Buildings and biomass cogeneration systems: integrated simulation approach

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Abstract

The aim of this work is the energy efficiency assessment of cogeneration systems based on biomass gasification for residential applications, using a multistage modelling approach. The gasification stage has been modelled through an enhanced (i.e., gas-solid) thermodynamic approach using the Cantera solver and the Gri-Mech thermodynamic properties. Several values of temperature and amounts of gasifying agent have been taken into account for the simulations. The efficiency of the whole CHP system has been evaluated supplementing the simulation of the gasification stage with the energy balance of the cogeneration set (i.e., internal combustion engine) and implementing the developed routines in the Matlab-Simulink environment. The CHP plant is considered to supply thermal energy to residential buildings. Dynamic simulations by means of EnergyPlus 7.1 code have been performed considering three main building configurations given by three different thermal resistances for the opaque building envelope. The building-system interactions have been performed for the climate of Milan. Domestic hot water consumption has been chosen in agreement with EN 15316-3-1:2007. The resulting building-system scenarios have been compared with a conventional scenario of separated production by means of PES (primary energy saving). The paper shows the system size range for the chosen residential applications and the optimal operating conditions. The economic return of a such power plant has been discussed. The results of this work confirm the gasification-based CHP technology allows energetic and economic benefits. It can have substantial room for improvement with respect to conventional separated generation systems at the same size.

1. Introduction

Combined heat and power (CHP) production systems based on biomass gasification represent a promising technological solution and a feasible alternative to biomass combustion, especially for small-scale applications. In this perspective, the integration of biomass gasification with high efficiency power generation systems is able to define competitive scenarios even if compared with conventional biomass cogeneration systems. The increase of the systems' efficiency, given by the application of this alternative technology, makes feasible the development of energy models based on distributed cogeneration at sizes that have never been sufficiently efficient until now.

The research concerning the coupling of biomass gasification with traditional power generators (gas engines and gas turbines) and with innovative generation systems (fuel cells) is well documented in the literature (M. Baratieri et al., 2009; Dong et al., 2009; Fagbenle et al., 2007). Besides the development of mathematical models for a given biomass processing systems, the simulation of a complete energy conversion plant is usually carried out through process simulators that offer advantages in the evaluation of the process performance in different operating conditions (Ahmed et al., 2012). The evaluation of the overall system performance still requires further development to assess the technologies integrated in their complete chain (biomass pre-processing, biomass energy conversion, energy distribution, final use).

Micro cogeneration systems based on biomass are not largely diffused in residential applications due to the high price and complex operation for residential end-users (Dong et al., 2009). Systems based on gasification are commercially available for micro generation but the heat production does not match a single apartment (Prando et al., 2012). The aim of this work is the energy efficiency assessment of a micro cogeneration system based on biomass gasification for residential applications. For this purpose a multistage model has been developed and used to assess the balance of plant and its performance.

moisture	ash	C	H	O	N	LHV	Ref.
[%wt$_{ar}$]						[MJ/kg$_{ar}$]	
15.0	1.1	41.2	5.0	37.2	0.4	14.936	(Van Ree et al., 1995)

Table 1 – Characteristics of poplar wood

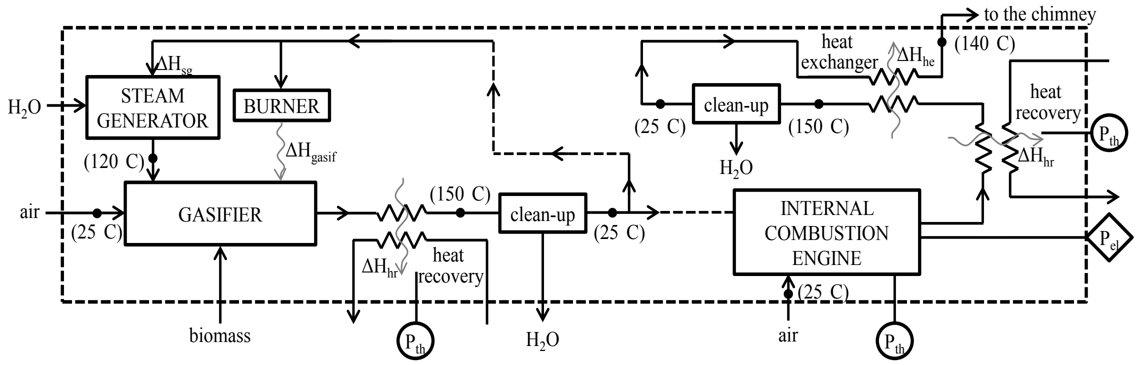

Fig. 1 – Schematic diagram of the power plant layout

2. Material and Methods

2.1 Power plant layout

The power plant layout (Figure 1) consists of the production and use of the syngas to generate electrical and thermal power. The syngas production section has been modelled as a fixed bed air gasifier operating in ideal conditions which can simulate the pyrolysis and air gasification process. The chemical reaction can be endothermic or exothermic depending on the process conditions. For an endothermic process the heat is provided by a burner fed by a syngas spilling. For an exothermic process the heat is supposed to be discharged. The pressure inside the gasifier is considered to be atmospheric. Before feeding the CHP, syngas is piped through heat recovery and clean-up sections. Heat exchangers are assumed to be adiabatic; the syngas is cooled from gasification temperature to 150 °C. This temperature has been chosen to minimize tar condensation that would clog up the heat exchanger. The clean-up section can be considered a condenser where tar and water vapour are condensed and cooled to 25 °C. The heat extracted from the clean-up section is not recovered but lost in the atmosphere. Electricity consumption and pressure losses due to the ancillary equipment and to the filters, respectively, have not been considered.

In this work, poplar wood has been used as feedstock for the gasification process. Its elemental composition, moisture content and heating value have been used as an input of the thermochemical equilibrium model. The characteristics of the feedstock have been reported in Table 1 on "as received" base (ar). Synthesis gas coming from gasification of biomass is used in an internal combustion engine (ICE) based on the Otto cycle. Like the gasifier, also the CHP has been modelled in a MATLAB-SIMULINK environment (M. Baratieri et al., 2009). The exhaust gases from CHP are processed by means of a heat exchanger and clean-up as previously described for the gasification section. Purified exhaust gas is then ready to be heated up to

140 °C through a heat exchanger and sent to the chimney.

The Otto cycle has been implemented in the simulation model in ideal conditions. Process air and synthesis gas are compressed in isentropic conditions according to a specified volume ratio (v1/v2). Then complete combustion occurs at constant volume, followed by an isentropic expansion of exhaust gases and a discharge of exhaust gases at a constant volume. Mechanical power is calculated considering the expansion work reduced by the compression work. The thermal power is considered to be produced by the exhaust gas cooling and the cylinder cooling. The cylinder is assumed to transfer 20% of the heat generated by the combustion to the cooling water. The Otto cycle is optimized in order to operate with gasoline which has different properties with respect to syngas. If compared to gasoline, syngas has a higher auto-ignition temperature, hence it enables the adoption of a higher volumetric ratio for the engine. In this work, volume ratio has been fixed to 15 in agreement with the scientific literature (Porpatham et al., 2012). Electrical power is converted from mechanical power considering an ideal electric generator. Thermal power is recovered by means of adiabatic heat exchangers, from both the gasifier and CHP sections. Electrical and thermal power have been computed to assess the electrical and thermal efficiency that have been calculated respectively as:

$$\eta_{el} = \frac{P_{el}}{LHV_{biom} \cdot Q_{m,biom}} \quad [1]$$

$$\eta_{th} = \frac{P_{th}}{LHV_{biom} \cdot Q_{m,biom}} \quad [2]$$

where LHV_{biom} is the lower heating value of the biomass and $Q_{m,biom}$ is the mass flow rate of biomass, P_{el} is the CHP electrical power and P_{th} is the thermal power recovered from both the gasifier and CHP.

2.2 Characteristics of the buildings

In this work the produced heat is supposed to be provided to four buildings, each one with ten floors. Each floor consists of one flat with the following characteristics: 100 m^2 of floor area without internal partitions, 3 m of internal height. The ratio between the surface area and the volume of the building (S/V) is equal to 0.47. The residential dwelling is supposed to be located in Milan (2404 Heating Degree Days with a base temperature of 20°C).

The vertical surfaces of the envelope are oriented towards the cardinal points. The basement of the building has been considered to be in contact with an unheated basement with high ventilation rate. All the surfaces are light coloured both on the internal and the external sides (absorption coefficient equals to 0.3), with the exception of the internal floor and the external roof (absorption coefficient equals to 0.6). The opaque elements present a simplified two-layer structure with a massive clay block layer with a thermal resistance equal to 0.8 m^2 K W^{-1} on the internal side and an insulating polystyrene layer (thermal conductivity 0.04 W m^{-1} K^{-1}, density 40 kg m^{-3}, specific heat capacity 1470 J kg^{-1} K^{-1}) on the external side. The effect of the thermal bridges has been neglected. The ratio between the area of the glazings and the internal floor is equal to 11.67 %. The windows are double-glazed with a thermal transmittance of the glazing area equals to 1.1 $Wm^{-2}K^{-1}$. The frame area is 19.9% of the whole window area (14.56 m^2) and its thermal transmittance is 1.2 $Wm^{-2}K^{-1}$. The ventilation rate has been fixed in 0.3 ach/h in accordance with the Italian technical standard UNI/TS 11300-1:2008 and the internal gains have been assumed as constant and equal to 4 Wm^{-2}, half radiant and half convective.

Several building configurations have been simulated considering different levels for the characteristics mentioned below. Four thicknesses of the thermal insulation layer have been considered: 0, 5, 10 and 15 cm. The thermal transmittances are respectively: 1.03, 0.45, 0.29 and 0.21 $Wm^{-2}K^{-1}$. The glazing components are supposed to be all in a single façade East oriented or West oriented. Two glazings with different solar heat gain coefficients (0.608 and 0.352) have been considered. Combining the four different opaque structures, the two different glazings and the two orientation of the windows, 16 different cases have been simulated. The simulation of the building's behaviour have been performed by means of EnergyPlus 7.1 (U.S. DoE, 2011) with a time step of 1 minute. The heating air temperature set point has been fixed to 20 °C in accordance with the UNI/TS 11300-1:2008 prescriptions for residential buildings. The building-system dynamic simulations have been performed for three selected configurations of buildings. The thermal insulation of the opaque components has been detected to be the parameter that mainly influences the load profile of the buildings. Therefore, the three selected cases have west-oriented windows with high solar transmittance but different thermal resistance of the opaque envelope (0, 5, 15 cm of thermal insulation).

2.3 Buildings Coupling with the Power Plant

For the building-system analysis, the buildings have been considered to be served by the same power plant (central system). Domestic hot water consumption has been determined in agreement with EN 15316-3-1:2007; it is representative of an average daily tapping pattern for a family with shower use. Heating and domestic hot water system consists of two main parts, the power production unit already presented and the power delivery system presented in this section.

Thermal losses of the delivery section have been considered constant for the whole year in agreement with the technical specification UNI TS 11300-2:2008. The domestic hot water system is characterized by an emission efficiency equals to 0.95 because no devices for the control of the supply are considered in the system. The distribution thermal loss has been considered negligible thanks to the thermal insulation of the distribution pipes. Concerning the heating system, the emission and distribution efficiencies depend on the envelope performance in agreement with the technical specification UNI TS 11300-2:2008. Three values are mentioned below: the first value refers to the building without thermal insulation, the second one to 5 cm of insulation and the third one to 15 cm. The emission efficiency has been considered equal to 0.90/0.93/0.95; it refers to the amount of heat transferred by means of radiators. The control efficiency can be considered the same for the three analysed buildings and equals to 0.94; it refers to an on/off temperature control for each room of the building. The distribution efficiency has been considered equals to 0.97/0.98/0.99; it depends on the insulation distribution of the building.

The experience shows that most of the gasifiers run as much as possible without care to the dissipated heat due to the high interest to the electricity production. Actually, from the economical point of view, there is more interest in the electricity valorisation (comprehensive incentive) than the heat valorisation. Furthermore most of the gasifiers require complex operations to reach the steady state performance hence a partial or on/off operational mode is still considered a future development. In this work the power plant is supposed to run without stops for the whole operational time of the year. The selected operational times are considered to be centred on the coldest day of the reference year. The entire electricity production is given to the electrical grid that can act as an infinite storage facility while only part of the thermal production is useful. When the buildings have no heat demand, heat has to be dissipated. In this perspective, PES (primary energy saving) has been calculated to evaluate the energetic convenience to adopt a cogeneration system instead of the separated production of heat and power. In agreement with the Directive 2004/8/EC (European Parliament, 2004), PES has been calculated as:

$$PES = 1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ \ H\eta} + \frac{CHP\ E\eta}{Ref\ \ E\eta}} \qquad [3]$$

where $CHP\ H\eta$ and $CHP\ E\eta$ are respectively the thermal and electrical efficiencies of the CHP calculated with the simulation model, $Ref\ H\eta$ is the efficiency reference value for separate heat production, $Ref\ E\eta$ is the efficiency reference value for separate electricity production. The efficiency reference values depend on the year of construction of the power plant and on the type of fuel; they have been determined in agreement with Italian law (European Parliament, 2004). Considering the plant construction at the present year and wood as fuel, $Ref\ E\eta$ is 0.3 and $Ref\ H\eta$ is 0.86.

2.4 Economic Analysis

The differential cash flow has been evaluated between the CHP plant and a traditional boiler, both systems have the same thermal power. The payback time (PBT) and the annual worth (AW) have been calculated considering the gasifier as a reference for the lifespan of the whole power plant. Both the economic indexes consider a real interest rate equals to 3 %. The discounted PBT estimates the time required to recover the investment cost and AW estimates the revenue per year of owning and operating an asset over its entire lifespan. Table 2 reports the costs and revenues required to perform the economic analysis. The heat economic valorisation has been calculated considering the natural gas LHV equals to 32.724 MJ/Sm^3 and the natural gas cost for residential use equals to 0.85 €/Sm^3. With the previous hypothesis, thermal power is valorised at 0.094 €/kWh. The cogeneration bonus is paid for the electricity that is produced if the heat is used in the proper way. In particular the cogenerative electricity coming from a cogenerative operation is calculated according to the Directive 2004/8/EC (European Parliament, 2004). The lifespan of the power plant has been considered to be 80 000 hours for the gasifier and 40 000 hours for the engine.

3. Results and Discussion

3.1 Syngas Production Section

The air gasification process has been simulated for different values of gasification temperature and equivalence ratio to define an optimum theoretical condition (Figure 2). The gasification temperature has been evaluated between 500 °C and 1000 °C. The equivalence ratio has been evaluated between 0.0 and 0.6. The optimization has been based on the electrical efficiency. The maximum electrical power has been obtained for a gasification temperature of 800 °C and ER of 0.1. In this configuration the CHP electrical efficiency is 0.23 and the CHP global efficiency is 0.79. The global efficiency has been computed as the sum of the electrical and the thermal efficiency. The optimal configuration corresponds to the complete conversion of carbon. The gasifier uses 26% of the produced syngas to feed the heater that keeps the gasification temperature. A share of 15% of the total thermal power is recovered in the heat recovery section of the gasifier, while a further share of 85% is recovered in the correspondent section of the CHP system.

parameter	value
IC, gasifier + engine [1] [€/kW$_{el}$]	4500
IC, engine [1] [€/kW$_{el}$]	2200
maintenance cost [1] [€/kWh$_{el}$]	0.080
biomass cost [2] [€/kg]	0.133
electricity revenue [3] [€/kW$_{el}$]	0.229
heat valorisation [4,5] [€/kW$_{th}$]	0.094
cogeneration bonus [3] [€/kW$_{el}$]	0.040
real interest rate [%]	3.00

(1)M. Prussi, personal communications, October 2012, C.R.E.A.R. University of Firenze; (2)Agriforenergy n.3/2012; (3)D.lgs 6th July 2012 n. 159; (4)Autorità per l'Energia Elettrica e il Gas, 2011, Relazione annuale sullo stato dei servizi e sull'attività svolta, Milan; (5)Ministry of Economic Development, 2011, Bilancio Energetico Nazionale 2010, Rome.

Table 2 – Parameters for the economic analysis

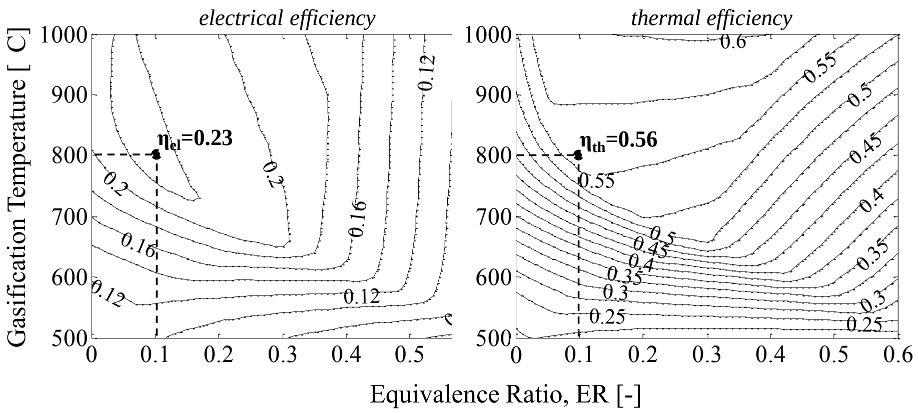

Fig. 2 – Electrical and thermal efficiency of the whole power plant layout

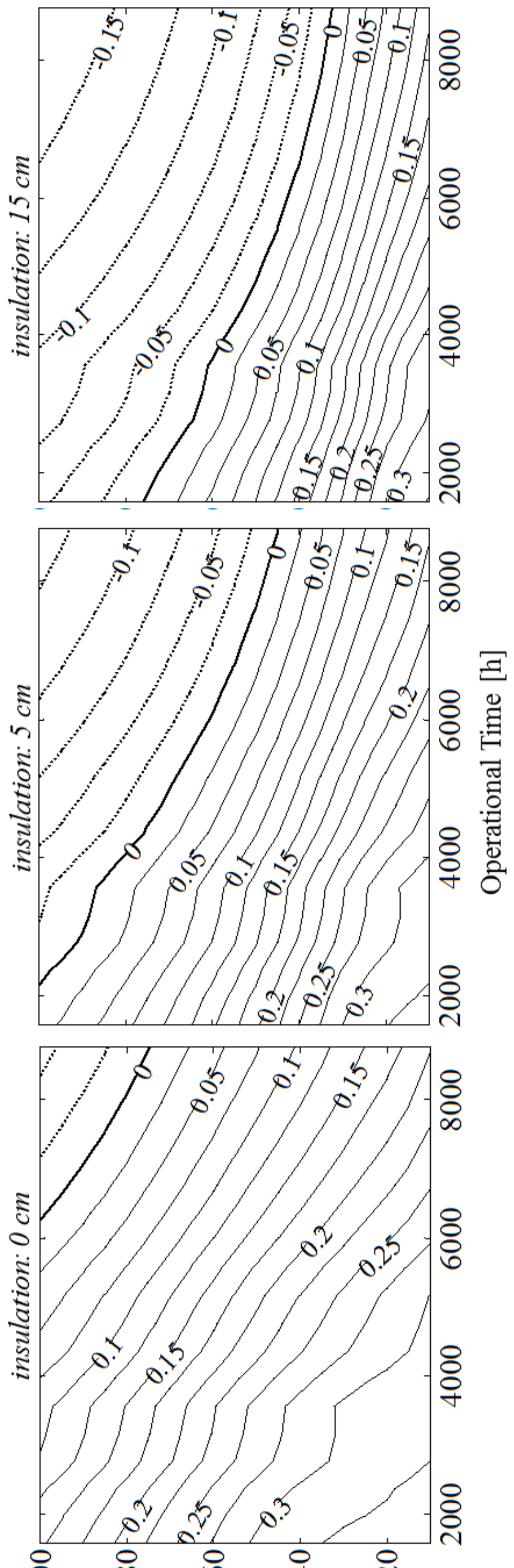

Fig. 3 – PES depending on the power plant size and the operational time for different building configurations

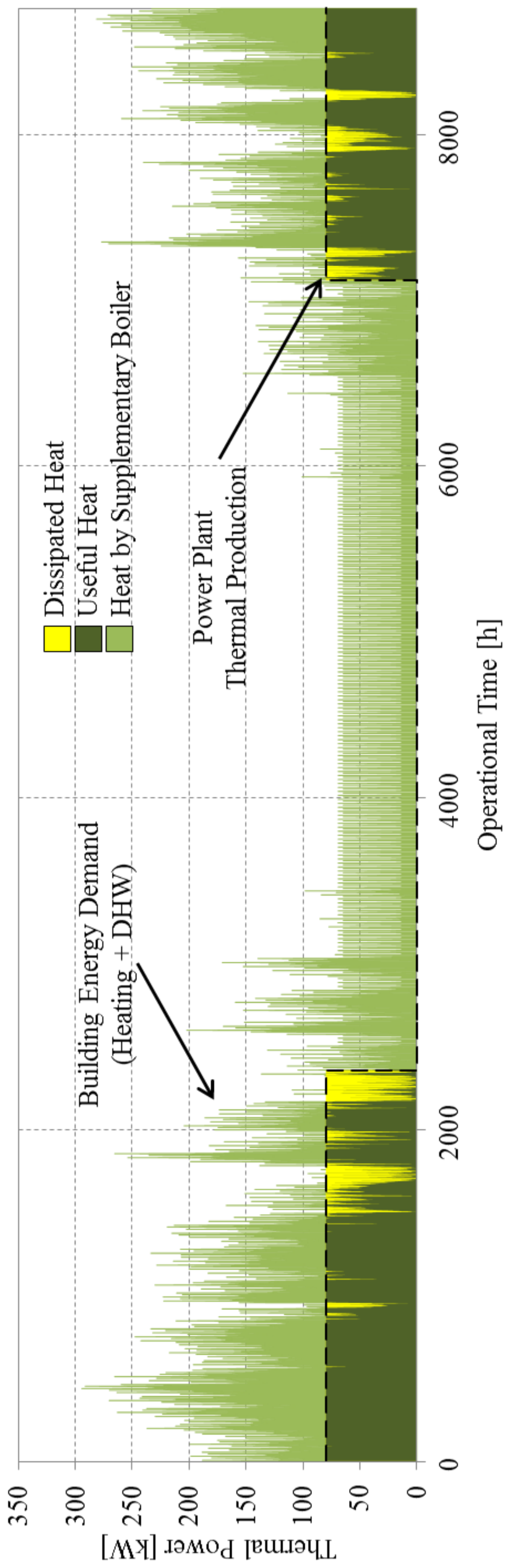

Fig. 4 – Heat demand of the building without envelope insulation and thermal power produced by a power plant of 30 kWel operating for 4000 hours per year

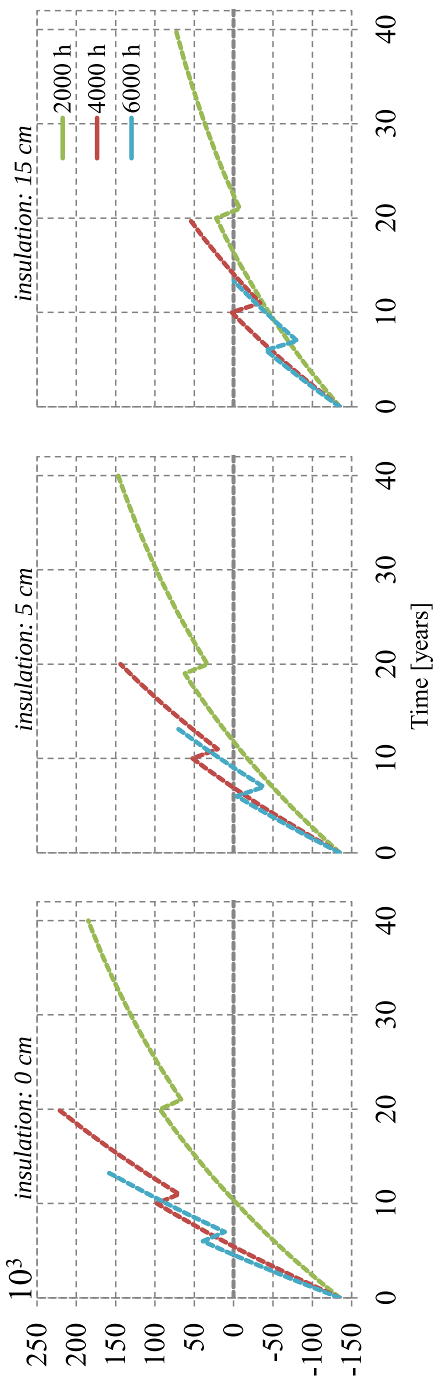

Fig. 5 – Payback time for a 30 kWel power plant, considering different operational times and building configurations

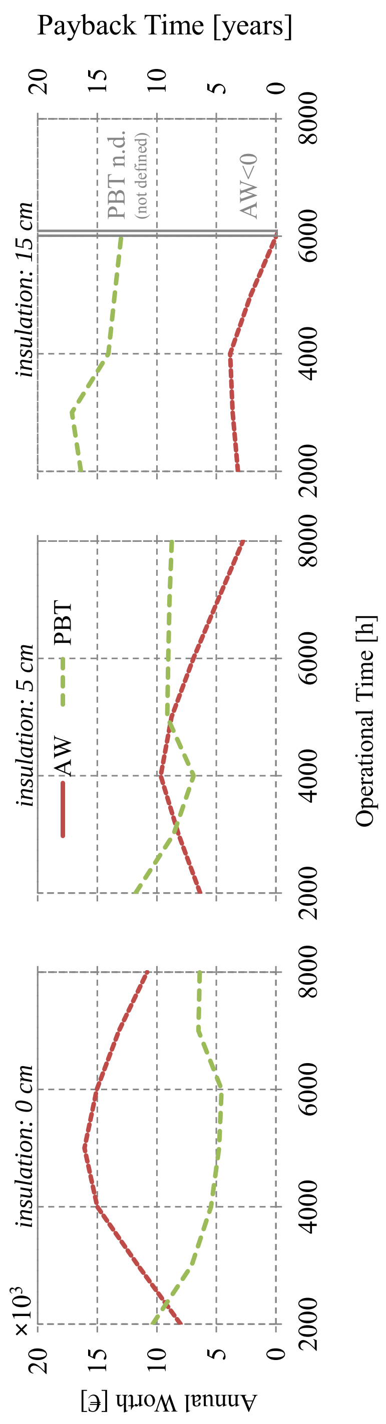

Fig. 6 – Annual Worth (AW) and Payback Time (PBT) for a 30 kWel power plant, considering different operational times and building configurations

Building Configurations:	Insulation: 0 cm	Insulation: 5 cm	Insulation: 15 cm
PES	0.29	0.23	0.15
Disposed Heat	14 %	29 %	46 %
Heat demand covering	52 %	70 %	73 %

Table 3 – Indexes summary for 30 kWel (plant size) and 4000 hours (operational time)

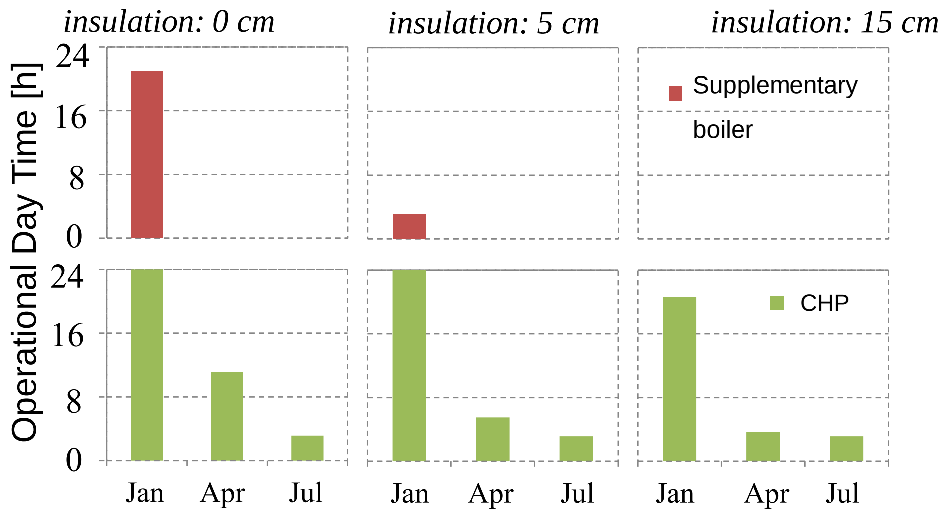

Fig. 7 – Operational time for a 30 kWel (80 kWth) power plant. Three average days (January, April, July) are considered for different building configurations. Supplementary boiler is supposed to be 80 kWth

3.2 Power Plant and Buildings

The primary energy saving (PES) of the power plant layouts is analysed in this section. The index has been calculated for several power plant sizes and operational times in order to trace some performance charts. Figure 3 shows areas of positive values of PES for all the three building configuration solutions. As the index is related to the exploitation of the produced heat, the less heat that is discharged, the larger the PES. Short operational time and small plant size reach higher primary energy saving values, but there are some limitations to consider, such as that no commercial plants smaller than 30 kW_{el} exist. Furthermore, operational times shorter than 4000 hours could lead to a high payback time. Figure 4 shows the thermal load of a building (i.e. building without envelope insulation) and the heat produced by a power plant for the whole year. As previously mentioned, a higher thermal power production could be entirely exploited only during the coolest months. For most of the operational time the produced heat would be discharged. Considering the smallest plant size (30 kW_{el}), Figure 5 shows the discounted cash flow for a power plant of 30 kWel that runs for 2000 h, 4000 h and 6000 h. The economic analysis has been performed for the three analysed building configurations (0/5/15 cm of the envelope insulation) and it confirms what has already been mentioned: power plants operating for 4000 hours have an interesting payback time that becomes less attractive decreasing the operational time. Furthermore, the supplementary boiler would run more frequently decreasing the operational time of the CHP: this means that the global efficiency of the power plant decreases due to the separated production of heat and power.

Figure 6 shows the payback time (PBT) and the annual worth (AW) for the three analysed building configurations. The choice of the optimal operational time could be based on the AW rather than the PBT depending on the optimization target. Considering the AW, the optimal operational time corresponds to 5000 h (16072 €/y) for the building without envelope insulation, 4000 h (9674 €/y) for the building with 5 cm of insulation and 4000 h (3838 €/y) for the building with 15 cm of insulation. Considering the PBT, the optimal operational time corresponds to 6000 h (4.6 y) for the building without envelope insulation, 4000 h (6.9 y) for the building with 5 cm of insulation and 6000 h (13 y) for the building with 15 cm of insulation. Both economic indexes show that the optimal operational times correspond with values between 4000 h and 6000 h for the three building configurations. Some detailed results are shown in Table 3 considering a power plant of 30 kW_{el} and 4000 hours of operational time. PES is greater than zero for the three building configurations. The discharged heat is considerably high for the building with 15 cm of insulation, which means that the power plant size does not match with the application. A better exploitation of heat could be reached increasing the number of users that are served by the power plant but in that case a district heating system is a more realistic approach. Heat demand covering represents the amount of heat demand that is covered by the cogeneration system. The complementary percentage should be provided by a supplementary boiler. A high operation of the supplementary boiler would decrease the global efficiency of the whole system due to the separated production of heat and power. An on/off operational mode seems a possible solution to reduce the wasted heat. In this perspective, Figure 7 shows the operational time of a 30 kW_{el} CHP system for three average days (January, April and July). The graph shows that for the winter months (i.e. January) the supplementary boiler is required to meet the building energy demand. For the summer, the spring and the autumn months the supplementary boiler is not required and an on/off operational mode could decrease the dissipated heat. Nevertheless, a power off followed by a power on in a short time span could lead to an energetic waste considering the energy lost to reach the steady state conditions. In fact the system starts to produce electricity as soon as the syngas meets the chemical composition required by the internal combustion engine. Further development has to be carried out for an exhaustive assessment of the on/off operational mode.

4. Conclusion

The analysed CHP gasifier presents an optimal operation for gasification temperature equals to 800°C and ER equals to 0.1. Electrical efficiency is 0.23 and global efficiency is 0.79. Gasification power plants smaller than 30 kW_{el} are not commercially available. Considering the smallest power plant (30 kW_{el}), the PES is positive for all the building configurations but the economic benefits are more interesting for the building with 5 cm of insulation and even more for the building without insulation. In the latter case the power plant has the lowest heat discharge (14 %) and a high operation of the supplementary boiler. In fact 52 % of the heat demand is provided by the non-cogenerative system, decreasing the global efficiency of the whole system.
Both the annual worth (AW) and the payback time (BPT) show that the optimal operational times correspond with values between 4000 h and 6000 h for the three building configurations.
Further developments of this work foresee the assessment of an on-off operational mode of the gasifier to increase the efficiency of the whole power plant. In fact, this operational mode can be considered as a feasible way to reduce wasted heat, even if a careful assessment of the energy losses - needed to reach the nominal condition - has to be carried out.

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UNI/TS 11300-1 Determinazione del fabbisogno di energia termica dell' edificio per la climatizzazione estiva ed invernale.

UNI/TS 11300-2 Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale e per la produzione di acqua calda sanitaria.