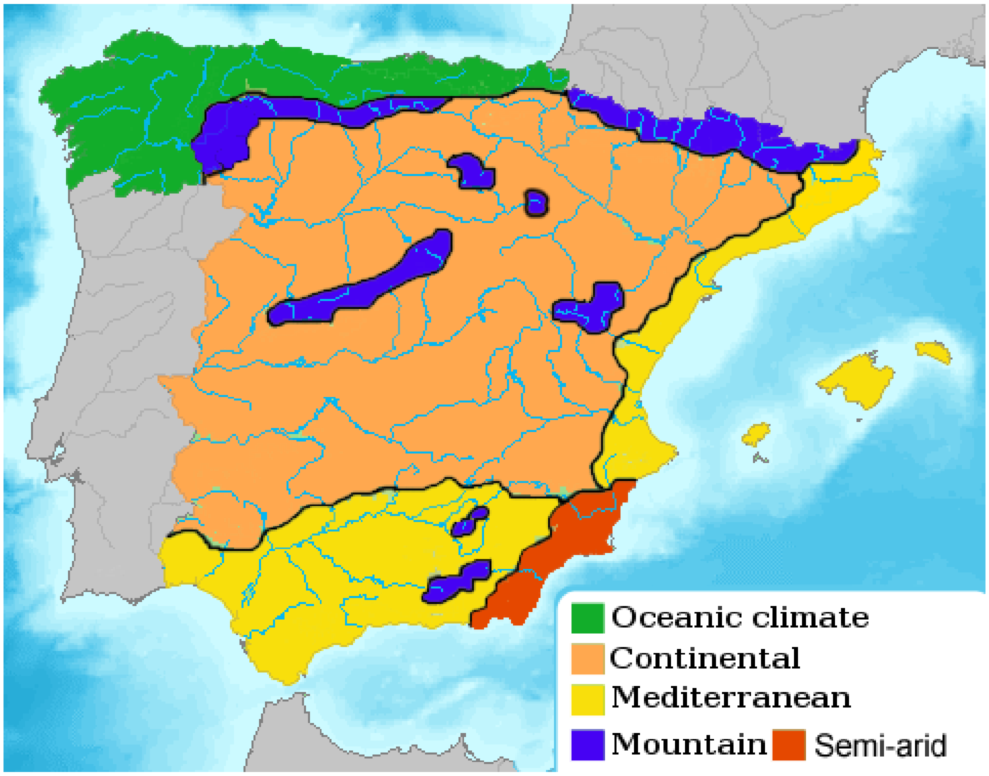
Therefore, a significant amount of energy can be generated using local biomass resources and thus reducing the environmental impact of the electricity produced. For the purposes of this study the smallest figure of 2191.56 hectares was considered, being a conservative approach and considering that brushes are not useful for electricity production applications.

### 4.1.2 Spanish climates

The population for this study is the country of Spain. Spain is a country within the European Union (EU), placed in the Iberia peninsula, at the west edge of the European continent. Spain is washed by both the Atlantic Ocean to the West and the Mediterranean Sea to the East. Therefore, although Spain is a relatively small country, several different climate areas exist in the nation. These different climates are, according to the Köpen climate classification (Peel, Finlayson, & McMahon, 2007), the oceanic, continental, mountainous, subtropical (only in the Canarias islands), semi-arid and Mediterranean climates (Wikimedia Commons, 2012) (see Figure 4.4). This variability directly causes considerable asymmetries in the types and amount of biomass available in the different regions.

It is also worth mentioning that, thanks to its particular climate, Spain is one of the Mediterranean countries with the highest percentage of its area covered by forest and other wooded land, only surpassed by Slovenia. In particular, Spain has 55% of its area covered by wooded lands while the average of the Mediterranean countries is 13.1% (FAO, 2011).

The sample selected, the *municipi* of Argençola, is found in the Mediterranean climate area. Mediterranean climates have a huge variability in both flora and fauna. Regarding the forests, the main species that can be found in Mediterranean forests are fir, beech, pine and oak (FAO, 2011), depending on the particular forests, but predominantly pine and oak.



Source: Wikimedia Commons (Wikimedia Commons, 2012)

Figure 4.4 Climate areas by geography

### 4.1.3 Validity and reliability

As a consequence of the high variability of climates in Spain, the validity of the sample is restricted to those areas with a similar climate, i.e. Mediterranean climate. However, that also makes the sample representative of other countries in the Mediterranean basin such as France, Italy or Greece. It is also worth mention that the ability to harvest biomass in each region is strongly linked to the terrain where a particular forest is found and, therefore, the sample may not be representative enough of regions with sheer or mountainous terrain.

### 4.1.4 Summary

From the population of the study, which is the country of Spain, a sample of a single rural township was selected. This sample is the *municipi* of Argençola, found in the *comarca* of Anoia, and the main criterion for this selection was the geographical situation in central Catalonia, close to the location of the research team which includes the researcher; the rural condition of that township, with less than 1000 inhabitants in a township of 4710 hectares; and the accessibility of information available.

The *municipi* of Argençola has 2974 hectares covered by Mediterranean forest (Federació ADF Anoia, 2011), which means a 63% of the whole area of the township.

Table 4.3 summarizes the main data for the sample selected:

Table 4.3 Main characteristics of the selected sample, *municipi* of Argençola

| | |
|---|---|
| ***Municipi* (township)** | Argençola |
| ***Comarca* (region)** | Anoia |
| **Population (2012)** | 245 inhabitants |
| **Surface** | 4710 hectares (47.1 km$^2$) |
| **Population density (2012)** | 5.20 inhabitants/km$^2$ |
| **Forest area** | 2191.56 hectares (21.92 km$^2$) |
| **Climate region** | Mediterranean |

Source: personal compilation based on IDESCAT (IDESCAT, 2012), (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) and Atlas of Spain (Wikimedia Commons, 2012)

## 4.2 Amount and characteristics of available resource

Once selected the sample of the study, the next step was to assess how much biomass is available within the township and find the heating value of such biomass as the main characteristic. As previously stated, the amount of biomass was calculated in terms of annual growth rate to assure that the resource is used in a sustainable way, i.e., without consuming more than the forest can regenerate by itself. The time frame of one year is appropriate for that purpose because it coincides with the period of the cyclical climate variations of the region, so similar figures of annual growth rate are likely to be expected among different years. This annual growth rate will be measured in metric tons per hectare and year, $tn/(ha \cdot year)$, so the total amount of biomass available will be obtained multiplying that average value by the forest surface comprised within the township (see §4.1.4)

To obtain a reliable figure of the available amount of biomass, several sources were accessed, including databases such as the *Forest inventory of Catalonia* (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) provided by the Centre for Ecological Research and Forestry Applications (Centre de Recerca Ecològica i Aplicacions Forestals, CREAF), technical reports such as the *report of Biomass Availability at the municipi of Argençola* (Codina & Rodríguez, 2009) provided by the Technological Forestry Centre of Catalonia (Centre Tecnològic Forestal de Catalunya, CTFC), and papers from specialized journals and organizations such as *Biomass and Bioenergy* or the *Food and Agriculture Organization, FAO*.

### 4.2.1 Wood biomass studied

Wood biomass resource takes several forms, including forest residues and wood wastes such as bark, wood chips and sawdust, and dedicated energy crops. All of them are suitable for electricity production, together with other agricultural crops and residues (Evans, Strezov, & Evans, 2010; Salomón, Savola, Martin, Fogelholm, & Fransson, 2011). From all these types of wood biomass suitable for electricity production, forest residues were selected as the focus of this thesis because nurseries are prohibited by the Catalan government; and regarding industrial residues, like those from timber industries, they are not as much widespread as forests throughout Catalonia. Accordingly, the availability of biomass coming from this source in the sample would not be representative of the whole population. Instead, the usage of forest residues in the sample will lead to higher amounts of available resource as well as more representative of the entire population.

### 4.2.2 Types of forest found in the region of study

The types of forest and the area covered by them in both the *comarca* and the *municipi*, were studied using information from two data sources: the *Forest Inventory of Catalonia*, (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) and the *report of Biomass Availability at the municipi of Argençola* (Codina & Rodríguez, 2009).

The first resource accessed is the *Forest Inventory of Catalonia* (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000), a comprehensive inventory of forests in Catalonia, species that form each forest and yearly growth rate. These data is presented in 8 *Forestry Regions* in which Catalonia was divided following their own system; each region consisting on several *comarques*. The selected sample is placed in the Forestry Region IV that comprises the *comarques* of Anoia, Bages, Berguedà and Solsonès.

The database provides information about the main tree species found in the region. In the Anoia, the predominant species are, sorted by importance:

- *Pinus halepensis*, commonly known as the Aleppo pine or *pi blanc* in Catalan.

Source: http://www.conifers.org/pi/pi/halepensis01.jpg

Figure 4.5 *Pinus halepensis*

- *Pinus nigra*, commonly known as European black pine or *pinassa* in Catalan.

Source: http://www.plantsystematics.org/users/kcn2/4_13_10_s/2010_April_13_Plantations_212.jpg.48.jpg

Figure 4.6 *Pinus nigra*

- *Pinus pinea, commonly known as stone pine or pi pinyoner in Catalan.*

Source: http://upload.wikimedia.org/wikipedia/commons/0/0a/Pinus_pinea_Wellington_Botanic_Gardens.jpg

Figure 4.7 *Pinus pinea*

- *Quercus humilis or quercus pubescens, commonly known as downy oak or roure martinenc in Catalan.*

Source: http://2.bp.blogspot.com/-xm3gP45G8gs/TZ2kiE3LnqI/AAAAAAAAAVs/CTRynEdaAGo/s1600/IMG_5110.JPG

Figure 4.8 *Quercus pubescens*

- *Quercus ilex*, commonly known as holm and holly oak or *alzina* in Catalan.

Source: http://upload.wikimedia.org/wikipedia/commons/thumb/5/55/Mendaza,_Navarra_Spanien-Steineiche.jpg/220px-Mendaza,_Navarra_Spanien-Steineiche.jpg

Figure 4.9 *Quercus ilex*

In addition to these predominant tree species, other species can also be found in the region of Anoia. Among these are the oaks family such as the *quercus faginea*, commonly called Portuguese oak or *roure de fulla petita*, and some of the pines family such as the *pinus sylvestris*, also called scots pine or *pi roig*.

The second set of data accessed is the *report of Biomass Availability at the municipi of Argençola* (Codina & Rodríguez, 2009), an assessment of the existing forestry area in Argençola made by the Technological Forestry Center of Catalonia. According to them, the forest cover found in that township can be classified in two categories:

- Medium mountain: within the small mountains found in the region, there are mainly *pinus nigra* (see Figure 4.6), together with *quercus* *pubescens* (see Figure 4.8) and *quercus faginea*, among other trees with less significance.

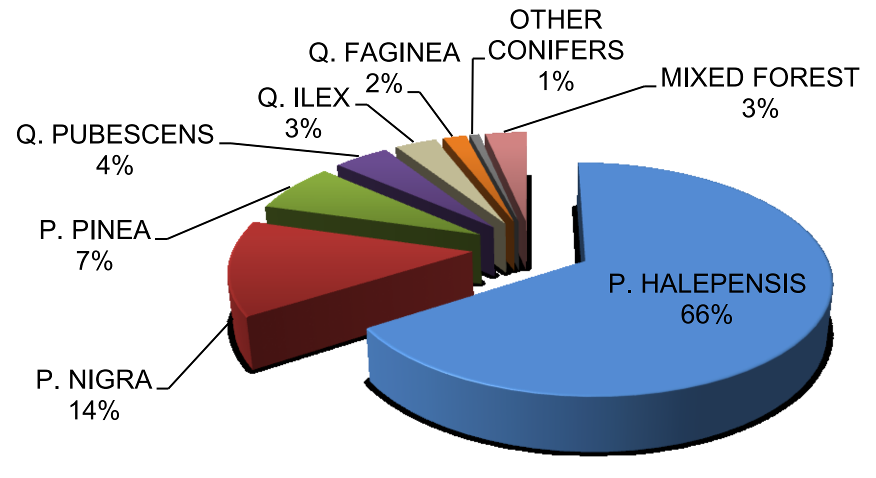
- Mediterranean lowland: most of the region of Anoia has this type of vegetation, where the *pinus halepensis* (see Figure 4.5) predominates along with the *pinus pinea* (see Figure 4.6) and the *quercus ilex* (see Figure 4.9). In this type of forests, there are a lot of bushes on the ground, but they're not considered for not being useful as a source of biomass.

In the particular case of this sample, the technicians of the CTFC divided all the forest area in 5 different kinds of forests according to the species that can be found: monospecific forest of *pinus halepensis*, monospecific forest of *pinus nigra*, mixed forest of *pinus halepensis* and *pinus nigra*, mixed forest of conifers (*pinus*) and oaks (*quercus*) and monospecific forest of oaks.

The relative importance of each species in the region studied according to Burriel, et al., (2000), is shown in Figure 4.10. For accurate information on forest area covered by each species, as well as the actual number of trees that can be found, please refer to Appendix A. Please note that the tree distribution is slightly different from the surface distribution as there are some species such as the holly oak that, although present in many parts of the region, rarely form dominant masses of forest.

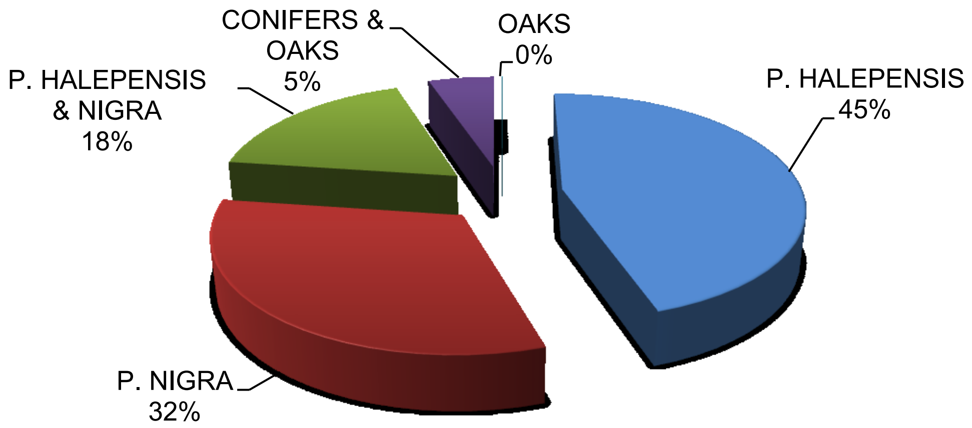
The relative importance of each species in the sample selected, Argençola, according to Codina and Rodríguez (2009) is shown by the type of forests defined by them, and is represented in Figure 4.11.

The area covered was selected as indicator of relative importance of each species because the number of trees is not indicative in those cases where the trees are scattered or found as a secondary species or in the lower layers of a forest. On the other hand, the forest surface provides better information about how much importance has a particular species, because it shows how much area is covered by it.



Source: Personal compilation based on IEFC (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

Figure 4.10 Relative importance of tree species in the comarca of Anoia



Source: Personal compilation based on report of Biomass Availability at the municipi of Argençola (Codina & Rodríguez, 2009)

Figure 4.11 Relative importance of tree species in the *municipi* of Argençola

The distributions presented above suggest that Argençola is quite far from the distribution of forest vegetation found in the region where it is placed because in Argençola the relative importance of the Aleppo pine is significantly smaller due to the increased presence of European black pine. However, these two species are very similar as they belong to the same tree family, the pines, so they share most of their characteristics. If we look at the relative importance of tree species in terms of tree families, we can see that in the *comarca* of Anoia, the pines are found in 91% of the forests while in Argençola this family covers 95% of the forest surface. Therefore, although the distribution of the different species is quite different in the sample compared with the region, the properties relevant to this study such as the heating value or the moisture content will be similar because almost all the forest surface is covered by trees from the pine family.

### 4.2.3 Annual growth rate

The main output sought with the assessment of biomass availability in the area of study is the annual growth rate of the forests, expressed in metric tons of dry biomass per hectare and year. Obtaining such value was done with a calculation based on growth rates of the species found in the sample and their relative significances and was checked using data available from the literature.

#### 4.2.3.1 Growth rate calculation

First step was the growth rate calculation using the growth rate of the tree species found in the forests of the sample.

In the *Forest Inventory of Catalonia,* Burriel, Gracia, Ibàñez, Mata and Vayreda (2000) provide the annual growth rate of all the species found in a certain region in $tn/(ha \cdot year)$. These annual growth rates are given for wood, branches and bark, together with the total (sum of the three rates).

The values of wood and total annual growth rates of the main species found in Anoia are summarized in Table 4.4:

Table 4.4 Annual growth rates of predominant trees in the *comarca* of Anoia

| Tree species | Wood annual growth rate ($\boldsymbol{tn^{1}/(ha \cdot year)}$) | Total[2] annual growth rate ($\boldsymbol{tn^{1}/(ha \cdot year)}$) |
|---|---|---|
| ***Pinus halepensis*** | 1.5 | 2.3 |
| ***Pinus nigra*** | 1.8 | 2.7 |
| ***Pinus pinea*** | 1.0 | 1.7 |
| ***Quercus pubescens*** | 0.7 | 1.1 |
| ***Quercus ilex*** | 0.4 | 0.7 |

Source: personal compilation based on IECF (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

[1] Tons of dry matter

[2] Total growth rate equals the sum of wood, bark, leaves and branches growth rates

From the annual growth rates presented above (see Table 4.4), and considering the distribution of the species in the selected sample (see Figure 4.11), an estimation of the average annual growth rate can be obtained. The mix of *pinus halepensis* and *nigra* has been considered to be exactly 50-50%. The mix of conifers and oaks have been considered to be 50% *p. pinea* and the remaining 50% an equal mixture of *quercus pubescens* and *ilex* with an average growth rate of 0.55. For the purpose of this thesis, only the wood annual growth rate was considered, provided that branches and bark are not usually useful for electricity production. The following result was obtained:

$$\begin{aligned}
&annual\ growth\ rate \\
&\quad = 0.54 \cdot 1.5 \frac{tn}{ha \cdot year} + 0.41 \cdot 1.8 \frac{tn}{ha \cdot year} + 0.025 \\
&\quad \cdot 0.55\ tn/(ha \cdot year) + 0.025 \cdot 1.0\ tn/(ha \cdot year) \\
&\quad = \mathbf{1.6}\ \boldsymbol{tn/(ha \cdot year)}
\end{aligned} \tag{1}$$

### 4.2.3.2 Reliability and validity of the obtained value

The validity of the measure of growth rate is guaranteed by the authority of the data sources accessed which are a technical report from public research center and the national forest inventory of Catalonia. In addition, the reliability, as explained below, was also checked using data from specialized journals ensuring, in turn, the validity of the calculation.

To check the reliability of the obtained value, it was compared with data available on the specialized literature.

The first source accessed is the *Forest Inventory of Catalonia* itself (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000). The researchers from CREAF obtained the average figure of annual growth rate of dry wood in the whole region of Anoia, which is $\mathbf{1.5}\ \boldsymbol{tn}/(\boldsymbol{ha} \cdot \boldsymbol{year})$.

The second source accessed is an article from a research group in the Fluid Mechanics department of the University of Zaragoza. The article, called *The potential for electricity generation from crop and forestry residues in Spain* (Gómez, Rodrigues, Montañés, Dopazo, & Fueyo, 2010) and published in the Biomass and Bioenergy journal*,* assesses the potential for electricity generation from both agricultural and forestry residues in Spain. From several sources accessed, the authors provide the following annual growth rates for the main tree families found in Spain (see Table 4.5):

Table 4.5 Yearly growth rate of some tree species

| **Category** | $\boldsymbol{\eta_i^p}(\boldsymbol{tn^1\ hm^2})$ | **Category** | $\boldsymbol{\eta_i^p}(\boldsymbol{tn^1\ hm^2})$ |
|---|---|---|---|
| Fir | 0.9 | Bushes | 0.5 |
| Maple | 1.0 | Other | 0.5 |
| Mixed forest | 0.8 | **Pine** | **1.6** |
| Chestnut | 1.3 | Poplar | 3.9 |
| Cypress | 1.1 | Meadow | 0.0 |
| Eucalyptus | 1.5 | **Oak** | **1.0** |
| Beech | 0.7 | Willow | 1.2 |
| Ash tree | 0.9 | Tamarisk | 0.9 |
| Juniper | 0.9 | Elm | 1.0 |

Source: Gómez, Rodrigues, Montañés, Dopazo and Fueyo (2010), emphasis added

[1] Tons of dry matter

As shown, the annual growth rates of the main species found in the sample, i.e., pines and oaks, are claimed to be $\mathbf{1.6}\ \boldsymbol{tn/(ha \cdot year)}$ for pines and $\mathbf{1.0}\ \boldsymbol{tn/(ha \cdot year)}$ for oaks. With these values, the average growth rate considering the tree distribution provided by Codina and Rodríguez (2009) (see Figure 4.11) is:

$$\begin{aligned} annual\ growth\ rate &= 0.95 \cdot 1.6 \frac{tn}{ha \cdot year} + 0.05 \cdot 1.0 tn/(ha \cdot year) \\ &= \mathbf{1.6}\ \boldsymbol{tn/(ha \cdot year)} \end{aligned} \tag{2}$$

The third and last source accessed with comparison purposes is the article *Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal* (Viana, Cohen, Lopes, & Aranha, 2010) published in Applied Energy. In their research, the authors analyze the availability of eucalyptus and pine forestry residues in several regions of Portugal. For the purposes of this study, the comparison is done with the North region because all other regions are significantly Southern than the sample studied, so big climate differences are likely to be expected. From the results provided in the article, it can be inferred that the production of biomass in tons per hectare and year is:

$$annual\ growth\ rate = \frac{B_d(tn/year) \cdot B_d(tn/ha)}{B_d(tn)} \tag{3}$$

The result obtained using the equation above is $\mathbf{1.6\ tn/(ha \cdot year)}$. Again, the figure is expressed in tons of dry wood.

### 4.2.3.3 Annual growth rate choice

Once performed the checking step, the first calculated figure of 1.6 tn[1]/(ha·year) was selected as the annual growth rate to consider in this study. The reasons behind this selection are that all other estimates, although they approach the result obtained, are calculated under different assumptions of tree species found in the forest and annual growth rate of these species.

The value given by the researchers of CREAF in the *Forest Inventory of Catalonia* (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000) was lower because that value is provided for the whole region of Anoia where the European black pine has a lower significance (14% in Anoia in front of 32% in Argençola, see Figure 4.10 and Figure 4.11). Since this species has a higher growth rate than other pines, the final weighted average is increased leading to the observed divergence.

---

[1] Tons of dry matter, considering only wood production (leaving bark, branches and leaves apart)

The value obtained using the data provided by Gómez, Rodrigues, Montañés, Dopazo, and Fueyo (2010) is also lower than the first calculated. This difference is caused by the growth rates used to perform the calculation. The authors provide an average figure for tree families as a whole and, once again, the fact that in the sample the prevalent species is the European black pine with a higher growth rate increase the calculated value. In this case the difference is so slight that the rounded result equals the calculated one.

Finally, the value obtained using the data from Viana, Cohen, Lopes, and Aranha (2010) is less accurate than the previous ones given the applicability of the data to the idiosyncrasies of the sample. The researchers provide a unique growth rate value for a mix of eucalyptus and maritime pine (*pinus pinaster*) and their research is conducted in Portugal. In addition, although the data for the Northern region of Portugal was used, which corresponds to a climate as similar as possible to the sample, the tree species are different from those to the sample and the precipitation and temperature patterns are also different.

However, even with their limitations as predicting values, all data observed in the literature provide both reliability and validity to the calculation performed insofar that their magnitude is close to that of the calculated value.

### 4.2.4 Heating value of existing biomass

In addition to the amount of available resource, another important parameter of the resource is the heating value of it, a magnitude that represents the chemical energy stored within the biomass. The heating value was calculated using empirical formulas and the validity and reliability of the obtained value were checked using data from existing literature.

### 4.2.4.1 Heating value calculation

The heating value of biomass was calculated using data available in the existing literature. It is worth distinguishing between the higher heating value (HHV) and the lower heating value (LHV). The former is basically the energy content in dry material, while the latter is the energy content obtained after subtracting the energy needed to evaporate the water formed from the hydrogen in the material and the moisture content from the HHV. Therefore, the LHV has an inverse relationship with the degree of moisture, i.e., the LHV decreases as the moisture content increases (Erhart, Strzalka, Eicker, & Infield, 2011).

For the purposes of this study, the LHV was used because when calculating the efficiency of the whole process the result accounts for the biomass drying process. The water content was assumed to be 30%, which is the value at which the chipping process is usually performed (Whittaker, Mortimer, Murphy, & Matthews, 2011).

The LHV “wet”, i.e., accounting for the water content, was obtained from the HHV “dry ash free”, i.e., of the fuel completely dry and without the ash content, using the equation provided by Quaak, Knoef and Stassen (1999) in Annex 1 of their book:

$$LHV_w = LHV_{daf}(1 - AC_w - MC_w) \tag{4}$$

The formula can be rearranged as follows (Quaak, Knoef, & Stassen, 1999):

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

$$where \begin{cases} AC_w\text{: } ash\ \% \\ MC_w\text{: } moisture\ \% \\ H_{daf}\text{: } hydrogen\% \end{cases} \tag{5}$$

The HHV, hydrogen content and ash content values were obtained from the Phyllis database (ECN, 2009). For pine wood chips HHV and hydrogen content of dry matter free of ashes are 20.4 MJ/kg and 6.2% respectively and the ash content of wet biomass is 3%. Therefore, the LHV of wood chips at 30% moisture is:

$$\begin{aligned} LHV_{ar} &= (20.4\ MJ/kg - 20.3 \cdot 0.062) \cdot (1 - 0.03 - 0.3) = 12.8\ MJ/kg \\ &= \mathbf{12.8}\ \boldsymbol{GJ/tn} \end{aligned} \tag{6}$$

### 4.2.4.2 Validity

The obtained value of 12.8 $GJ/tn$ was checked with data from the literature. Whittaker, Mortimer, Murphy and Matthews (2011), provide the value of 12.1 $GJ/tn$ for LHV of biomass at 30% moisture, which only differs in 0.7 $GJ/tn$ to the value obtained above.

Vallios, Tsoutsos and Papadakis (2009) reported that typical LHV of biomass range from 10.8 $GJ/tn$ to 15.9 $GJ/tn$, varying with the moisture content, and for their analysis they picked the value of 13.69 GJ/tn corresponding to a 20% of moisture content. This figure is slightly higher than the one obtained, a result that should be expected provided that the moisture content assumption for the purposes of this thesis was higher leading to a lower LHV.

Values of both HHV and LHV were also found in another paper for different wood biomass fuels such as wood pellets, wood chips, bark or sawdust (Obernberger, 1998). The values are presented in kWh/kg in the article, but for consistency they are presented in $GJ/tn$ (or $MJ/kg$) in Table 4.6:

Table 4.6 Gross calorific value, water content and net calorific value of different wood biofuels

| **Wood biofuel** | **Water content (%)** | **HHV ($GJ/tn$)** | **LHV ($GJ/tn$)** |
|---|---|---|---|
| **Wood pellets** | 10.0 | 19.8 | 16.56 |
| **Wood chips: hardwood, pre-dried** | 30.0 | 19.8 | 12.24 |
| **Wood chips: hardwood** | 50.0 | 19.8 | 7.92 |
| **Wood chips: softwood, pre-dried** | **30.0** | **19.8** | **12.24** |
| **Wood chips: softwood** | 50.0 | 19.8 | 7.92 |
| **Grass: high pressure bales** | 18.0 | 18.36 | 13.68 |
| **Bark** | 50. | 20.16 | 8.28 |
| **Triticale (cereals): high pressure bales** | 15.0 | 18.72 | 14.4 |
| **Sawdust** | 50.0 | 19.8 | 7.92 |
| **Straw (winter wheat): high pressure bales** | 15.0 | 18.72 | 14.4 |

Source: Self-calculation from Obernberger (1998), emphasis added

In this case the comparable values are those given for softwood pre-dried wood chips, in this case, 12.24 $GJ/tn$. Again, although slightly smaller, the value given in Obernberger (1998) is very highly close to the previously calculated one. In this case the difference is likely to be related to the usage of a type of wood other than pine.

#### 4.2.4.3 Heating value selection

The calculated value was again selected as the most accurate result, while all other values obtained from the literature (Whittaker, Mortimer, Murphy, & Matthews, 2011; Vallios, Tsoutsos, & Papadakis 2009; Obernberger, 1998) suggest reliability of both the method and the result due to a very similar order of magnitude with the calculated one as well as consistency in the variation pattern with moisture content. The selection of the calculated result was justified by the higher accuracy that provides the usage of the specific type of biomass found in the region in form of forestry residues, i.e. pine wood chips.

### 4.2.5 Amount and chemical energy of yearly available resource

According to the results obtained in the previous calculations (see §4.2.3 and 4.2.4), the average annual growth rate of the existing biomass within the sample is 1.5868 tons of dry matter per hectare and year, with a heating value of 12.8247 GJ/tn. Such biomass is spread over forests that cover 2191.56 hectares as presented in the sample selection section (see §4.1). Therefore, the gross amount of dry biomass available within the forests found in the sample is:

$$gross\ dry\ biomass = 1.6\frac{tn}{ha \cdot year} \cdot 2191.56\ ha = \mathbf{3506.50}\frac{\boldsymbol{tn}}{\boldsymbol{year}}^{2} \qquad (7)$$

This amount of biomass stores the following amount of chemical energy. Please note that the LHV is used so the chemical energy does not account for the energy necessary to dry the feedstock. Accordingly, the amount of biomass

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[2] Tons of dry matter

has been increased by 30% to consider the increased weight due to having a wet biomass as a fuel input.

$$\begin{aligned} chemical\ energy &= 3506.50\frac{tn}{year}\cdot 1.3\cdot 12.8\frac{GJ}{tn} = \mathbf{58348.16\frac{GJ}{year}} \\ &= 16207.82\frac{MWh}{year} \end{aligned} \tag{8}$$

### 4.2.6 Summary

The availability of biomass in the studied sample was assessed from the tree species found in the forests of the area under study and the extension of them. The outputs sought were the annual growth rate of forest wood biomass expressed in tons[3] per hectare and year and the heating value of such biomass in gigajoules per ton.

After a comprehensive study of the types and extension of forests found in the region, the average annual growth rate was obtained from the growth rates of each tree species weighted with the proportion of area covered by them. The obtained value was validated through a comparison with data found in the specialized literature. The selected value for this thesis is presented in Table 4.7.

The lower heating value of biomass was identified as the relevant value for further calculations, as it accounts for the energy required to dry the biomass. A tentative moisture value of 30% was selected according to information found in the literature. Again, the reliability and validity of the obtained result was checked by comparison with data found in specialized journals. The selected value for this thesis' purposes is presented in the table below (see Table 4.7).

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[3] Tons of dry matter, considering only wood production (leaving bark, branches and leaves apart)

Table 4.7 Outcomes of the resource assessment step

| Output | Value (units) | Source |
|---|---|---|
| **Average annual growth rate** | 1.6 $(tn^1/(ha \cdot year))$ | Self-calculation |
| **Gross amount of biomass** | 3506.50 $(tn^1/year)$ | Self-calculation |
| **HHV, dry matter ash free** | 20.4 $(GJ/tn)$ | (ECN, 2009) |
| **LHV, 30% moisture** | 12.8 $(GJ/tn)$ | Self-calculation |
| **Chemical energy available** | 58348.16 $(GJ/year)$ | Self-calculation |

Source: personal compilation.

[1] Tons of dry matter

## 4.3 Technology selection

The third and final analytical step consists on an analysis of the efficiencies of current biomass conversion technologies for electricity production and selection of a proper technology considering the idiosyncrasies of the sample selected such as amount and type of biomass available. After analyzing the current efficiencies of commercial technologies, a proper power output was selected according to the amount of biomass available in the sample. Then, the technology with higher efficiency was selected as the most appropriate and the average efficiency of that technology was approached using data from literature.

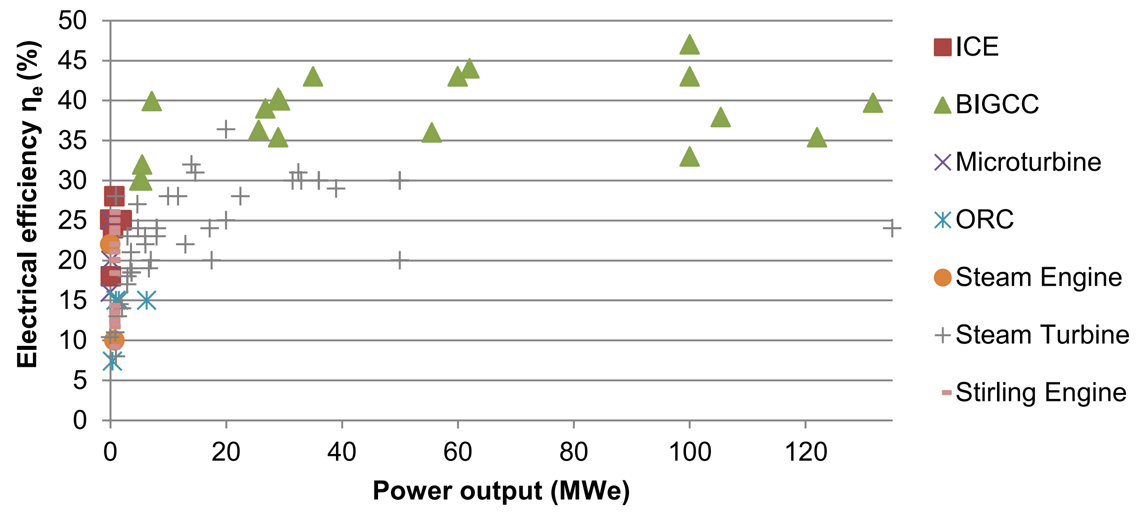
### 4.3.1 Assessment of current efficiencies of available technologies

A comprehensive analysis of existing efficiency data available in the literature was performed. The functional unit to compare different efficiencies of available technologies was the electrical power output. Therefore, data of both electrical and overall efficiencies were collected along with the electrical power output. Please refer to Appendix B for detailed information of data.

The technologies considered were those that were commercially available at the time of the study. To ascertain which ones fulfill this condition, several papers were accessed. According to the review *Small-scale biomass CHP plants in Sweden and Finland* by Salomón, Savola, Martin, Fogelholm and Fransson (2011), the commercially available technologies are conventional Rankine cycle (steam turbine), gas turbine with heat recovery steam generator (BIGCC), steam engines, microturbines, internal combustion engines (ICE) and Stirling engines. Several articles reported efficiencies from actual experiences using these technologies. Another technology to be considered currently available is the Organic Rankine cycle (ORC), according to some reviews (Barbieri, Spina, & Venturini, 2012; Dong, Liu, & Riffat, 2009). In addition, there are some articles reporting efficiencies from existing ORC-based power plants fuelled with wood biomass (Bini, Di Prima, & Guercio, 2010; Erhart, Strzalka, Eicker, & Infield, 2011; Obernberger & Hammerschmid, 2001; Obernberger, Thonhofer, & Reisenhofer, 2002).

There are significant differences in suitability of these technologies regarding the scale of the power plant. For example, for small residential buildings or medium-size public or industrial buildings, ICEs, microturbines and Stirling engines have been identified as the most competitive options (Alanne & Saari, 2004; Kuhn, Klemes, & Bulatov, 2008; Monteiro, Moreira, & Ferreira, 2009; Onovwiona & Ugursal, 2006). Other authors add to these technologies the ORCs (Barbieri, Spina, & Venturini, 2012). On the other hand, in regard to large-scale, the most efficient technologies are the conventional Rankine cycles and the gas turbine combined cycle (Dornburg & Faaij, 2001; Gustavsson & Madlener, 2004). In the present study, all technologies were considered in a first approach, by then focusing in small and micro-scale technologies, due to the relatively low amount of biomass available within the selected sample (see §4.2.3).

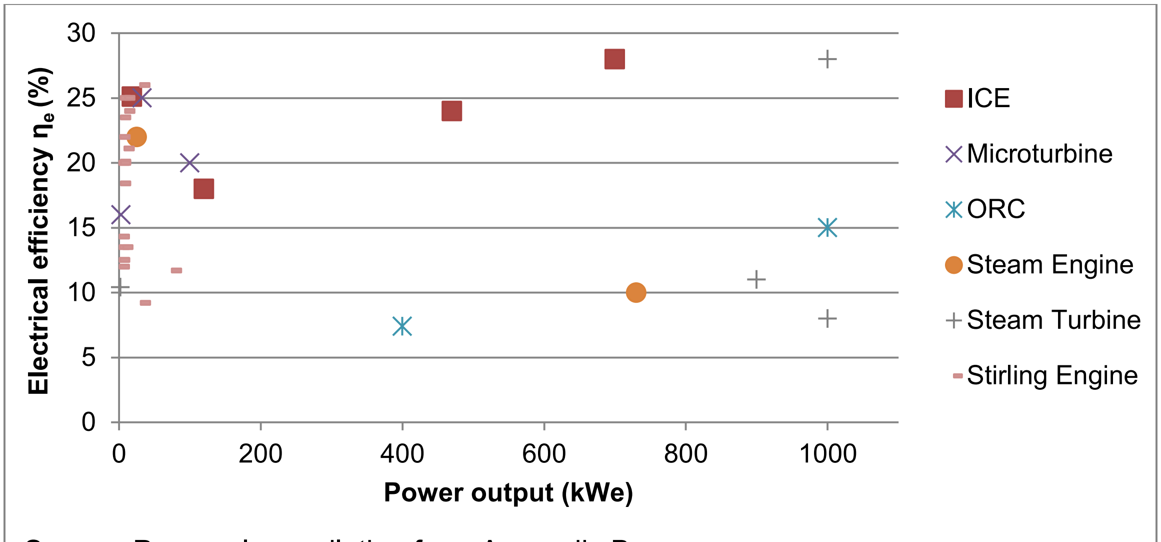
All the electrical efficiency data found in the literature is presented in the following plot (see Figure 4.12):



Source: Personal compilation from Appendix B sources

Figure 4.12 Summary of electrical efficiencies (%) against power output (MWe)

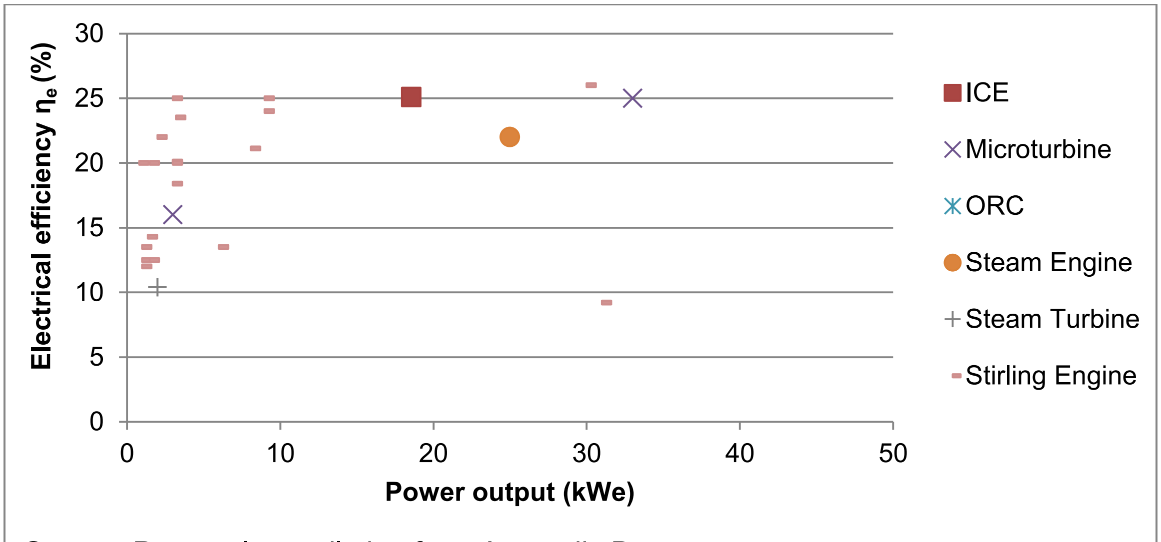
However, the amount of biomass available is not enough to feed a large-scale generation system, so the study of efficiencies was narrowed to small-scale power plants, i.e. those with 1 MWe of power output or less. The new plot (see Figure 4.13) have not BIGCC data, as this technology is only implemented in the medium and large scale, and a lot of steam turbine-based power plants are also left out:



Source: Personal compilation from Appendix B sources

Figure 4.13 Summary of electrical efficiencies (%) of small-scale existing power plants against power output (kWe)

To clarify the efficiencies in the micro-scale range, an enlargement was done, limiting the power output to 50 kWe, the upper limit of micro-scale cogeneration technologies. The resulting plot is presented in Figure 4.14.



Source: Personal compilation from Appendix B sources

Figure 4.14 Summary of electrical efficiencies (%) of micro-scale existing power plants against power output (kWe)

All distributions show a similar pattern that was, of course, anticipated: the bigger is the power plant output, the higher is the electrical efficiency. However, there seems to be a technological limit to that efficiency. For large-scale technologies, this threshold is about 45%, for small-scale technologies it is slightly less than 30% and for micro-scale technologies, it is approximately 25%.

### 4.3.2 Selection of a tentative power output

The selection of an appropriate power output was done using an estimative process. The power output of a hypothetical power plant depends on the efficiency of the technology selected and the most appropriate technology and its efficiency depends on the scale of generation, i.e. the power output. Therefore, the selection was done approaching the efficiency of the power plant by then calculate the approximate output of a power plant that would use the available energy from the biomass resource with the approximate overall electric efficiency and while operating a certain number of hours, value that was obtained from literature.

Having obtained the chemical energy stored in the yearly available biomass (see 4.2.5), the hours of operation of a hypothetical power plant and the approximate efficiency are the last parameters left to calculate the tentative power output. Kuhn, Klemes, and Bulatov (2008) claim that “the number of hours in full usage differs (…) between 1250 and 8000h” (Kuhn, Klemes, & Bulatov, 2008; p. 2042). From all this range, the value of 5500 hours was selected for being the upper limit of the design value of natural gas combined cycle power plants in Spain (Navarro, 2011), which are the more similar power plants in terms of usage patterns. For the electrical efficiency, an approximate value of 30%, which is the upper limit for small-scale power plants (see §4.3.1), was chosen. With these values, the tentative size of the power plant would be:

$$tentative\ power\ output = 16207820\,\frac{kWh}{year}\cdot\frac{1\ year}{5500\ hours}\cdot 0.30 = \mathbf{884.06\ kWe} \qquad (9)$$

### 4.3.3 Technology selection and average efficiency

From the estimation of the technically feasible power output, it was obtained the figure of 884 kWe of electrical generation (see section above).

That means that, using the amount of wood biomass produced by the forests within the township of study during a year, one power plant of approximately 885 kW of electric output could be fuelled during 5500 hours of operation in a year, more than 60% of the time. The selection of 5500 hours of operation was made by comparison to usage patterns of natural gas combined cycle power plants because these power plants show a similar usage patterns than biomass-fuelled power plants due to the controllable supply of both as well as relatively quick ignition and shutdown that allow them to be a backup for renewable sources. Obviously, the same amount of biomass could be used to fuel several smaller power plants that together add up to 884 kWe of installed capacity, for example if a distributed generation scheme was adopted in the township with the installation of micro-scale cogeneration systems in several residential buildings. However, that would mean a decrease in efficiency according to the pattern observed in the assessment of current efficiencies (see §4.3.1). Thus, a single power plant was the configuration chosen for the study.

At that such scale of generation, the most appropriate technology in terms of current efficiency is the internal combustion engine (ICE) fed with syngas from biomass gasification, with an overall electrical efficiency somewhere between 25 and 30% (see Figure 4.13). Due to the lack of specific data – the closest datum of efficiency found corresponds to 28% of efficiency at 700 kWe – the efficiency was approached to the value of 25%, being that a conservative value – the actual efficiency could be greater than 25% but it is very unlikely to be smaller.

### 4.3.4 Validity and reliability

The solution adopted as "best" is valid only under the assumption that the power plant will be in operation during approximately 60% of year. Slightly variations of this figure are not going to affect the validity of the choice, especially if these variations mean higher usage ratios, but lower usage ratios could lead to higher installed capacity and thus switch the choice of the better technology to other options. However, as the main purpose of such hypothetical power plant is to supply electricity, which is an energy commodity used daily, high usage ratios should be expected as long as it is economically feasible, and in this thesis the potential for electricity generation is being assessed so the hypothesis of lower usage ratios for strategic purposes was not considered.

The reliability of the result is assured by the authority of the data sources used to determine the electrical efficiency variation with power output pattern and values, as well as by the reliability of previously obtained results for growth rate and heating value of the wood biomass found in within the sample. Regarding the use of an arbitrarily chosen efficiency value, an iterative process could have been done in case of having observed a great disparity between the chosen and the obtained value, although it was not necessary as the choice was made using the upper limit of small-scale technologies.

### 4.3.5 Summary

After a comprehensive analysis of data found in the specialized literature about electrical efficiencies from actual power plants fueled with wood biomass, a general pattern of electrical efficiency against power output was identified. The next step was the calculation of a tentative electricity output of a hypothetical power plant that would use the available resource characterized in terms of amount and heating value in the previous section (see §4.2). Since the most appropriate technology is strongly linked to the size of the power plant, the amount of electricity technically feasible to produce was calculated from the amount of wood biomass produced by the forests found within the sample, the heating value of such biomass and a tentative efficiency and number of hours of operation of the power plant. The result was not anything else than a rough approach, but enough to select the better conversion technology according to the scale of generation. Once the technology was selected, the efficiency was calculated from the data analyzed in §4.3.1. In this case, the chosen figure was a downward approximation, due to the lack of specific data of electrical efficiency.

The tentative power output, technology selected and efficiency of the power plant are presented in Table 4.8. It is worth mention that the tentative power output is not the actual value of electricity production potential, because it was calculated based on an arbitrary efficiency value. The actual electricity production potential calculation is presented in the following section.

Table 4.8 Outcomes of the technology selection step

| **Output** | **Value (units)** | **Source** |
|---|---|---|
| **Tentative power output** | 884 (kWe) | Self-calculation |
| **Technology selected** | ICE | Self-calculation |
| **Average efficiency** | 25% | Data accessed |

Source: personal compilation.

## 4.4 Electricity production potential and power plant size

The last step of this study was the calculation of the electricity production potential of the sample only using the wood biomass feedstock yearly produced by the forests of the area, obtained in §4.2, and the technology selected in §4.3.

The input data of this calculation are presented in Table 4.9:

Table 4.9 Input data to calculate the electricity production potential

| **Input** | **Value (units)** | **Source** |
|---|---|---|
| **Gross amount of biomass** | 3506.50 $(tn/year)$ | Self-calculation |
| **Chemical energy available** | 16207.82 $(MWh/year)$ | Self-calculation |
| **Technology selected** | ICE | N/A |
| **Efficiency** | 25% | See Appendix B |
| **Full usage hours of operation** | 5500 (h) | (Navarro, 2011) |

Source: personal compilation.

The electricity production potential is the amount of electricity that can be produced using the ICE technology with 25% efficiency. Thereby, it was calculated as follows:

$$\begin{aligned} electricity\ production\ potential &= 16207.82\frac{MWh}{year}\cdot 0.25 \\ &= \mathbf{4051.96\frac{MWh}{year}} \end{aligned} \tag{10}$$

The calculation of the power plant size is an analogue process to the tentative power output calculation, but using in this case valid and reliable data of efficiency instead of an arbitrarily chosen one. The result, therefore, is:

$$power\ output = 16207820\ \frac{kWh}{year}\cdot\frac{1\ year}{5500\ hours}\cdot 0.25 = \mathbf{736.72\ kWe} \tag{11}$$

Therefore, it can be concluded that, in the township of Argençola, there is the potential for generating about 3000 MWh of electricity each year only using the wood biomass that is yearly produced by the forests found in the township. This electricity would be obtained in a 735 kWe ICE-based power plant, i.e. a power plant consisting on a gasifier coupled to an internal combustion engine.

Nevertheless, the overall energy production potential could be increased if heat production was considered. According to the accessed data, the overall efficiency is about 90% for the selected technology and power plant size (see Appendix B), again rounding down the value to make a conservative approach. Thereby, the thermal efficiency would be about 65%, meaning that for each Watt of electricity produced; more than two and a half Watts of heat would be additionally generated. So, if thermal energy demand was found nearby the power plant, the overall efficiency could be increased improving the exploitation of the available resource.

The heat production potential, using the above mentioned figures would add up to the following value. Please note that the estimation of how much heat is produced has not been made considering the most efficient technology, but it has been made considering how much heat is additionally produced using the most efficient technology for electricity production.

$$heat\ production\ potential = 16207.82 \frac{MWh}{year} \cdot 0.65 = \mathbf{10535.08} \frac{\boldsymbol{MWh}}{\boldsymbol{year}} \qquad (12)$$

Such heat would be produced in the combined heat and power plant that would be equivalent to a heat generation plant of the following size:

$$heat\ output = 16207820\ \frac{kWh}{year} \cdot \frac{1\ year}{5500\ hours} \cdot 0.65 = \mathbf{1915.47}\ \boldsymbol{kWth} \qquad (13)$$

The results are summarized in Table 4.10:

Table 4.10 Electricity production potential of the sample and optimal power plant size

| Input | Value (units) | Source |
|---|---|---|
| **Electricity production potential** | ~4000 ($MWh/year$) | Self-calculation |
| **Optimal power plant size** | ~735 ($kWe$) | Self-calculation |
| **Heat production potential** | ~10500 ($MWh/year$) | Self-calculation |
| **Equivalent heat generation plant** | ~1915 ($kWth$) | Self-calculation |

Source: personal compilation.

# CHAPTER 5. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

Many conclusions can be extracted from the gathered results and findings detailed in the previous chapter. These are presented in this final chapter after a short summary of the research questions, the employed methodology and the main findings. After that, a discussion about the data analysis and implications of this research are presented. Finally, some recommendations for future work, including industrial practices and research to be done, are suggested.

## 5.1 Summary of Research Questions, Methodology and Findings

As a reminder for the readers, the research questions that were laid out are the following:

- How much forest wood biomass is available in a sample township in rural Catalonia?
- What is the most suitable commercially available technology for small-scale electricity generation using forest biomass?
- How much electricity can be generated using the available forest wood biomass in the township under study and the selected technology?

In the last chapter, all of them were addressed.

The available amount of biomass was calculated multiplying the average annual growth rate – obtained using the annual growth rate of the tree species found in the forests of the sample weighted using their significance in terms of area covered – by the total area covered by forest in the sample. Additionally, the heating value of biomass was calculated to obtain the amount of chemical energy stored in the available biomass resource.

The selection of the most suitable technology to maximize the advantage taken of the available biomass in terms of electricity production was made calculating a tentative power output of a hypothetical power plant and looking the efficiency of commercially available technologies at that scale of generation. A comprehensive analysis of actual power plant data efficiency was made to ascertain the pattern and values that the electrical efficiency of biomass-based power plants shows with plant size variations.

Finally, the potential for electricity production in the sample and the power plant size were determined multiplying the available chemical energy by the efficiency of the technology selected and dividing it by the number of hours of full usage, a value taken from the natural gas cogeneration power plants which are the most similar ones in usage patterns to a biomass-based power plant.

## 5.2 Conclusions

After performing the data analysis and calculations detailed in Chapter 4, the conclusions and findings detailed below were obtained:

### 5.2.1 Conclusions of Research Question 1

The analysis of size and characteristics of forest cover in the sample yielded to an average growth rate of 1.6 $tn/(ha \cdot year)$ which, in a township with 2191.56 hectares of forest means 3506.50 $tn/year$ of available biomass. This figure only accounts for that biomass that forests produce each year, so the usage of this entire amount would not jeopardize at all the size and health of existing forests.

Then, the heating value of the biomass was calculated. Considering that 95% of the forested cover of the sample consists of pine forest, the heating value of pine wood chips was the target value. The lower heating value was identified as the relevant calorific value as it subtracts the energy required to dry the biomass, and it was calculated for biomass with 30% moisture content according to the accessed literature. The figure of 12.8 $GJ/tn$ was obtained, which led to the result of 58348.16 $GJ/year$ of available energy.

The results show that there is a significant amount of biomass available in rural areas of Catalonia similar to the sample selected. It is also worth mentioning that, nowadays, this biomass is not being used in any way, so there is a missed opportunity of taking advantage of a valuable resource that is self-produced by the forests. Additionally, that would help to reduce the risk of wild fires that is significant in Mediterranean regions.

### 5.2.2 Conclusions of Research Question 2

The assessment of current efficiencies of biomass-based power plants showed a pattern of increasing efficiency with size of the plants. The relationship, although being clearly positive, was not lineal; it showed a potential behavior with an upper limit that was around 45% for large-scale technologies, significantly lower for small-scale technologies (30%), and even lower for micro-scale technologies (25%). According to this observed pattern, the best configuration to maximize the exploitation of the available resource is a single power plant with the higher output as possible.

The most appropriate technology depends on the scale of generation. While for large-scale power plants BIGCC and steam turbines show the best behavior, for small-scale and micro-scale internal or external combustion engines perform better. Thus, after obtaining an approximate power plant size of 884 kWe for 5500 hours of full usage, the technology of ICE was selected as the most appropriate in terms of efficiency. The efficiency of ICEs at that scale of generation was considered to be 25% according to the accessed data. A downward approximation was made to provide a conservative value of electricity production potential in the next step of analysis.

### 5.2.3 Conclusions of Research Question 3

The electricity production potential obtained was slightly higher than 4000 $MWh/year$, that could be produced, under the assumption of 5500 of annual usage, in a 735 kWe power plant with a gasification – ICE layout. In addition, if the adoption of a cogeneration scheme was possible, 10500 $MWh/year$ could be additionally produced using the same technology and power plant size. That would be equivalent to a power plant of 1915 kWth.

## 5.3 Discussion

Throughout all the research carried out, it has been shown that rural areas of Catalonia have an undeniable technical potential for electricity generation using wood biomass without going beyond the regeneration capacity of the indigenous forests. This local production if combined with local consumption would encourage the distributed generation and link well to a smart grid. Moreover, the local production of electricity using indigenous renewable sources would reduce the transport requirements and, consequently, the associated carbon footprint, in addition to mitigating fire damage potential.

However, it was also shown that the exact potential for electricity generation is a variable strongly linked to the idiosyncrasies of the sample selected such as the area covered by forests or the tree species mainly found in them. Therefore the potential for electricity generation may not be representative if extrapolated to other areas with different forest characteristics.

Moreover, the choice of technology would also be affected by the amount of available biomass because of the different performances of conversion technologies depending on the scale of generation (see §5.2.2). Other relevant factors that affect the final choice of technology are the annual full usage hours of the power plant and the economic competitiveness of the electricity generated. Although these other factors are very significant, they were left out of the scope of this research due to their relationship with national economy and electricity market behavior.

With respect to the biomass resource assessment, it is worth mention that the high variability of climates in Spain makes it invalid to extend the findings of this research regarding the type and amount of biomass produced, and chemical energy stored within it, to other regions of the country with different climates. Yet, these findings are applicable to all the area of Catalonia as well as other countries with Mediterranean climates like Italy, some parts of France, or Greece; provided that the terrain makes possible to harvest the biomass that is located there. This is a very important point since the focus of this research was placed only in the potential evaluation but without considering the technical or economic difficulties that could appear due to inaccessible or protected forests because of the local character of these issues, and the lack of problems of this nature in most of the geography of rural Catalonia. In addition, harvest rates higher than the obtained growth rate have been proven in managed forests (Siry, Cubbage, & Ahmed, 2005) so once the initial thinning or pruning actions were performed, all the available biomass could be harvestable over the following years.

Another important point is that forest management strategies are claimed to affect the growth rate of trees (Karjalainen, et al., 2000). In particular, growth rates are higher for young forests and they decrease as the forest gets older. Therefore, the results are conservative as they are based on current growth rates that could be higher if forest management strategies were implemented. Sustainable forest management strategies could increase the growth rate up to 2.5 $tn/(ha \cdot year)$ for pine forests (Siry, Cubbage, & Ahmed, 2005). Even with only the thinning and pruning practices required to harvest the yearly produced biomass, i.e. without active forest management strategies such as logging of trees, the growth rate of forest would increase as a result of forest rejuvenation. Therefore, growth rates greater than calculated should be expected once started the exploitation of the available resource (Karjalainen, et al., 2000).

Regarding the selection of the most appropriate technology, the choice was made in terms of current efficiencies that can be found in the market. Other variables were not considered for the selection of technology. For example, cost, operation and maintenance requirements, noise levels, life cycle, reliability, payback period… have not been studied, and they could affect the choice if it was desired to consider them. Furthermore, as shown, the technology selection is strongly linked to the scale of generation so other samples with larger or smaller amounts of available resource would possibly have other optimum conversion technologies that maximize the exploitation of their resource.

Even though all the implications of climate, terrain and variables affecting the technology are very important and might change the final results of the research, the whole methodology of this study is really applicable anywhere as a procedure for assessment of technical potential – not economic – for electricity generation from biomass and selection of the most appropriate technology to maximize the usage of the available resource.

It is also worth mention that the whole study focused on electricity generation potential, overlooking the production of heat associated to all processes involving combustion of a fuel as the case of biomass-based technologies is. However, the overall efficiency of the conversion system would be significantly increased if it was taken advantage from the produced heat. According to the accessed data, the overall efficiency of the biomass conversion system could be as high as 90% at the selected scale of generation. The main hurdle to overcome is obtaining a demand for such heat at the point of generation or close to it due to the large difficulty to transport heat in comparison with electricity.

Finally, it is also noteworthy to mention that this research studied the technical potential for electricity generation using forest wood biomass only through the assessment of available wood resource and current efficiencies of conversion technologies. Therefore, the electricity production potential could have been overestimated because the obtained available biomass value only accounts for the biomass that is found in the sample without considering possible issues or difficulties that may appear when harvesting such resource and the efficiency data were obtained from peer-reviewed sources, but since they came from a wide variety of layouts, such as actual power plants, demonstrative plants, manufacturer data…, there is some grade of uncertainty this value. However, both the available biomass and the efficiency values were downwardly approximated to obtain a conservative result. In addition, regarding the available resource calculation, only the growth rate of wood resource was considered to guarantee a homogeneous resource in terms of heating value, moisture content, size and shape of the chips but the total available resource, i.e. including bark, branches and leaves, is higher than calculated. On regards to efficiency values, higher values are likely to be expected due to the constant improvement in conversion technologies. For all these reasons, the obtained result should be considered a conservative approximation that should be tight to reality.

## 5.4 Recommendations for future work

With this research, many results related to the availability of biomass in rural areas and conversion technologies for electricity production have been gathered, and the main conclusions and findings have been summarized throughout the previous sections. However, there are still many areas for future work.

### 5.4.1 Recommendations for practice

An important area of future work involves the size and full usage hours of a power plant that would take advantage of the available resource. The power plant size provided as a result is a calculated value rather than an actual commercial option and the full usage ratio is a tentative figure. A market study should be done to find the closest commercially available engine and gasifier size as well as the actual full usage ratio that could be expected.

Another important area of future work is the study of the economic value that wood residues have in the region due to the cost of harvesting such residue. As previously stated, the difficulty to harvest biomass in areas of difficult access could raise the cost of such residue to non-profitable values, despite the fact that this residue is not being used and has a very low cost in areas where the harvest process is easy to be done.

### 5.4.2 Recommendations for further research

First of all, further studies are required to test the environmental impact and economic viability of the different technologies to inform a better choice of technology considering these factors in addition to the electrical efficiency. In particular, a life cycle assessment would be very useful to evaluate the energy return on investment and would help to consider if the pre-processing and conversion alternative chosen have a good energy return on energy invested ratio as well as how significant are the greenhouse gas emissions associated to the whole electricity generation process.

A second area of future work is the assessment of cogeneration possibilities. As shown, the electrical efficiency of biomass conversion technologies is relatively small and higher overall efficiencies would be achieved if electricity production was combined with heat production. Hence, cogeneration opportunities should be sought, for example in industrial or public buildings installations. This research showed that up to two and half watts of heat would be produced for each watt of electricity using current CHP technologies.

Finally, another area of future research involves the integration of different renewable energy sources. As previously stated, biomass-based conversion technologies allow the possibility of being used as backup for non-predictable renewable energy sources. Smaller power plants or amount of biomass usage could be beneficial if the main goal of such power plant was to backup other renewable electricity generation technologies. Hence, optimization studies would help to determine the optimal size of a hypothetical biomass-based power plant serving as backup of small wind or solar farms that could be installed in rural areas of Catalonia.

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# REFERENCES

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# APPENDICES

# Appendix A Forest characterization of the region of Anoia and the township of Argençola

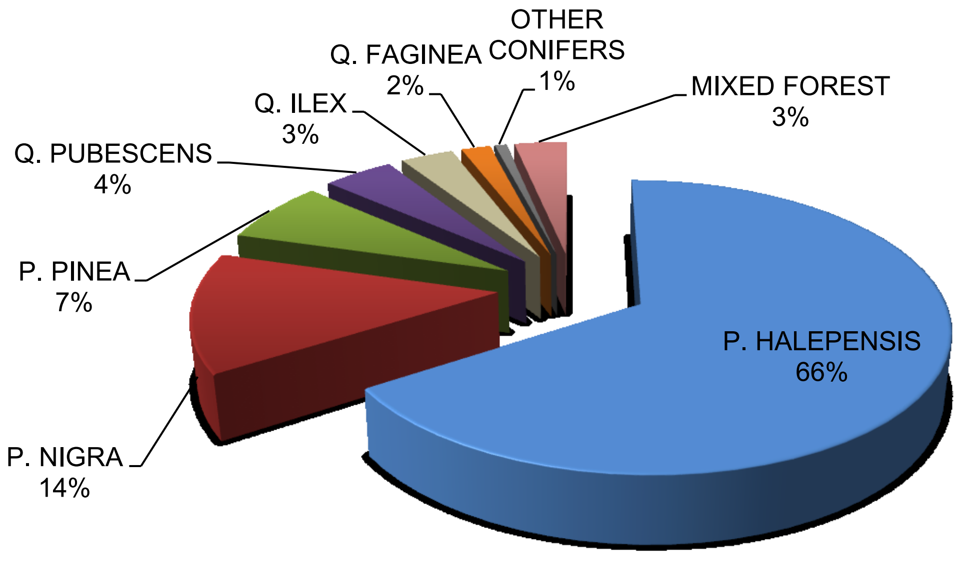
For the region of Anoia, the forest characterization is presented in terms of area covered and tree species. The values are detailed in Table A 1 and figures Figure A 1 and Figure A 2.

Table A 1 Area covered by the different kinds of trees in the *comarca* of Anoia and actual number of trees sampled

| **Tree species** | **Forest area (ha)** | **# of trees (thousands)** |
|---|---|---|
| ***Pinus halepensis*** | 18117 | 13982 |
| ***Pinus nigra*** | 3724 | 3144 |
| ***Pinus pinea*** | 1912 | 1082 |
| ***Quercus pubescens*** | 1208 | 1759 |
| ***Quercus ilex*** | 906 | 2169 |
| ***Quercus faginea*** | 503 | 1003 |
| **Mixt forest** | 906 | - |
| **Other oaks (*quercus*)** | - | 626 |
| **Other conifers *(pinus)*** | 202 | 159 |

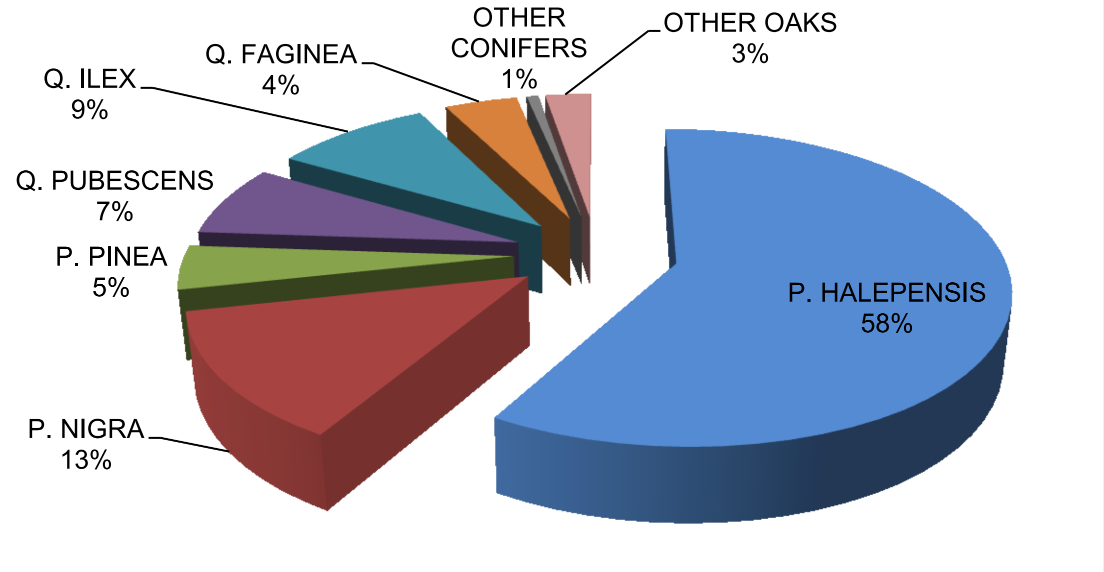
Source: personal compilation based on IECF (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

The relative importance of each tree species based on forest area covered is represented in Figure A 1, and the relative importance of each tree species based on actual number of trees is represented in Figure A 2.



Source: Personal compilation based on IEFC (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

Figure A 1 Relative importance of each tree species in Anoia, forest area basis



Source: Personal compilation based on IEFC (Burriel, Gracia, Ibàñez, Mata, & Vayreda, 2000)

Figure A 2 Relative importance of each tree species in Anoia, number of trees basis

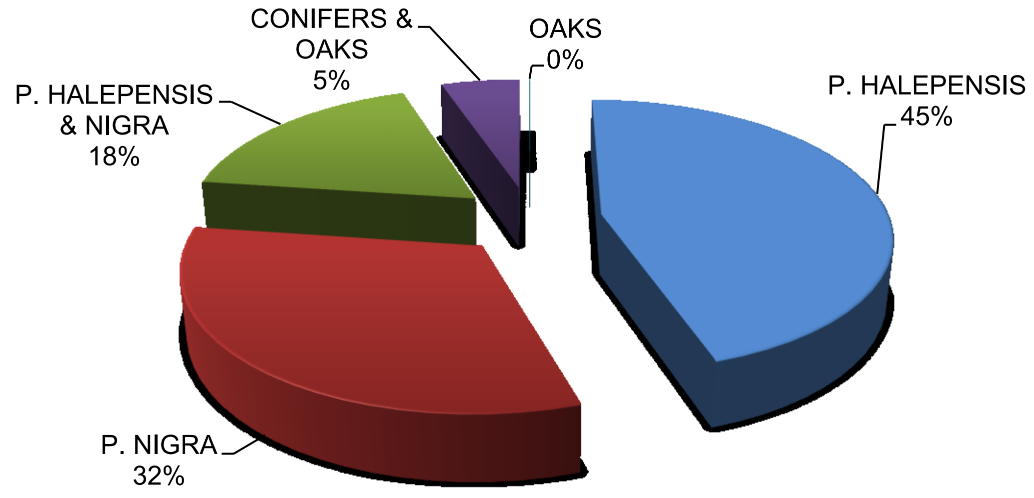
For the township of Argençola, the forest characterization is presented in terms of area covered. The values are detailed in Table A 2 and represented in Figure A 3.

Table A 2 Area covered by the different kinds of trees in the *municipi* of Argençola

| **Type of forest** | **Forest area (ha)** |
|---|---|
| **Monospecific forest of *pinus halepensis*** | 999.84 |
| **Monospecific forest of *pinus nigra*** | 713.19 |
| **Mixt forest of *p. halepensis* and *p. nigra*** | 391.57 |
| **Mixt forest of conifers (*pinus*) and oaks (*quercus*)** | 115 |
| **Monospecific forest of oaks (*quercus*)** | 0.58 |

Source: personal compilation based on Codina and Rodríguez (2009)

The relative importance of each tree species based on forest area covered is represented in Figure A 3.



Source: Personal compilation based on report of Biomass Availability at the municipi of Argençola (Codina & Rodríguez, 2009)

Figure A 3 Relative importance of each tree species in Argençola, forest area basis

# Appendix B Summary of efficiencies of biomass conversion technologies

The electrical efficiencies, power plant name and size, conversion technology used and source from which the information was retrieved are presented in Table B 1. All data comes from real biomass-based power plants or manufacturer data, as specified.

Table B 1 Power plant location and size, electrical efficiency, conversion technology and fuel used and reference of different real biomass-based power plants

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **Viking Gasification Plant** | Denmark | 18.55 | 25.1 | N/A | ICE | Wood chips | (Ahrenfeldt, et al., 2006) |
| **BERI project** | India | 120 | 18 | 81 | ICE | Wood chips | (Ahrenfeldt, et al., 2006) |
| **Tervola** | Finland | 470 | 24 | 82 | ICE | Wood residues | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Harboøre** | Denmark | 700 | 28 | 96 | ICE | Wood chips | (Ahrenfeldt, et al., 2006) |
| **Kokemäki** | Finland | 1800 | 25 | 60 | ICE | Wood chips, sawdust, bark | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Güssing** | Austria | 2000 | 25 | 81 | ICE | Wood chips | (Ahrenfeldt, et al., 2006) |
| **Hawaii Paia** | Hawaii | 5000 | 30 | N/A | BIGCC | Bagasse | (Rollins, et al., 2002) |
| **Värnamo** | Sweden | 5500 | 30 | 76 | BIGCC | Wood chips | (Wahlund, Yan, & Westermark, 2001) |
| **Värnamo** | Sweden | 5500 | 32 | 83 | BIGCC | Wood chips | (Stahl & Neergaard, 1998) |
| **Biocycle** | Finland | 7200 | 39.9 | 77.3 | BIGCC | Wood | (Rollins, et al., 2002) |
| **Simulation** | The Netherlands | 25600 | 36.3 | N/A | BIGCC | Organic domestic waste | (Faaij, et al., 1997) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **Simulation** | The Netherlands | 26800 | 39 | N/A | BIGCC | Verge grass | (Faaij, et al., 1997) |
| **Simulation** | The Netherlands | 29000 | 40.3 | N/A | BIGCC | Clean Wood | (Faaij, et al., 1997) |
| **Simulation** | The Netherlands | 29000 | 35.4 | N/A | BIGCC | Sludge-demolition wood mixture | (Faaij, et al., 1997) |
| **Simulation** | The Netherlands | 29300 | 40 | N/A | BIGCC | Demolition Wood | (Faaij, et al., 1997) |
| **Bioflow** | Sweden | 35000 | 43 | 86 | BIGCC | Wood | (Gustavsson & Johansson, 1994) |
| **Institute of Gas Technology (IGT) RENUGAS®** | Hawaii | 55500 | 36[2] | N/A | BIGCC | Wood chips | (Craig & Mann, 1996) |
| **Plant without CO2 capture** | N/A | 60000 | 43 | 86 | BIGCC | N/A | (Gustavsson & Madlener, 2004) |
| **Plant without CO2 capture** | N/A | 60000 | 43 | 86 | BIGCC | N/A | (Gustavsson & Madlener, 2004) |
| **Vega project** | Sweden | 62000 | 44 | 90 | BIGCC | Wood | (Gustavsson & Johansson, 1994) |
| **Modelization of Plant without CO2 caputre** | N/A | 100000 | 43 | 86 | BIGCC | Salix and forest/ logging residues | (Uddin & Barreto, 2007) |
| **Modelization of Plant with CO2 capture** | N/A | 100000 | 33 | N/A | BIGCC | Salix and forest/ logging | (Uddin & Barreto, 2007) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | | residues | |
| **Plant without CO2 capture** | N/A | 100000 | 47 | N/A | BIGCC | | (Gustavsson & Madlener, 2004) |
| **World Bank's Global Environment Facility (GEF)** | Brazil | 105400 | 37.9[2] | N/A | BIGCC | Wood chips | (Craig & Mann, 1996) |
| **Battelle Columbus Laboratory, Burlington, VT** | USA | 122000 | 35.4[2] | N/A | BIGCC | Wood chips | (Craig & Mann, 1996) |
| **Institute of Gas Technology (IGT) RENUGAS®** | Hawaii | 131700 | 39.7[2] | N/A | BIGCC | Wood chips | (Craig & Mann, 1996) |
| **Simulation** | N/A | 204502 | 36.27 | N/A | BIGCC | Biomass poplar | (Corti & Lombardi, 2004) |
| **ETSU B/U1/00679/00/REP** | UK | 30 | 17 | 80 | Microturbine | Wood pellets | (Pritchard, 2002) |
| **Admont, Styria** | Austria | 400 | 7.4 | 48.2 | ORC | Wood chips, sawdust | (Obernberger & Hammerschmid, 2001) |
| **Lienz CHP plant** | Austria | 1000 | 15 | 97 | ORC | Wood chips | (Obernberger, Thonhofer, & Reisenhofer, 2002) |
| **Ostrow Wielkopolski** | Poland | 1500 | 15 | 89 | ORC | Wood chips | (Bini, Di Prima, & Guercio, 2010) |
| **Schnarhauser Park, Ostfildern** | Germany | 6300 | 15 | 81.6 | ORC | Wood chips | (Erhart, Strzalka, Eicker, & Infield, |

| **Power Plant** | **Location** | **Power Output (kWe)** | **Electrical efficiency[1] $\eta_e$ (%)** | **Overall efficiency $\eta_{tot}$ (%)** | **Conversion tech.** | **Fuel** | **Reference** |
|---|---|---|---|---|---|---|---|
| | | | | | | | 2011) |
| **Australian Nat University rural electricity supply syst** | Fiji Islands | 25 | 22 | N/A | Steam Engine | Sawmill, crop wastes | (Prasad, 1990) |
| **Hartberg, Styria** | Austria | 730 | 10 | 80 | Steam Engine | Wood chips, bark, sawdust | (Hammerschmid, Stallinger, Obernberger, & Piatkowski, 2004) |
| **Lion Powerblock** | manufacturer | 2 | 10.4 | 94 | Steam Turbine | Wood pellets, Natural Gas, Oil | (Barbieri, Spina, & Venturini, 2012) |
| **Kiuruvesi** | Finland | 900 | 11 | 85 | Steam Turbine | Bark, sawdust, wood chips | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Karstula** | Finland | 1000 | 8 | 85 | Steam Turbine | Bark, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Renko** | Finland | 1300 | 13 | 81 | Steam Turbine | Bark, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Tranas** | Sweden | 1600 | 14.5 | 104 | Steam Turbine | Sawdust, bark | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Hallsberg** | Sweden | 2050 | 14 | 80 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  | Wahlund, Yan, & Westermark, 2001) |
| **Vilppula** | Finland | 2900 | 17 | 80 | Steam Turbine | Bark, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Älvsbyn** | Sweden | 3000 | 23 | 100 | Steam Turbine | N/A | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Malä** | Sweden | 3000 | 18 | 86 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Lomma** | Sweden | 3500 | 19 | 93 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Björknäs** | Finland | 3600 | 21 | 104 | Steam Turbine | Wood chips, wood residues | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Motala** | Sweden | 3700 | 18.5 | 95 | Steam Turbine | Wood chips, bark, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Lextorp (Trollhättän)** | Sweden | 3700 | 18.5 | 87 | Steam Turbine | Wood chips, bark, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |

| **Power Plant** | **Location** | **Power Output (kWe)** | **Electrical efficiency[1] $\eta_e$ (%)** | **Overall efficiency $\eta_{tot}$ (%)** | **Conversion tech.** | **Fuel** | **Reference** |
|---|---|---|---|---|---|---|---|
| **Kuhmo** | Finland | 4800 | 24 | 88 | Steam Turbine | Wood residues | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Kankaanpää** | Finland | 6000 | 23 | 89 | Steam Turbine | Peat, wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Kuusamo** | Finland | 6100 | 22 | 86 | Steam Turbine | Peat, wood chips, sawdust | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Bäckelund** | Sweden | 7000 | 20 | 85-90 | Steam Turbine | Wood chips, MSW | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Falun** | Sweden | 8000 | 23 | 109 | Steam Turbine | Bark, wood residues, wood chips | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Lieksa** | Finland | 8000 | 24 | 89 | Steam Turbine | Peat, wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Nässjö** | Sweden | 8070 | 24 | 103 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Sala** | Sweden | 10000 | 28 | 89 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **Härnösand** | Sweden | 11700 | 28 | 106 | Steam Turbine | Forest residues, bark sawdust, peat | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Hudiksvall** | Sweden | 13000 | 22 | 82 | Steam Turbine | Wood, peat (50-50) | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Lycksele** | Sweden | 14000 | 32 | 84 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Iisalmi** | Finland | 14700 | 31 | 93 | Steam Turbine | Peat, wood, REF | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Forssa** | Finland | 17200 | 24 | 91 | Steam Turbine | Wood, REF | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Karlstad** | Sweden | 17500 | 20 | 111 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Kokkola** | Finland | 20000 | 25 | 89 | Steam Turbine | Peat, wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Enköping** | Sweden | 22500 | 28 | 98 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; |

| **Power Plant** | **Location** | **Power Output (kWe)** | **Electrical efficiency[1] $\eta_e$ (%)** | **Overall efficiency $\eta_{tot}$ (%)** | **Conversion tech.** | **Fuel** | **Reference** |
|---|---|---|---|---|---|---|---|
| | | | | | | | Wahlund, Yan, & Westermark, 2001) |
| **Nyköping** | Sweden | 31500 | 30 | 96 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Skelleftea** | Sweden | 32500 | 31 | 84 | Steam Turbine | Wood, peat (80-20) | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Växjö** | Sweden | 33000 | 30 | 87 | Steam Turbine | Wood, peat (80-20) | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Plant without CO2 capture** | N/A | 36000 | 30 | 90 | Steam Turbine | | (Gustavsson & Madlener, 2004) |
| **Plant without CO2 capture** | N/A | 36000 | 30 | 90 | Steam Turbine | | (Gustavsson & Madlener, 2004) |
| **Brista** | Sweden | 39000 | 29 | 87 | Steam Turbine | Wood | (Wahlund, Yan, & Westermark, 2001) |
| **Modelization of Plant without CO2 caputre** | N/A | 50000 | 30 | 90 | Steam Turbine | Salix and forest/ logging residues | (Uddin & Barreto, 2007) |
| **Modelization of Plant with CO2** | N/A | 50000 | 20 | N/A | Steam Turbine | Salix and | (Uddin & Barreto, 2007) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **capture** | | | | | | forest/ logging residues | |
| **Allmänna** | Sweden | 50000 | 30 | 86 | Steam Turbine | Wood | (Gustavsson & Johansson, 1994) |
| **Kristianstad** | Sweden | 135000 | 24 | 87 | Steam Turbine | Wood | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011; Wahlund, Yan, & Westermark, 2001) |
| **Plant without CO2 capture** | N/A | 200000 | 40 | N/A | Steam Turbine | | (Gustavsson & Madlener, 2004) |
| **Harboøre Varmeværk** | Denmark | 1000 | 28 | 94 | Steam Turbine | Wood chips | (Ciferno & Marano, 2002) |
| **Assens** | Denmark | 4700 | 27 | 80 | Steam Turbine | Wood chips | (Babcock & Wilcox Vølund, 2010) |
| **TPS Termiska Processor, Greve Chianti** | Italy | 6700 | 19 | N/A | Steam Turbine | Wood pellets | (Ciferno & Marano, 2002) |
| **MVV Königs Wusterhausen, Königs** | Germany | 20000 | 36.4 | N/A | Steam Turbine | Industrial wood and waste wood | (Siewert, Niemelä, & Vilokki, 2004) |
| **Älvkarleby** | Sweden | 0.8 | 20 | 80 | Stirling Engine | Wood pellets | (Salomón, Savola, Martin, Fogelholm, & Fransson, 2011) |
| **Sunmachine pellet test** | manufacturer | 1.38 | 14.3 | 72.1 | Stirling Engine | Wood pellets | (Thiers, Aoun, & Peuportier, 2010) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **Sunmachine pellet** | manufacturer | 1.5 | 20 | 90 | Stirling Engine | Wood pellets | (Thiers, Aoun, & Peuportier, 2010) |
| **Sunmachine pellet** | manufacturer | 3 | 25 | 90 | Stirling Engine | Wood pellets | (Thiers, Aoun, & Peuportier, 2010) |
| **Sunmachine** | manufacturer | 3 | 20.1 | 90.6 | Stirling Engine | Wood pellets | (Barbieri, Spina, & Venturini, 2012) |
| **Sunmachine** | manufacturer | 3 | 20 | 90 | Stirling Engine | Wood pellets | (Angrisani, Roselli, & Sasso, 2012) |
| **DISENCO** | N/A | 3 | 18.4 | 92 | Stirling Engine | Wood pellets | (Barbieri, Spina, & Venturini, 2012) |
| **Joanneum Research (Energy Research Institute)** | Austria | 3.2 | 23.5 | - | Stirling Engine | Wood chips | (Podesser, 1999) |
| **Joanneum Research (Institute of Energy Research)** | Austria | 30 | 26 | - | Stirling Engine | Wood chips | (Zeiler, Padinger, Spitzer, & Podesser, 2007) |
| **Technical University of Denmark** | Denmark | 31 | 9.2 | 90 | Stirling Engine | Wood chips | (Biedermann, Carlsen, Schöch, & Obernberger, 2003) |
| **Technical University of Denmark** | Denmark | 75 | 11.7 | 85.9 | Stirling Engine | Wood chips | (Biedermann, Carlsen, Obernberger, & Schöch, 2004) |
| **SOLO161 Stirling** | Germany | 2 | 22 | 92 | Stirling Engine | Wood chips | (Kuhn, Klemes, & Bulatov, 2008) |
| **BAXI Ecogen** | manufacturer | 6 | 13.5 | 94.6 | Stirling Engine | Wood chips | (Angrisani, Roselli, & Sasso, 2012) |

| Power Plant | Location | Power Output (kWe) | Electrical efficiency[1] $\eta_e$ (%) | Overall efficiency $\eta_{tot}$ (%) | Conversion tech. | Fuel | Reference |
|---|---|---|---|---|---|---|---|
| **SOLO161 Stirling** | Italy | 9 | 24 | 96 | Stirling Engine | Wood chips | (Parente, Galletti, Riccardi, Schiavetti, & Tognotti, 2012) |
| **SOLO161 Stirling** | manufacturer | 9 | 25 | 97.2 | Stirling Engine | Wood chips | (Angrisani, Roselli, & Sasso, 2012) |

Source: personal compilation.

[1] LHV basis

[2] HHV basis

# VITA

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## Education

M.Sc. in Technology, Leadership and Innovation, 2013, Purdue University, Indiana, United States
M.Sc. in Sustainability, 2013, Universitat Politècnica de Catalunya, Catalunya, Spain
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Junior Project Engineer, 2010-2011, Applus LGAI, Cerdanyola (Barcelona), Catalunya, Spain
Fluid dynamics engineering internship, 2010, Universitat Politècnica de Catalunya, Catalunya, Spain

## Research Interests

Sustainability
Renewable Energy Technologies