

Small-Scale Wood-Fuelled CHP Plants: a Comparative Evaluation of the Available Technologies

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Actually, several applications of small (≤ 1 MWe) CHP (Combined Heat and Power) plants fuelled with solid wood can be found in Europe. Innovative technologies are facing the market, giving new perspectives for wood utilisation in district heating and/or in industrial-commercial activities. However, while the energy saving and the environmental benefits of CHP plants are undoubted, technological and no technological barriers still obstacle their large diffusion.

The present study reports a comparative evaluation of the different available technologies in terms of thermal and electric efficiencies and their possible applications. Taking into consideration the electric-thermal performances of each configuration and the actual economic incentives guaranteed by the Italian government, a preliminary estimation of economic convenience of each plant is given.

1. Introduction

In the last few years there has been a lot of interest around small CHP plants (≤ 1 MWe) fuelled with solid wood in the form of woodchip which can be produced from various sources such as clean industrial and commercial wood waste, tree surgery waste and forestry residues (Dong et al., 2009). Innovative technologies are emerging on the market with promising prospects for the near future, giving new perspectives for woody biomass utilisation in district heating and/or in industrial-commercial activities. Moreover, especially in Europe, the opinion that small CHP plants are better suited for production with wood is becoming diffuse since the availability of the fuel is not a serious problem for them as for larger plants and also because it is easier to find an end-user for the heat produced in respect to larger CHP plants. So, wood fuelled small CHP plants are currently considered to be better performing environmentally and socially.

At present several applications of small CHP plants can be found in Europe, especially those based on Gasification and Organic Rankine Cycle (ORC) technology. However, while the energy saving and the environmental benefits of these plants were undoubted, technological obstacles still remained against their large diffusion, because systems with low price and easy-to-use operation for residential end-users are still being under development at the time. Therefore, future introduction of small CHP plants for domestic/commercial applications will depend on the available technology, matching of electrical and thermal loads, and the gas and electricity prices. These economic and technical uncertainties curb the diffusion of small CHP plants at the moment, especially in those countries where not economic incentives are provided for bio-energy.

The present study is focused primarily on the comparison among different technologies currently available on the European market, in terms of electric and thermal efficiencies and possible applications of small CHP plants, fuelled with solid wood. In fact, depending on the technology adopted, the electric efficiency of small CHP plants can differ considerably from one to other. Also the heat produced is not easily comparable since it is available at different temperatures. Moreover, depending on the technology adopted, the overall cost of the plant (thermodynamic plant cost plus civil constructions) can greatly change and so the economical convenience of a particular CHP plant has to be carefully evaluated.

2. CHP plant configurations

Nowadays several small scale wood fuelled CHP plants are proposed in Europe. Some of them are still at the level of prototype (e.g. gasification/micro-turbine, gasification/Stirling engine, combustion/ rotary steam engine) and they will not be analysed in this study. Others (such as gasification/internal combustion engine or combustion combined with steam engine, Stirling engine, ORC or micro-turbine) are commercially available, even if the installations of some of them are still limited. The plants proposed on the market are in general well automated, requiring only periodic controls and a planned maintenance program which changes from one technology to other. The amount of ash produced from these plants varies from one technology to other, but usually falls in the range of 4-5 % of the total woody biomass utilised. In the following sections, the performance of different technologies has been expressed in terms of overall Electric Efficiency (EE), Thermal Efficiency (TE) and average temperature at which the heat is available since thermal energy applications depend on this. EE and TE have been evaluated as follows:

- EE (%) = (gross electric energy produced / utilised biomass energy) x100
- TE (%) = (thermal energy available for cogeneration / utilised biomass energy) x100

2.1 Gasification and Internal Combustion Engine

Gasification is a thermo-chemical process which converts biomass, through partial oxidation, into a fuel gaseous mixture (syngas) consisting mainly of H₂, CO, CH₄, CO₂ and N₂. Biomass gasification in CHP plant has recently received considerable attention for its potential high electrical efficiency compared to conventional combustion unit (François et al., 2012). Yet, a major barrier for the development of biomass gasification plant resides in the presence of tars and inorganic compounds (heavy metals) in the produced syngas, hence gas clean up system is the critical part (technically and economically) of a gasification plant. Commercial small gasification-CHP plants (~ 100 kW_e) consist in a down-draft (fixed bed) design coupled with an ICE (Holzenergie, 2013). Figure 1 shows a typical lay-out of a gasification-CHP plant. Down-draft gasifiers tend to produce low levels of tars, but require more stringent biomass requirements (low humidity, homogeneous chips size). The ICE gives typically an heat to electric output ratio of 2:1, but roughly 50 % of the total heat available must be employed to dry the biomass. Table 1 reports the characteristics of a typical gasification-CHP plant together with the ones of the other CHP plants analyzed hereafter. Thanks to its high EE (> 20 %), gasification tends to be the most promising technology to meet biomass electricity generation needs at around 100 kW_e. Moreover, heat can be made available at different temperatures (from 80 °C of the engine cooling to 500°C of the exhaust gas) giving to gasification-CHP plant an high thermal flexibility.

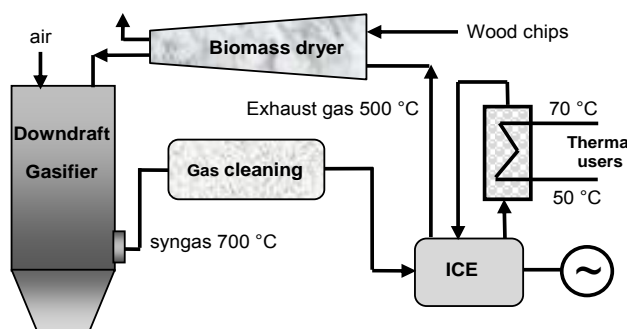


Figure 1: Typical lay-out of a gasification-CHP plant.

2.2 Combustion and Reciprocating Steam Engine

The thermodynamic cycle of a reciprocating steam engine (RSE) is based on the conventional Rankine cycle. The use of small-scale Rankine cycles, characterized by low steam-flow rate, shifts the expander technology from turbomachines towards volumetric machines, since some of the major problems of using turbines as expanders in small-scale applications are their very low efficiency and high production costs (Bidini et al., 1998). Volumetric machines include reciprocating and rotary expanders, but this last solution, which is often based on the Wankel or screw-type engine concept, shows technological difficulties, while RSE results in an easier design and construction (Badami et al., 2009). With the utilization of an appropriate boiler, RSE gives the possibilities to use wood with different humidity (up to 50 %) and different quality, granting an higher fuel flexibility in respect to gasification. Wood-fuelled RSE-CHP plants are available commercially (Spilling Energie Systeme, 2013), with electrical output from 100 kW_e to about 1500 kW_e, offering robust and well proven technology.

Table 1: Main thermodynamic characteristics of wood fuelled CHP plants in the power range of 100 kW_e

characteristic	Gasification	RSE	ORC	SE	EFMGT
Specific biomass consumption (humidity 40 %), kg/kWh _e	1.2-1.7	4-5	2.5-3.5	3.5-4	2.5-3.5
EE, %	~ 25	~ 8	~ 12	~10	~12
TE, %	~ 25	~ 75	~ 70	~ 60	~ 40
Heat temperature available, °C	80-500	100-150	30-80	60-85	40-80
Operation time, h/y	7000	7000-8000	8000	7000	7000-8000
Specific Cost, €/kW _e	3000-5000	5000-6000	5000-7000	6000-8000	6000-7000

The EE, however, tends to be very low in small plants (<300 kW_e) with typical values of ~ 8-10 %, with a thermal to electrical output ratio of 6:1 or greater, depending on the system and size. The exhaust heat at the steam condenser is available, for cogeneration, at temperature ranging from 100 to 150 °C, so not suitable for steam production but still good for some industrial-commercial applications. However, the RSE adopts a "closed cycle" for the working fluid (vapor) and this leads to the presence of a dedicated cooler for steam condensation (air or water type) separated from the heater for cogeneration since the entire exhaust heat is not always absorbed by the final utilizer. This increments the complexity, the internal electric energy demand and the overall cost. In Figure 2-a the typical lay-out of a CHP-RSE plant is shown, while Table 1 reports its main thermodynamic characteristics.

2.3 Combustion and ORC

Among the modern technologies used for decentralized heat and power generation from biomass, ORC (Organic Rankine Cycle) plants are commercially available systems for biomass utilization, which ensure good conversion efficiencies (Strzalka et al., 2010), especially in the electric power range of ≤ 1 MW_e (Quoilin et al., 2013). In fact, at small scales, the classic water Rankine Cycle becomes very inefficient and expensive owing to the high temperatures and pressures required. It is possible to replace water as the working medium with an organic compound with a lower boiling point, such as a silicone oil or organic solvent. This allows the system to work more efficiently at much lower temperatures, pressures and at smaller scale. In a typical ORC biomass combustion device (see Figure 2-b), thermal oil transfers the heat from the combustion chamber into the organic working fluid, therefore, when the efficiency of the system is calculated, also the one of the thermal oil boiler has to be taken into consideration. The preheated working fluid is then evaporated and expanded in a turbine, which drives a generator. The vapor exiting the turbine is finally condensed in a condenser and the waste heat can be used to produce hot water (up to 80 °C) for district heating. Most of the efforts in the literature includes ways of maximizing the efficiency of the thermodynamic cycle for best waste heat recovery. Small biomass ORC-CHP plants are now commercially available from a number of manufacturers (Triogen, 2013). Electrical outputs are typically in the range of 100-160 kW_e (Ingeco, 2013) with thermal to electrical output ratio typically around 5:1. The principal thermodynamic characteristics of a ORC-CHP plant are reported in Table 1. As for the RSE-CHP plant, the utilization of an appropriate biomass furnace guarantees a very high fuel flexibility. However, also in ORC-CHP plants the presence of a dedicated cooler for vapour condensation (air or water type, separated from the heater for cogeneration) is necessary, and this increments the complexity, the internal electric energy demand and the overall cost.

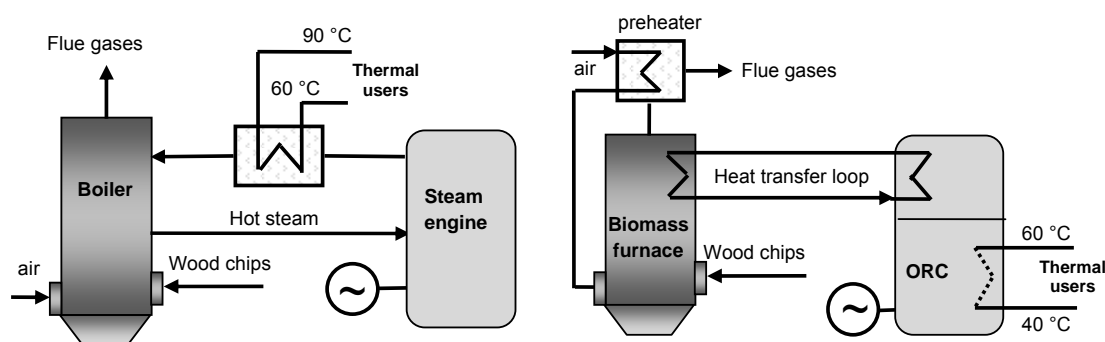


Figure 2: (a-left) Typical RSE-CHP plant lay-out; (b-right) typical ORC-CHP plant lay-out.

2.4 Combustion and Stirling Engine

The Stirling Engine (SE) is an external combustion engine, where the working gas is alternately compressed in a cold cylinder volume and expanded in a hot cylinder volume (Hargreaves, 1991). As for RSE, the SE works with heat from an external heat source (furnaces): hot flue gas from direct combustion of biomass enters the heater of the Stirling engine at high temperature and heat is transferred into the engine. The working temperature of the engine heat exchanger is typically between 700 and 800 °C. In the engine, the heat is converted into work and lower temperature-level heat is rejected in the cooler (see Figure 3-a). This last can be used as the heater for cogeneration with low temperatures (40-60 °C). However, as for the RSE, the SE adopts a "closed cycle" for the working fluid, so it needs the presence of a dedicated cooler separated from the heater for cogeneration. Fouling problems come from the use of biomass fuels and affect the heat exchanger that transfers heat into the engine (Biedermann et al., 2003). Moreover, perfect sealing of the working gas contained into the SE represents another big challenge. All these factors lead to high maintenance costs. This is less well proven, more experimental technology than a conventional ICE, a RSE or an ORC, and, respect to an ICE, a SE tends to be less efficient, with an EE typically in the range of 10-12 % and a TE of roughly 60 %, giving an heat to electricity output ratio of 5:1 or greater. Stirling engines are available commercially with a net electrical output from 35 to about 140 kW_e (Wudag, 2013). Table 1 shows the main technical characteristics of a SE-CHP plant.

2.5 Combustion + Externally Fired Micro Gas Turbine

In the last decades, gas micro-turbines have experienced a very noticeable performance improvement. Among the various configurations, the possibility of combining an externally fired micro gas turbine (EFMGT) with a biomass combustion system appears attractive (Kautz et al., 2007). A simplified scheme of a small EFMGT-CHP plant is shown in Figure 3-b. The biomass feeds the biomass furnace (usually with conventional grate) together with the hot air exiting from the turbine. The high temperature gases produced by the biomass furnace are cooled in the high temperature heat exchanger (HTHE) by heating the compressed air up to the required turbine inlet temperature (up to 950 °C). The hot air exiting from the turbine is used as preheated combustion air for the biomass combustor, while the heat contained in the exhaust gasses from the furnaces can be recovered through a low temperature heat exchanger for hot water production (up to 90 °C). Also in this case, the advantage of combustion on a grate is that a wide variety of biomass fuels may be used. The main thermodynamic characteristics of a EFMGT-CHP are reported in Table 1. Electrical outputs are typically in the range of 75-100 kW_e with thermal to electrical output ratio typically around 3:1 or greater (Spraytech, 2013). The HTHE, which replaces the combustion chamber, is the most critical and expensive component of the overall EFMGT systems. Therefore, the development of the HTHE involves noticeable problems, as the availability of suitable materials for high temperature operation, the long-term reliability of welding and sealing devices, as well as the reduction of construction costs.

3. Technology comparison

The small wood fuelled-CHP plants here analyzed differ considerably from one to the other in respect to the EE, TE and also in the plant lay-out and cost, this last is reported in Table 1 in terms of the Specific Cost (SC), defined as cost per kW_e of the maximum electric power of the plant (€/kW_e). This means that a careful evaluation of the final application has to be done before choosing one technology, especially with regard to the residual thermal energy that can be effectively utilized. It is not easy to define a general strategy. However, starting from data acquired on the market, some useful considerations can be done:

- Downdraft gasification coupled with an ICE, even if gas cleaning and regularity in biomass quality still represent a challenge, seems to be the best choice when the electric energy production is the priority and when the high temperature (up to 500 °C) of exhaust gas is required. Some reliability problems concerning the gasifier and the engine have to be solved as well.
- Combustion with RSE is the oldest and, probably, the most reliable CHP technology. The boiler accepts wood biomass with a wide range of variety and humidity. However, in the range of 100-200 kW_e, the EE is very low and the presence of an additional heat exchanger (cooler), other than the one for cogeneration, represents an additional plant and energetic cost. The TE is the highest among the CHP configurations analysed, and the exhaust heat can be utilised with a temperature up to 150 °C.
- Combustion with ORC shows, even at small scale, an acceptable EE, a good TE and satisfying reliability. As for the RSE, the presence of a furnace with classical grate assures a considerable fuel flexibility. The presence of an additional heat exchanger, other than the one for cogeneration, is necessary. Depending on the organic fluid utilized, hot water up to 80 °C can be produced.

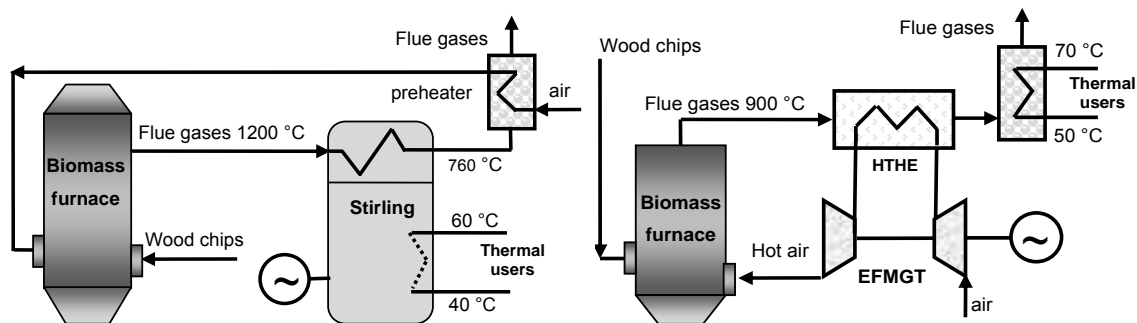


Figure 3: (a-left) Typical Stirling Engine-CHP plant lay-out; (b-right) typical EFMGT-CHP plant lay-out.

- Combustion with SE can represent a good choice for very small scales (35 kW_e). As for the RSE and ORC configurations, the presence of a furnace assures a very good fuel flexibility. However, the EE is not high and fouling problems of the high temperature heat exchanger, as well as the overall reliability, represent a strong limitation for this technology. The presence of an additional cooler is still necessary and hot water for cogeneration can be produced with a temperature up to 85 °C.
- Combustion with EFMGT appears the less promising technology among those analysed. While the presence of an external combustion device guarantees a good fuel flexibility, the reliability of the HTHE represents a big challenge. The EE is in the range of 12-14 % and no additional cooler is necessary other than the one for cogeneration. Hot water up to 80 °C can be obtained.

4. A case study: the Italian economic incentives

At present, the Italian government, with the last "D.M. of July the 6th, 2012", guarantees economic incentives for electric energy produced by biomass fuelled plants. For small plants (< 300 kW_e) the electric energy is remunerated with 0.257 €/kWh, which reaches 0.297 €/kWh in the case of CHP configuration. The incentive time period is 20 y and, still by law, 17 % of the gross electric energy produced is considered absorbed by the auxiliary equipment of the plant.

On the basis of the electric/thermal performances shown in Table 1, a comparison of the economical convenience of the different wood-fuelled CHP plants, varying the plant SC (€/kW_e), can be done using the Net Present Value (NPV) method. All the configurations are compared at the same a gross electric power production of 100 kW_e, which means that, by law, only 83 kW_e can be remunerated. For all the plants, the presence of one operator, 8 hours a day per 220 days/y, is considered, with a gross cost equal to 30000 €/y. For the biomass, which is usually sold with an humidity equal to 40 %, an average cost of 50 €/t was adopted, which is the present average biomass cost in Italy for a private user. The average maintenance cost can be estimated equal to about 0.03 €/kW_e. The parameters used for the NPV calculation are listed in Table 2. Two cases are analyzed (Figure 4): in the first (left) the plant produces only electric energy so the incentive for the electric energy produced is 0.257 €/kWh; in the second (right) the plant works in the CHP configuration, so the incentive reaches 0.297 €/kWh. In the CHP configuration, a realistic 30 % of the total thermal energy produced is supposed sold, at a price of 0.07 €/kWh_t which is roughly 30% lower than one that is paid by an end user utilizing a domestic boiler fueled with natural gas. A tax rate of 40 % is considered for a private owner (end user) of the biomass plant.

Even if the values reported on the graphs of Figure 4 can differ considerably changing the biomass characteristic and cost, the amount of the taxes and the rate of discount, the general trend still remains valid and shows that this kind of application finds its own economic justification only in the CHP configuration. At least in Italy, owing to its higher EE, if the plant specific cost is sufficiently low, gasification + ICE is the only configuration which can guarantee a positive NPV even producing only electric energy; on the contrary, in the CHP configuration, combustion + ORC appears the best choice.

Table 2: Main parameters used in the NPV calculation

parameter	value	parameter	value
Plant net electric power	83 kW	Maintenance costs	0.03 €/kW _e
Biomass LHV (humidity 40%)	10 MJ/kg	Rate of discount	4 %
Biomass cost	50 €/t	Depreciation charge	10 %/y
Cost of the labour	30000 €/y	Taxes	40 %

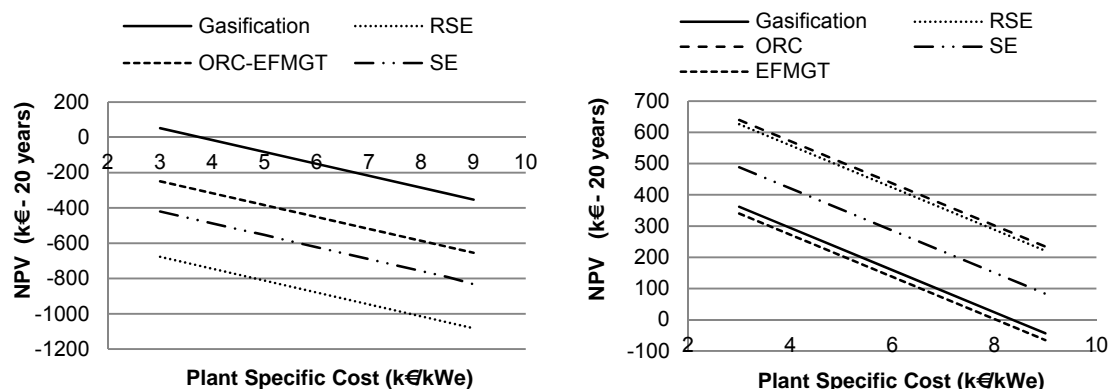


Figure 4: NPV after 20 years producing only electric energy (left) or adopting a CHP configuration (right).

5. Conclusions

At present, several small wood fuelled CHP plants (~ 100 kWe) are proposed on the European market. They differ considerably in terms of EE, TE, plant lay-out and cost. This means that a careful evaluation of the final application has to be done before choosing one technology. The economical convenience of a technology is strictly related also to the possibility to use local economic incentives and to make the maximum use of the thermal energy available for cogeneration. On the basis of the EE and the specific overall cost of the plant, gasification tends to be the most promising technology, especially, to meet biomass electricity generation needs at around 100 kWe. Moreover, gasification + ICE allows the obtainment of an high enthalpy fluid for cogeneration (high pressure steam) which can be utilized in domestic and industrial applications. However, gas clean up and overall reliability still represent the main obstacles in the development of this technology. Instead, taking into consideration the global cogeneration efficiency (EE + TE), combustion with ORC guarantees the highest economic potential, with the advantage, compared to gasification, of being less restrictive on the quality of biomass thanks to the utilization of a furnace in place of a gasifier.

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