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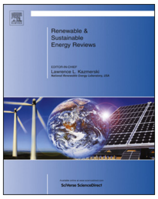

Review of micro- and small-scale technologies to produce electricity and heat from Mediterranean forests' wood chips

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ABSTRACT

In the current energy conjunction, with an expected growth of energy consumption in a context of fossil fuel depletion, more focus is being placed on renewable energy sources (RES) for electricity generation. One of the most appealing alternatives is biomass, which can be efficiently used to generate electricity as well as heat with the application of cogeneration technologies that enhance the efficiency of the entire energy conversion process. The Mediterranean basin is a region with a recognized potential for electricity and heat production using primary forest biomass and sub-products from sawmills, among which highlight wood chips for their easiness to be obtained, processed and dried as well as for their good and stable burning or gasification behavior. However, in order to efficiently use the available resources, that is, minimizing logistical requirements to reduce the energy necessary for the electricity generation process, the biomass found in Mediterranean forests can only be used at micro- and small-scale levels to be compatible with sustainable forestry practices. This article is aimed to describe the different technological alternatives to convert wood chips into electricity and heat and it also reviews and compares the current performances in terms of efficiency of these technologies at the micro- and small-scale levels.

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1. Introduction

Over the past decades, the levels of greenhouse gases (GHG) in the atmosphere and, specifically, of the most prevalent one, carbon dioxide (CO_2), have raised way over safe limits of Earth's boundaries [1]. Particularly, CO_2 levels have risen from around 280 ppm of pre-industrial era [1,2] to near-400 ppm at present time [4] continuing to grow at increasing rates [5]. Among the identified causes of worldwide GHG emissions, energy production is claimed to be the main one. In particular, CO_2 emitted from the combustion of fossil fuels for transportation, industry, electricity and heat production is the major contributor to the greenhouse effect [6]. Energy production is expected to have continuous growth during next decades [7], shaping a context of current and future global environmental issues, namely sea-level rise and weather pattern changes [8], worsening agriculture production [9] and producing water shortages in some places and intense flooding in some others [10,11]. Such changes will likely have significant implications in ecology, economics and public conflicts and policy [12]. In addition to these environmental concerns, fossil fuels have another important drawback: despite the fact that they are the main energy source throughout the world, they entered in a depletion process over the last decades, a concern to be added to the environmental degradation that they contribute to [7,13]. In a free-market economy, this means increasing prices and thus decreasing competitiveness. Moreover, in countries with low or even no indigenous fossil fuel availability, their usage results in energy dependency on foreign countries.

Facing all mentioned odds, there are the renewable energy technologies which often are indigenous sources of virtually perpetual energy, scalable and carbon neutral [14]. These technologies will help to implement the distributed generation model which consists on energy production close to both renewable energy sources (RES) and consumption. Consequently, large production plants could be partially substituted by small- and micro-scale plants [15]. Distributed generation, in turn, has been labeled as a key tool to address the problems of security of supply, CO2 emissions and to improve the efficiency of energy systems [16], as well as to overcome the problem of rising electricity costs and shortages [14]. 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 [14,17] and by generating new income opportunities through revaluation of local resources [18]. Therefore, several public policies have been set up in many countries in order to increase the share of RESs to the electricity supply, including the goal of reaching 20% of electricity share in both the European Union (EU) and the United States (US) or the goal of 35% share in Asian countries such as China or India [19].

However, RESs have an undeniably important drawback: from the three most exploited sources, hydroelectric, wind and photovoltaic (PV) power, two of them, namely wind and PV, are weather- or climatic-dependent [20], meaning that it cannot be assured their dispatch on demand because they only can be produced when the natural resource is available. To face and overcome this issue, more flexibility has to be achieved to ensure permanent meeting of demand by the supply side. Among the available grid-scale flexibility achievement techniques, which include demand-side management, overcapacity installation and large-scale storage systems, the latters are the best option because they allow maximizing the usage of generation without impacting the consumers' habits of use of electrical power [21]. According to Barnhart and Benson [21], large-scale storage systems include conventional batteries (Li-ion, sodium sulfur or lead-acid batteries), flow batteries (vanadium redox or zinc-bromine), compressed air electricity storage (CAES) and pumped hydro storage (PHS). Carrasco and Franquelo [22] also consider flywheels, hydrogen fuel cells, supercapacitors and superconducting magnetic energy storage (SMES) as feasible alternatives. If small-scale solutions, namely micro-wind turbines or stand-alone photovoltaic systems are chosen, battery energy storage systems (BESS) to be used as a backup are even more necessary due to their scalability and low cost [23]. Hence, additional costs should be attributed to the installation of these RESs if the requirement of storage is taken into account when designing a so-called hybrid system that includes renewable energy production technologies and storage systems [20]. Moreover, the small size of these systems adds another potential issue: the integration of many small power sources instead of a few large ones requires additional control measures to ensure stability, prevent failures and make mid- and long-term electricity production estimations [24,25]. According to some sources [19], the setup of large energy farms, both wind and photovoltaic, that supply power as a single power unit is also required in order to ease their integration into the electric grid.

Among all the RES, biomass is one of the most promising options. Particularly, the fact of being based on proven technologies, its flexibility of operation and installation [14], easy and efficient scalability and low and stable price because of being often a waste product [17] are strong reasons for its use. Moreover, biomass is the only renewable source that can be used in solid, liquid or gaseous form [26,27], which allows using it for industrial purposes in the case of solid biomass, for electricity and heat production when it is in both gaseous and solid phases, and for transportation purposes for liquid biofuels [28]. It also offers the possibility of having the plants near the resource, thus minimizing transportation costs [29] that lead to environmental impact reduction due to a more efficient utilization [30]. In addition, biomass is, together with hydro, the unique RES that can be stored and continuously used to have a predictable output not dependent of weather [31], so it would reduce the requirement of storage systems mentioned above. Finally, another important advantage of biomass is its flexibility to be converted to several forms of energy. Therefore, combined heat and power (CHP) technologies or combined cooling heat and power (CCHP) [32], which have better efficiencies [33], lower consumption [34] and CO_2 emissions [16] than heat and electricity production individually, can be used. Biomass-fuelled CHP systems have low operating and maintenance costs, high total efficiencies and low noise, vibration and emissions levels [16]. Moreover, heat pumps can be integrated with CHP plants to relocate the excess heat produced from the production site to a consumption node or to a storage facility [35]. CHP technologies reach the highest efficiencies if woody biomass is used rather than non-woody biomass [36], so it is interesting to use primary forest biomass and sub-products from sawmills for these purposes. Another important aspect to be considered is the quality of the wood chips, since current technologies require specific quality standards according to the end-user needs [37].

In Europe, nowadays, about one half of the forests are privately owned, and most of these ownerships are small-scale holdings. These holdings average between two and four hectares in Western Europe countries such as Spain and apply different management styles related to livelihood systems rather than to economic purposes [38]. In particular, in Spain most of the forest owners are retired foresters (46%) or absentee owners (41%) [38], which means that few or null proper forest management should be expected. This entails a high risk of wild fires with ecological and also economic and social implications [39], especially during the dry summer season in the Mediterranean area [40,41]. This risk has increased over the past decades in both number and severity due to increased drought conditions together with both inappropriate management practices and abandonment of forests and agricultural lands that facilitate an over-accumulation of dead fuels [42]. This lack of programmed management leads to increased homogeneity of landscape that facilitates fire continuity and propagation [43]. Hence, improved management strategies adapted to the new paradigm of warmer and drier climates and focused on fuel load reduction would reduce the risk of forest fires [42]. Otherwise, fire reduction capacity will be overwhelmed in the future due to increased dryness and droughts triggered by climate change [44].

Through the promotion of forest biomass usage as a RES in the Mediterranean basin, which is a region with high potential [45], it may be given economic value to forest resources currently untapped, sawmill operators could increase their income by converting hardwood sawmill residues to woodchips [46], rural employment in the energy sector could be created [38,47] and the national energy industry could be supported whereas partial energy independency would be achieved in rural areas. Moreover, forest management would be improved [48], but it is important to stress that new management strategies should be sustainable, preserving primary production, carbon storage capacity and biological diversity [41] while also minimizing wild fire risk and increasing their biomass productivity rates [49]. Otherwise, human pressure historically borne by Mediterranean forests, especially in the Northern rim [41], would jeopardize the continuity of those forests.

Biomass is characterized by having low energy density and by being spread, problems that increase harvesting and transportation costs [50,51]. This is the case of Mediterranean forests, where biomass availability is especially low when compared with other forested areas with less importance of dry periods and better ownership schemes. Considering this particularity of low biomass production together with the disaggregated ownership in small portions of land, it can be concluded that energy production from wood forest biomass in Mediterranean forests is, regardless of the available technology, limited to small-scale projects that would take advantage of the limited available biomass within a single or a few properties found in the vicinities of the power plant [29].

Among the forest woody biomass useful for electricity and heat generation, wood chips are one of the trendiest options. This is so because wood chips can be easily obtained and do not require additional treatment such as densification processes which are necessary for pellets production [51] nor require additional energy input in the drying process as they can be dried by only leaving them covered. Therefore less energy consumption and associated environmental impacts are involved in the wood chips process. Moreover, they are low ash-content biomass fuels [52] that do not generate co-products, and burn better than entire logs because wood chips have more contact surface with the air flow. However, pellets still dominate the wood biomass market [53] but wood chips are starting to gain importance.

Nowadays, wood chips are mainly obtained from forest harvesting (from stem and whole tree wood) and remnants of forest operations, from sawmills residues and from lignocellulose energy crops [54], but their harvesting is expected to grow as they will likely be obtained from stumps and round wood as well [48].

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

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

2. Electricity and heat generation from wood chips

Biomass can be converted into other forms of energy by means of biological conversion, chemical conversion and thermochemical conversion. The former, known as bio-digestion, is suitable for moist biomass as it uses microorganisms to produce gas from biomass. Chemical conversion produces biofuels such as ethanol or other chemical products such as furfural by using enzymes [55]. The latter is appropriate for dry biomass [56] as it is based on the application of heat and pressure, and is more efficient for electricity and heat generation than digestion [57,58]. Chemical conversion mechanisms are left out of the study because they are not focused on electricity generation but on biofuels production. Between biological and thermochemical conversion mechanisms, the latters are reviewed in this study because wood chips are quite dry, or can be dried without using additional amounts of energy, so these technologies are well-suited for these applications.

Thermochemical conversion of wood chips into another form of usable energy for electricity and heat production can be done essentially in two ways (primary conversion technologies): through direct combustion or gasification. It could be added pyrolysis as the third primary conversion technology, but since this process is directed to transportation fuels production [27,59] due to the maximization of liquid fraction in the process [60], and since nowadays there are no commercial plants for electricity production based on this process [61], pyrolysis is omitted in this analysis.

These primary conversion technologies are coupled with secondary conversion technologies responsible for the electricity production and, additionally, heat production. Direct combustion converts the chemical energy stored within the wood chips in thermal energy that can later be harnessed using steam engines or steam turbines and their variation of organic Rankine cycles (ORC) and with external combustion engines, also called Stirling engines.

On the other hand, gasification converts the chemical energy of biomass into a low-heating value gaseous fuel, also known as syngas, which makes this process more polyvalent than direct combustion [62]. The chemical energy of this gas can be utilized by means of gas turbines, internal combustion engines (ICE) or Stirling engines as well. All mentioned conversion paths accept the use of both electricity production and combined heat and power (CHP), depending on the exploitation or not of the excess heat available after electricity generation. Some CHP layouts combine two different secondary technologies, for example, gas turbine for electricity production and steam turbine for heat retrieval.

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

It is noteworthy to mention that these conversion paths are nowadays at different development stages. For example, direct combustion coupled with steam turbine and gasification coupled with ICE are the most deployed options due to more commercial viability and maturity [14,64]. GTs are also appealing, while other technologies are still at demonstration, development or research stage.

2.1. Primary conversion technologies

As mentioned, primary conversion technologies suitable and efficient for electricity and heat production using low moisture biomass such as forest residues are direct combustion and gasification [65].

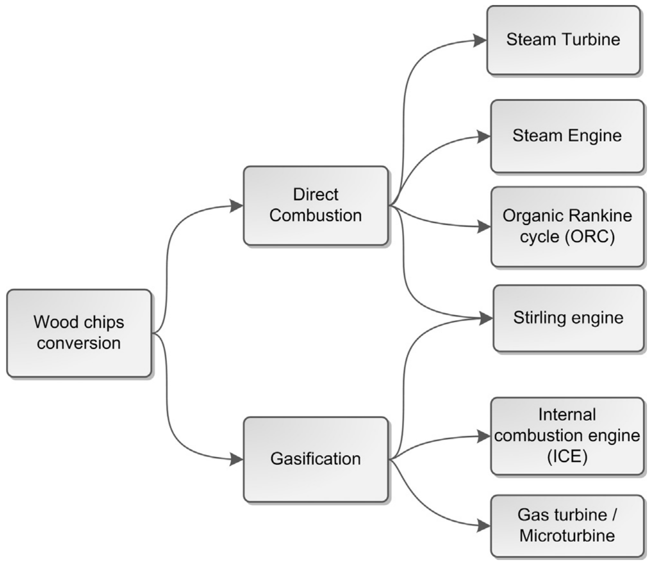

Fig. 1. Commercial conversion paths of wood chips to electricity and heat. Own elaboration based on Buragohain, Mahanta [14], Monteiro, Moreira [15], Salomón, Savola [63].

2.1.1. Direct combustion

This thermochemical process consists on the complete oxidation of biomass in an aerobic environment [66], releasing heat at the level of 800–1000 °C, typically. Despite the fact that direct combustion applications are the most mature technologies [52] and account for more than 90% of the biomass-based worldwide capacity installed [67], they have in average higher emissions due to smaller efficiencies than gasification applications [59]. Although the heat released in the combustion process can be harnessed using several conversion technologies, steam production to then generate electricity in a steam turbine is the most common conversion path [68].

Direct combustion can be performed in different combustors, among which highlight pile burners, stoker grates, bubbling or circulating fluidized beds and suspension burners [68]. Each one has its own particularities, for example, fluidized beds are suitable for large-scale plants (>10 MWth) while stoker grates are more appropriate for small-scale layouts (<6 MWth) with higher moisture content [52]. In addition to these combustors, there are some non-conventional alternatives such as suspension burners or WholeTree®. In general terms, it can be asserted that fixed-bed grates are preferable for micro-scale applications and that increasing boiler sizes result in the usage of moving grates but the kind of fuel is also influential and hence chip boilers are more suitable for moving grates layouts [53].

Table 1 summarizes the different types of combustors currently available.

2.1.2. Gasification

This process consists of the partial oxidation of biomass in a low-oxygen content environment [62,66,69]. The main product of this process is a low-heating value gas, called syngas, that can be used for heating and cooking purposes as well as for electricity generation [58,70]. This process also generates hydrogen, methanol or other biobased products such as alcohols or polyesters [71]. It is worth distinguishing between syngas obtained from thermochemical gasification and biogas obtained from anaerobic or aerobic digestion. Although the main components of both gases are the same, the processes and their conversion efficiencies are completely different: electricity is produced through gasification at efficiencies about 30–35% for dry biomass, dropping with higher moisture contents down to 15% for moisture contents about 70% in weight, matching the efficiency of electricity production from anaerobic digestion which do not depend of moisture content [65].

The main driving factors of the gasification reaction are the temperature, time of residence and particle size. In general, it can be asserted that higher particle sizes and times of residence lead to higher gasification rates of the fuel and the temperature increase

Table 1
Direct combustion technologies summary. Personal compilation based on Bain, Overend [68].

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

results in an increase in hydrogen content and yield of syngas but also in a decrease in methane content and thus in lower heating value (LHV) [72].

The gasification process has several advantages, among which highlight its versatility and flexibility to be combined with different secondary conversion technologies [68]. In addition, this process allows to use biomass fuels at a wider range of moisture content than direct combustion does; and, thanks to the different gasification technologies available, that is, the different kinds of gasifiers commercially available, it can be used from as low as kilowatt-scale to as high as hundred megawatt-scale [14], which makes it highly adaptive to different niches [67].

Gasification can be performed in different reactors, called gasifiers, that may be classified according to the gasification agent (air, steam, oxygen), the operating pressure (atmospheric, pressurized), the source of heat (indirectly or directly heated) or according to the fluid-biomass contact interface [73], which is the most common one. There are, accordingly, fixed bed, fluidized bed and entrained flow reactors following the latter criterion [14,58,68,74,75].

Fixed bed reactors are characterized by having biomass fuel in an almost static position while the gasification agent flows through it. The direction in which the fluid passes through the fuel establishes where the different reaction zones are located [76] and distinguish, in turn, three different subtypes of fixed-bed reactors: updraft, downdraft and cross-flow. The first has a counter-current flow of gasification agent, the second has a co-current flow, and in the third case the fluid is introduced by one side, exiting by the opposite.

Fluidized bed reactors are characterized by introducing a third agent, the fluidizing material into the equation and thus reducing the slagging of the reaction [77] and improving the uniformity and adjustability of the temperature distribution [58,75], thus increasing the biomass conversion rate up to 100% [78]. According to the velocity of the gasification agent flow, two different types exist: bubbling fluidized bed and circulating fluidized bed. In the former, equilibrium is reached between the fluidizing material and the fuel, while in the latter higher velocities are achieved, so the fuel is entrained by the fluidizing material. Fast internal circulating fluidized bed is a recent improvement that includes a combustion zone in addition to the gasification zone increasing the velocity of the reaction due to increased temperature in the reactor [79].

Last type of gasifier is the entrained flow reactor, in which the fuel is introduced in powdered form together with the gasification fluid [73].

Table 2 summarizes the different types of gasification reactors currently available.

2.2. Secondary conversion technologies

There are many secondary conversion technologies, some of them more appropriate for direct combustion technology and others for gasification technologies (see Fig. 1). The conversion efficiencies of these technologies vary depending on the technology used and the output scale [80]. In general, however, it can be asserted that the bigger is the output, the higher is the efficiency regardless of the technology.

2.2.1. Internal combustion engine (ICE)

The internal combustion engine is a well-known and well-proven technology, widely used for transportation vehicles but also of relevance in the field of electricity generation, CHP and CCHP. ICEs comprise the Otto engine that works with spark-ignition and the Diesel engine, both requiring a liquid or gaseous fuel which is combusted in an internal combustion chamber. The former is more suitable for small-scale applications while the latter is more appropriate for large-scale ones [81]. ICEs are widely used thanks to their durability, affordability and good performance [82].

Due to their mode of operation, they have better performances with smooth consumption profiles [83]. Otherwise, some storage system can be added to the system to smoothen the consumption profile [84]. In any case, they have been labeled as an efficient solution for small- and micro-scale applications [79] due to low upfront costs and good part-load performance [32,63] so better return on investment rates are achieved at such scales of electricity generation [82].

2.2.2. External combustion engine (Stirling engine)

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

Stirling engines have low maintenance requirements [16] and noise levels [15], especially when compared with the ICE [85]. These benefits, together with their good performance and high thermal efficiency and output [86], especially compared with that of its main competitor Diesel engine [87], at very low output scales make Stirling engines a suitable option for residential dwellings and other micro-scale applications. Their main drawback, however, is precisely their novelty and lack of proven operation for biomass conversion to electricity [88].

2.2.3. Steam engine

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

Table 2
Gasification technologies summary. Personal compilation based on Ciferno and Marano [74].

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

Table 3
Summary of biomass conversion secondary technologies suitable for wood chips conversion. Personal compilation based on Buragohain, Mahanta [14], Monteiro, Moreira [15], Chiaramonti, Oasmaa [61], Henderick and Williams [64], Invernizzi, Iora [94], Larson, Williams [100], Franco and Giannini [113].

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

Steam engines are well-proven technologies, with a high level of maturity. However, their relatively low performance and inability to take advantage of excess heat is driving their current replacement by steam turbines [63].

2.2.4. *Steam turbine (ST)*

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

As the combustion takes place in a boiler before transferring the heat through a heat exchanger to evaporate the working fluid, steam turbines accept all kinds of fuels. In the case of biomass, bark, sawdust, wood chips and pellets can be used [89]. A pre-drying stage is recommendable before the combustion in order to increase the efficiency. Otherwise, the efficiency drop may have great impact [90]. The main advantage of STs is their high time availability [82].

2.2.5. *Organic Rankine cycle (ORC)*

ORCs are a slight variation of steam turbines in which water is replaced as a working fluid by “organic” fluids. Toluene or n-pentane are used as working fluids for high-temperature ORCs with more than 200 kWe of output, thus obtaining high efficiencies and allowing the production of heat. On the other hand, for low-temperature ORCs, those with less than 200–250 kWe of output, lower efficiencies and the impossibility of setting up CHP layouts, the working fluids used are hydrocarbons [88,91]. The low vaporization temperature of these organic fluids makes it possible to set up Rankine cycles with lower temperature than that of the conventional ones, thus enabling the use of low-heating value fuels such as biomass, without lowering the efficiency [92–94]. As they are based on the Rankine cycle, ORCs are appropriate for combustion of solid fuels although the low working temperature make them suitable even for geothermal or solar applications [94,95].

In addition to increased efficiency of the thermodynamic cycle, ORC applications also offer the advantage of reduced blade damage risk [96], good part-load operation [97] and lack of requirement of a pre-heating stage [94], mainly due to decreased vaporization temperature of organic fluids compared with water.

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

GT technology consists on the combustion of previously compressed gaseous fuels in an internal combustion chamber and the subsequent expansion of the combustion gases in a turbine. When a gasification unit, gas cleaning unit and a heat recovery steam generator (HRSG) are integrated together with the GT, the system is called BIGCC [98–100]. BIGCC can also be laid out with a gas engine [101], but the alternative of the GT is the most deployed due to its high exhaust temperatures [82]. Inside the designation of BIGCC, there are many possible combinations depending on the gasification technology or including or not the HRSG [102]. All these conversion pathways require a gaseous fuel to operate.

BIGCC is a high-efficient process [103], especially for large-scale applications, in which BIGCC beats equivalent-size steam turbine [100] and gas engine [104] layouts. Their main drawback is that, since they are based on existing natural gas-based technology, modifications in the fuel handling system are required because syngas yields higher mass flows than natural gas due to its lower heating value. This modification can be an increase in gas pressure or a decrease in gas temperature or de-rating, the most usual alternative, at the turbine inlet [105]. In addition, such GTs are limited to large-scale applications ($>$ 1 MWe). Hence, this technology is not considered in the efficiency comparison section performed in this study.

2.2.7. *Microturbine*

Microturbines are down-scaled versions of GT, being more suitable for small-scale applications. Accordingly, microturbines can be used in places with low biomass production rates such as Mediterranean forests. The electric output of these devices ranges from a few kWe up to 500 kWe [95] although some authors limit this output to 250 kWe [16].

In microturbines, the compressor and the turbine have a solidary shaft, so less maintenance requirements are necessary due to their simplicity [15]. Their performance is quite good even with biomass-based fuels, with which better efficiencies can be achieved than with diesel fuel [81] or than with ICE technology, although being less commercially proven [78].

2.2.8. *Other GT-based designs*

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

The externally-fired GT is a modified version of GT in which the combustion chamber is replaced by a heat exchanger. Therefore, the combustion can take place outside the turbine [106] and thus a cleaner fluid operates the thermodynamic cycle and solid fuels are accepted for the operation besides the gaseous ones [107]. It is usual to add an auxiliary burner of high-LHV fuel, for example, methane, to raise the temperature up to the design point of the turbine inlet [82] operating in a co-firing mode. The turbine cycle can be an open cycle with working fluid discharge or a closed loop with re-usage of the working fluid, thus reducing the maintenance requirements [108].

The evaporative GT consists on a GT layout in which water is vaporized in the air stream before combustion [109] to increase the mass flow [110] and thus the efficiency [111].

Another option is the bottoming cycle, based on the usage of the excess heat to produce more electricity through another steam cycle placed at the exhaust of the GT [95,112], providing an alternative to those situations where heat has no demand.

Finally, another appealing option, especially in terms of efficiency, is the co-firing of biomass fuels with fossil fuels [113–115]. This alternative provides a cost-effective electricity generation process even using biomass with high-moisture content [116]. In particular, biomass has a higher cost on a unit energy basis than coal, meaning that co-firing with coal is worth pursuing from an economic point of view [117]. The co-firing can be done essentially in two ways: with two cycles, the topping one fuelled with fossil fuel and the bottoming one fuelled with biomass; or, conversely, with a single generation cycle fuelled with a mix of fossil and biomass fuels.

2.2.9. R&D alternatives

In addition to the above mentioned commercialized layouts, there are other layouts currently under development. Salomón, Savola [63] mention pulverized-fired GTs and powdered-fuelled ICEs.

Wood-fired ICEs are also studied by [118] who claim that particulates of less than 30 μm can be used to fire a conventional Diesel engine. They claim that the process is feasible but the fuel injection system should be improved to overcome the issue of matching powder feeding and dust cleaning in a continuous operation engine.

Table 3 summarizes the available secondary conversion technologies with a brief summary of their principles of operation.

3. Technology efficiencies comparison

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

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

$$\eta_e = \frac{P_{out}\ (\mathrm{kW_e})}{LHV\ (\mathrm{MJ/kg}) \cdot m\ (\mathrm{kg})}$$

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

$$\eta_e = \frac{P_{out}\ (\mathrm{kW_e}) + H_{out}(\mathrm{kW_{th}})}{LHV\ (\mathrm{MJ/kg}) \cdot m\ (\mathrm{kg})}$$

When looking at the efficiencies of the different available alternatives, it is important to distinguish between the different scales of energy production. Hence, micro-scale technologies, those with less than 50 kWe of output; small-scale technologies, with output between 50 kWe and 1 MWe; and large-scale technologies, with an electrical output greater than 1 MWe, exist [119].

3.1. Current efficiencies of selected technologies

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

In the literature, it can be found efficiencies and other technical characteristics for natural gas fuelled ICE micro-CHP systems, which range between 20% and 31% for electricity generation and between 50% and 90% for cogeneration [15,81,120,121]. Small-scale devices reach a slightly higher efficiencies of 25% and 90% at 100 kWe of power output [86].

Data of actual power generation or CHP plants fuelled with wood chips or similar biomass fuels are of more interest for the present review. Electrical efficiencies of micro-scale plants are between 13% and 25% [76,79,122–127] and total efficiencies between 60% and 74% [124,126]. At small-scale level, slight increases are found: electrical efficiencies are 12.5–28% [56,101,122,123,128,129] and total efficiencies can reach 96% [122]. As expected, large-scale plants perform better. In particular, electrical efficiencies of 25–30% have been proven [101,122] with total efficiencies around 81% [122].

Stirling engines are deployed for smaller applications, namely for micro-and small-scale CHP systems due to their high thermal efficiency even with low electrical efficiencies. In particular, micro-CHP Stirling-based units have electrical efficiencies of 9.2–33% while the total efficiencies range between 65% and 92% [15,16,81,120,130–135]. At small-scale, Stirling engines reach 12–35% of electrical efficiency and 85–90% of total efficiency [86,88]. These figures are supported by Simbolotti [80], who claim that efficiencies are around 11–20% for Stirling engines with less than 100 kWe of electric output. Alanne and Saari [83] provide data for natural gas-fuelled Stirling engines, which reach electrical efficiencies around 25–35% compared with the 15% obtained using syngas at similar scale. Large-scale data is not available for Stirling engines since these devices are only suitable for micro- and small-scale applications whereas they are rapidly beaten at greater sizes.

Data found for steam engines show low efficiencies: at micro-scale, 16% of electrical efficiency is reached [17] and a small-scale CHP system has been proven to reach 10% and 80% of electrical and total efficiencies [30].

More data can be found for STs. In addition, this technology coupled to a combustor is especially suitable for excess heat usage and, together with the high maturity degree have made it the most deployed biomass conversion solution for the last decades. At large-scale, electrical efficiencies can be as low as 15% reaching up to 44% as the output power increases [80,89,90,113,136,137] while total efficiencies are always over 60% [14,89,137]. With micro-scale systems, the electrical efficiency drops to 6–8% [138].

STs are also used with gasification layouts, the efficiencies of such power plants are reported to be 19–36.4% and 80–94%, increasing with the power output [74,77,139].

A better solution for small-scale Rankine cycles is the ORC. With this variation of conventional ST cycle, electrical and total efficiencies of 7.5–13.5% and 60–80% are obtained at micro-scale [88,93], efficiencies that grow up to 7.5–23% and 56–90%

Table 4
Biomass conversion technologies' efficiencies. Personal compilation based on indicated sources.

Power plant	Loc.	Po[a] (kWe)	η_e[b] (%)	η_{tot}[c] (%)	Tech.	Fuel	Ref.
Honda EP 5500 GX340	Brazil	5.5	12.82	N/A	ICE	Wood chips (eucalyptus)	[76]
Naresuan University	Thailand	10	10	N/A	ICE	Wood chips	[123]
GM Corsa Engine	Brazil	15	21.42	51.42	ICE	Wood	[125]
Viking Gasification Plant, Tech University of Denmark	Denmark	18.55	25.1	93	ICE	Wood chips	[79,122]
CTFC	Spain	20	25	74	ICE	Forest residues	[124]
Ford DSG423	USA	28	20.6	N/A	ICE	Red oak wood	[127]
Ford DSG423	USA	28	23	N/A	ICE	Pine wood	[127]
Long Ashton Research Station	UK	30	20	60	ICE	Wood chips	[126]
Suranaree University of Technology	Thailand	100	17.72	N/A	ICE	Wood chips	[123]
BERI project	India	120	18	81	ICE	Wood chips	[155]
Not specified	China	200	12.5	N/A	ICE	Agricultural residues	[128]
Tianyan Ltd	China	200	15	N/A	ICE	Forest and agricultural residues	[101]
Tervola	Finland	470	24	82	ICE	Wood residues	[63]
Harboøre	Denmark	700	28	96	ICE	Wood chips	[122]
Tianyan Ltd	China	1000	16	N/A	ICE	Forest and agricultural residues	[101]
Putian Huaguang Miye Ltd, Fujian Province	China	1000	17	N/A	ICE	Sawdust, rice husk or straw	[129]
Guangzhou Institute of Energy Conversion	China	1000	17	N/A	ICE	Rice husk	[128]
Experimental system	Performance test	2.7	12.3	N/A	Microturbine	Biogas	[150]
University of Science Malaysia (USM)	Malaysia	5	7.82	30.5	Microturbine	Wood	[108]
Capstone 330 (30 kWe)	Performance test	30	26	N/A	Microturbine	Biogas	[81]
ETSU B/U1/00679/00/REP	UK	30	17	80	Microturbine	Wood pellets	[138]
Chinese village trigeneration system	China	75	28	86	Microturbine	Agricultural residues	[64]
Viking Gasification Plant, Tech University of Denmark	Denmark	140	28.1	N/A	Microturbine	Wood chips	[152]
National Technical University of Athens	Greece	225	26.1	70.7	Microturbine	Dry biomass	[153]
Notthingham	UK	1.5	7.5	80	ORC		[93]
Notthingham	UK	2.71	13.5	80	ORC		[93]
Admont, Styria	Austria	400	7.4	48.2	ORC	Wood chips, sawdust	[96]
Lienz CHP plant	Austria	1000	15	104	ORC	Wood chips	[96]
Australian Nat University rural electricity supply syst	Fiji Islands	25	22	N/A	Steam Engine	Sawmill, crop wastes	[17]
Hartberg, Styria	Austria	730	10	80	Steam Engine	Wood chips, bark, sawdust	[30]
Lion Powerblock	manufacturer	2	10.4	94	Steam Turbine	Wood pellets, Natural Gas, Oil	[121]
Kiuruvesi	Finland	900	11	85	Steam Turbine	Bark, sawdust, wood chips	[63]
Karstula	Finland	1000	8	85	Steam Turbine	Bark, sawdust	[63]
Harboøre Varmeværk	Denmark	1000	28	94	Steam Turbine	Wood chips	[74]
Älvkarleby	Sweden	0.8	20	80	Stirling Engine	Wood pellets	[63]
Sunmachine pellet test	Manufacturer	1.38	14.3	72.1	Stirling Engine	Wood pellets	[134]
Sunmachine pellet	Manufacturer	1.5	20	90	Stirling Engine	Wood pellets	[134]
Sunmachine pellet	Manufacturer	3	25	90	Stirling Engine	Wood pellets	[134]
Sunmachine	Manufacturer	3	20.1	90.6	Stirling Engine	Wood pellets	[121]
Sunmachine	Manufacturer	3	20	90	Stirling Engine	Wood pellets	[120]
DISENCO	N/A	3	18.4	92	Stirling Engine	Wood pellets	[121]
Joanneum Research (Institute of Energy Research)	Austria	3.2	23.5	-	Stirling Engine	Wood chips	[133]
Joanneum Research (Institute of Energy Research)	Austria	30	26	-	Stirling Engine	Wood chips	[135]
Technical University of Denmark	Denmark	31	9.2	90	Stirling Engine	Wood chips	[131]
Technical University of Denmark	Denmark	75	11.7	85.9	Stirling Engine	Wood chips	[130]
SOLO161 Stirling	Germany	2	22	92	Stirling Engine	Wood chips	[16]
BAXI Ecogen	Manufacturer	6	13.5	94.6	Stirling Engine	Wood chips	[120]
SOLO161 Stirling	Italy	9	24	96	Stirling Engine	Wood chips	[132]
SOLO161 Stirling	Manufacturer	9	25	97.2	Stirling Engine	Wood chips	[120]

[a] Power output.
[b] Electrical efficiency.
[c] Total efficiency.

for small-scale plants [88,92,93,96,97] and up to 15% and 82–89% for the large-scale ones [140,141].

GTs offer good performance at large scale. In particular, electrical efficiencies between 22% and 50% have been reported for cogeneration plants by several authors [80,89,90,103,142–148]. Total efficiencies are claimed to be about 76–90% also at large scale [89,103,144,146–148].

Microturbines, the small version of GTs, reach electrical efficiencies between 12.3% and 26% for micro-scale units [15,81,149,150] and total efficiencies in the range 62–73% [15,81]. Small-scale microturbines perform slightly better, with electrical efficiencies of 25.2–33% [15,64,81,95,106,149,151–153] and total efficiencies of 62–89% [15,81,153], decreasing with the pressure ratio at levels greater than the optimum and increasing with the temperature at the turbine inlet [152].

The efficiency of externally-fired GTs is claimed to be around 30% for large-scale layouts of several MWe [89,113]. In addition, there are several experiences of externally-fired GTs at micro-scale fuelled with biomass. For example, electrical efficiencies of 15–17% and total efficiencies around 80% have been obtained for a 30 kWe externally-fired micro gas turbine fed with pellets [138,154]. At even smaller sizes, the efficiency drops down to 7.8% as demonstrated for a 5 kWe externally-fired micro gas turbine [108]. Conversely, at small-scale, the electrical efficiencies obtained are 14.6% using pulverized biomass alone and 18.4% using pulverized biomass along with natural gas [106].

Evaporative gas turbines have not been deeply tested nor are found in commercial plants. However, simulations yield electrical efficiencies as great as 45% due to the increased mass flow, so it is a promising technology [109].

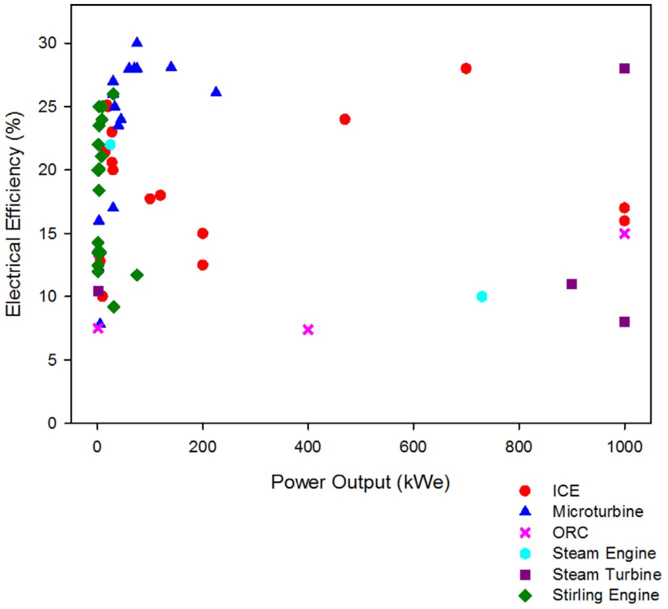

Fig. 2. Electrical efficiencies of biomass conversion technologies. Personal compilation based on indicated sources.

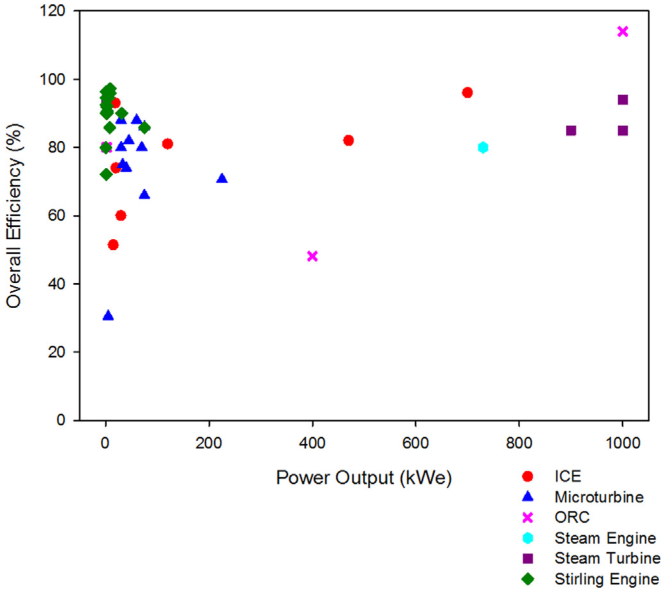

Fig. 3. Total efficiencies of biomass conversion technologies. Personal compilation based on indicated sources.

With co-firing of biomass, better efficiencies can be obtained. However, the two proposed layouts perform different: in a small-scale plant, with the co-firing of biomass and natural gas in a topping cycle electrical efficiencies between 46% and 49.6% are obtained while with a natural gas-fired topping cycle and a biomass-fired bottoming cycle the electrical efficiency is around 38–41%. Nevertheless, it still performs better than a stand-alone biomass plant equivalent in size, which only reaches 35.5% or 38% of electrical efficiency depending of the type of turbine used, ST or GT [114]. The same pattern is also shown in Domenichini, Gasparini [117].

3.2. *Efficiency data and comparison*

Biomass conversion efficiencies have been continuously improving over the past years due to the learning curve effects and upscaling required for advanced applications [67]. However, and especially in recent years, significant efforts have also been made on R&D of small-scale applications that have improved their performance [83] as a result of the growing involvement of governments, mainly in the EU [16].

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

Electrical and total efficiencies of biomass conversion technologies, along with type of fuel, accessed source and power plant output and location, are summarized in Table 4 and plotted in Figs. 2 and 3. As previously mentioned, large-scale plants are not considered in this analysis due to the unsuitability to use these technologies in Mediterranean forests using only locally available resources. This approach leaves out of scope BIGCC layouts, co-firing layouts based on both ST or GT technologies, and most of ST-based plants.

4. Discussion

4.1. *Efficiencies of different technologies*

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

It is also important to remark that the efficiency increases with the power output, showing an asymptotic behavior especially for biomass-to-electricity conversion. At micro-scale, 25–26% is the current technological limit of biomass conversion to electricity efficiency; at small-scale, it increases a bit reaching values close to 30% and at large-scale, efficiencies as great as 45–47% can be obtained for electricity generation. These values are obviously greater when the thermal efficiency is considered: total efficiencies can be greater than 100% at large-scale and even at micro-scale due to the good behavior of Stirling engines and STs at their respective scales and provided that flue-gas condensation is used [63] to cool the working fluid down below its dew point. With this process, heat from the atmospheric air can be recovered thus enhancing the efficiency to values greater than 100% because the efficiency is calculated in relation to energy input from biomass not including the energy stored within the atmospheric air in form of heat.

4.2. Costs of technologies

Other important factors that drive the selection of technology in current power plants are investment, operation and maintenance (O&M) costs. Regarding the investment costs, it is worth mentioning that these conversion technologies are at different developmental and commercial stages, so different cost structures should be expected. Regarding the O&M costs, those technologies involving less moving parts or, in the case of gasification, those that have low tar production rates, require less maintenance than those with rotating components or high tar production rates. Accordingly, those technologies based on direct combustion use to require less investment costs as gasification and gas pre-cleaning stages are not required [107].

This is the reason underlying the fact that the most usual biomass conversion to electricity path is through direct combustion and steam turbine [61]. Although it is not the most efficient technology for electricity production, it requires less investment and O&M costs [60] due to its high maturity and commercial viability [14]. In addition, their high time availability also results in lower costs of electricity produced [156].

In an analogous way, there are differences between the gasification technologies: fixed bed reactors, in particular the downdraft ones due to their low tar content of the produced gas [74,76], require lower investments [75] and engine cleaning operations [14] than fluidized bed reactors. Therefore, fixed bed reactors are the most suitable alternative for small-scale gasification applications [58,101] that are constrained to have low O&M costs [64,157] while fluidized beds have been claimed to be more appropriate for mid- and large-scale applications [58,67,81,101]. However, fixed bed reactors have two major drawbacks: they require a fuel with low-moisture content at the inlet and they drop the gas at high temperature at the outlet [14,74]. In addition, fixed bed reactors produce a low-heating value gas [158], which is only a minor problem in small-scale plants. On the other hand, fluidized bed reactors are constrained to be fuelled with low-size and low-density fuels such as sawdust [58,75], especially in the case of circulating fluidized bed reactors [129].

It is not surprising that ICEs using syngas obtained from biomass gasification are also a commercially viable alternative for biomass conversion to electricity [14] due to the high level of maturity of ICE's technology that lower the investment costs.

This asymmetrical deployment of technologies shows that the cost of the conversion technologies is a driving factor when it comes to the choice of a technology combination and energy source. However, even though biomass conversion technologies are more expensive than those for fossil fuel conversion, the lower price of the fuel may counteract the difference in capital investment [53]. Hence, it is of paramount importance to work in distributed generation schemes that take advantage of local resources to produce electricity and heat, thus reducing the costs associated to transportation of the energy source. For such purpose, wood chips are an interesting alternative because they can be easily obtained on-site, transported and processed with low energy requirements in the entire process. Moreover, it is worth mention that such usage of local wood chips could also have the economic and social benefits associated to wildfires' avoidance and environmental preservation. The consequences of such wildfires are important economic costs and losses to society comparable with those of big catastrophes such as hurricanes derived from fire extinction and damage relief, property losses and tourism affectations [159]; as well environmental damages such as CO_2 release and increased risk of erosion in hilly areas [39], particulates emissions [159] or ecosystems services affectations [160]. Including these avoided costs of wildfires into the economic study of biomass-based conversion technologies, these technologies would have lower electricity generation costs thus being more competitive than they are at present.

5. Conclusions

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

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

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