INTERNATIONAL JOURNAL OF HEAT AND TECHNOLOGY

ISSN: 0392-8764
Vol. 35, Special Issue 1, September 2017, pp. S172-S178
DOI: 10.18280/ijht.35Sp0124

A publication of IIETA

IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

http://www.iieta.org/Journals/IJHT

Dynamic behavior investigation of a micro biomass CHP system for residential use

Vania Malaguti, Chiara Lodi, Matteo Sassatelli, Simone Pedrazzi*, Giulio Allesina, Paolo Tartarini

Dept. of Engineering "Enzo Ferrari", Via Vivarelli 10/1, 41125 Modena, Italy

Email: simone.pedrazzi@unimore.it

ABSTRACT

Aim of this work is to define a dynamic model developed in the Trnsys software environment where a biomass boiler and two micro-CHP gasifiers are considered as heat source for a detached house. The selected case study is a detached house of about 240 m^2 near Bologna, Northern Italy, where the HVAC system is currently equipped with a diesel oil boiler with 40 kW of thermal power. The building is connected to a farm and the total electrical consumption is about 13850 kWh/year. The thermal energy demand was calculated and validated in Trnsys using measured diesel oil consumption data. Two different retrofitting solutions for the heating system have been investigated: biomass boiler and micro-CHP gasifiers. Results show the capability to use biomass boiler and micro-scale gasifiers as heat source for the building with a wood consumption of 23 and 86 ton/year respectively. The gasifier electricity production is greater than the electrical demand and an extra energy of 64800 kWh/year is injected into the grid. The cost-benefits economical assessment of these retrofitting solutions is reported considering subsidies for renewable energy production.

Keywords: Gasification, Trnsys, Combined Heat and Power, Dynamic Simulation, Biomass.

1. INTRODUCTION

Wood biomass as heat source for residential building HVAC plants is widely diffused [1]. Low cost and environmental impact reduction in terms of CO_2 balance are the main drivers that facilitate the extensive use of wood feedstocks such as wood logs, chips and pellets [2]. Several studies report the behavior of residential wood stoves and boilers [3], while literature shows few studies about micro-CHP gasifier for residential use [4,5]. On the other hand, micro-scale gasification systems are arising interest due to their economical and sustainability advantages [6-7]. These plants are used as bio-energy investment and they are normally used to produce a constant electrical power for 7500 hour/year [8-10]. Cost and maintenance of these plants is significant and yearly biomass consumption is high in order to achieve faster economical return, with the help of subsidies [11]. Nominal electrical power output of these plants ranges between 45 kW and 1 MW [12].

In general, in gasification power plants the thermal power is taken from the engine coolant and engine exhaust and it is often used to dry the biomass feedstock into rotative dryer or for district heating [13]. Excess heat is high especially in summer when the biomass moisture is lower and this heat is commonly disposed through cooling towers.

In this paper, a further application of biomass gasifiers is presented through this case study: a small-scale gasifier power plant for heat and power production for a residential building located on the hills near Bologna, Northern Italy. The gasifier is a commercial All Power Labs PP20 [14] able to produce about 15 kW of electrical power and 20 kW of thermal power.

The simulations have been carried out using TRNSYS 17 dynamic thermal modeling software [15]. TRNSYS contains dynamic simulation models that allow to accurately evaluate the buildings energy performances. The inputs of such models are normally geographical, geometrical and thermal properties of the case study as well as information about the HVAC system, occupant's behavior and internal gains. Furthermore, TRNSYS integrates large number of sub-systems (called types) with the final aim to understand the effect and the output of the interaction. Sub-systems can describe boilers, renewable energy systems, district heating etc. [15].

The building here presented has a diesel oil boiler as thermal sources. First, a simulation with this fuel solution was done in order to validate the dynamic model. Second, the application of a biomass boiler instead of the diesel oil boiler was simulated. Finally, two micro-CHP gasifiers were evaluated as retrofitting solution. In this case, the electricity production is used by electrical loads in the house and in the farm and the surplus is injected into the grid. Peak thermal power demand to the gasifier results in about 40 kW, requiring the use of two PP20 gasifiers in parallel.

An economical assessment was performed considering the use of wood logs as fuel for the biomass boiler and wood chips as fuel for the for the gasifiers. In the biomass boiler scenario, the return of the investment is guarantee by the cost reduction of the biomass fuel compared to the diesel-oil fuel and the 65% tax deduction applicable for this solution [16]. With gasifiers, the return of the investment is given by the cost reduction of the biomass fuel compared to the diesel-oil fuel, in addition subsidies for the electrical power injected into the grid are taken into account.

2. MATERIAL AND METHODS

2.1 Trnsys dynamic model of the building

The case-study is a typical Italian detached house built in 1975. It is composed by four floors: the basement and the attic are unheated zones while the first and second floors are the location of two independent apartments with central heating system. The building has a total heated usable area of about 239,04 m^2.

External walls are composed by a brick layer, while the floor and ceiling towards unheated zones are non-insulated concrete layers. The windows are all wooden-framed and single glazed. Thickness and thermal transmittance of the envelope components are shown in Table 1.

Table 1. Characteristics of the building envelope components**.**

Component type	Length [m]	[W/(m^{2}K)]
Wall	0.265	1.644
Window	-	5.68
Floor/Ceiling	0.295	1.796

The existing heating system is a conventional hydronic, composed by one diesel-oil boiler and radiators often positioned under the windows. There is a manual regulation; all the heated system has been installed during the construction of the building. The sub-systems performance is shown in Table 2 (the values have been estimated according to UNI TS 11300 [17]).

Table 2. Performance of the subsystems [17]

Subsystems	Thermal efficiency
Emission	η_{em} = 0.88
Distribution	η_{dis} = 0.90
Regulation	η_{reg} = 0.88

The simulations were conducted over the 2015-2016 heating season. The meteorological data used in the simulations are given by Trnsys weather database [15]. The hourly weather data includes horizontal global radiation, dry bulb temperature, wind speed and relative humidity. Monthly billings were used to calibrate the dynamic simulation model of the building.

Internal gains, such as lighting, equipment and occupants have been gathered with audits. This study evaluates the hourly heating power demand of the building $Q_{H,dem}$ [kW] considering the thermal dissipation of the building elements, the thermal power dissipated by ventilation and thermal gains as suggested by UNI TS 11300 standard [17]. The hourly thermal power consumption of the building $Q_{H,con}$ [kW] for the three simulation cases (changing the generation sub-system performance) is evaluated with the following formula:

$$Q_{H,con} = \frac{Q_{H,dem}}{\eta_{gen}\eta_{em}\eta_{dis}\eta_{reg}} \quad (1)$$

where η_{gen} [-] is the nominal efficiency of the thermal generator. This value changes for every simulation depending of manufacturer data.

2.2 Diesel-oil boiler

The diesel-oil boiler is actually used as heat source of the HVAC system. It is an UNICAL EXOCELL 2-41 [18] with a maximum thermal power of 58.1 kW. The nominal thermal efficiency of this machine is about 85%. In the simulation, the lower heating value of the diesel oil is assumed to be 10 kWh/liter and this cost is 0.95 €/liter [19]. Other assumptions are an annual regular maintenance cost of about 300 € and a not-ordinary maintenance cost of about 5% of the boiler cost every 5 years.

2.3 Biomass boiler

The biomass boiler used in this work is a Mescoli GLUP 38 HT LP/200 [20] depicted in Figure 1. It is a reversed flame biomass boiler with 91.3% of thermal efficiency. The biomass is loaded through the front door. It burns high quality wood logs with a maximum length of 0.5 m that have a cost of about 152 €/ton [21]. About 60 kg of wood logs can be loaded in the combustion chamber. About 1% of the inlet biomass becomes ash and it is disposed with a cost of 50 €/ton [21]. This boiler version has also an extra pellets combustor and pellets container of about 200 l. The pellets are burned automatically if wood logs finish to burn. In this paper only wood logs as fuel are considered and the lower heating value of this biomass is set to 4.5 kWh/kg that it is the minimum value suggested by the standard [22]. Assumptions about annual regular maintenance and not-ordinary maintenance cost are similar to the ones chosen for the diesel-oil boiler scenario.

Figure1. Mescoli GLUP 38 HT LP/200 [11]

2.4 Wood chips gasifiers

The gasifier simulated in this work is a PP20 of the Californian company All Power Labs [14]. The plant is showed in Figure 2. It is an Imbert type downdraft gasifier with internal heat recovery. Wood chips are loaded in the hopper that has a volume of about 300 l. The chips are moved to the gasification reactor by an auger and they are converted in wood gas and biochar. About 5% in mass of the inlet biomass is converted into biochar. In this paper, the biochar is disposed with a cost of about 50 €/ton [21]. The wood gas is cooled down and purified in the filter. During this process, a tarry condensate is produced and this need to be disposed as special waste with a cost of and 500 €/ton [21]. The condensate yield is about 2% of the inlet biomass. After the filtration, the wood gas is mixed with air and it is burned into the engine that drags an alternator to produce electrical power. The engine is equipped with a heat exchanger that extracts about 20 kW of thermal power form the engine coolant when the electrical generator produces 15 kW of electrical power. System specification are summarized in Table 3. About biomass fuel, conventional wood chips P16 W10 with a lower heating value of 4.5 kWh/kg are considered [21]. In this case, a regular maintenance cost of 0.03 € every electrical kWh produced is take into account; the not-ordinary maintenance is similar to the other scenarios (5% of the gasifier cost every 5 years of working).

Figure 2. All Power Labs PP20 [10]

Table 3. Specification of the All Power Labs PP20 with CHP auxiliary subsystem

Continuous electrical power rating	15 kW_{el} @50 Hz
Continuous thermal power rating	20 kW_{th} at 15 kW_{el}
Biomass P16 W10 consumption	1.2 kg/ kW_{el}
Biomass moisture content	5-30% dry basis
Electrical efficiency with P16 W10	18.5 %
Thermal efficiency with P16 W10	24.6 %
Installed foot print	1.36 x 1.36 m
Run time with hopper fill	3 hours at 15 kW_{el}

3. RESULTS AND DISCUSSION

3.1 Energy and efficiency results

Figure 1 reports the thermal power demand of the buildings during the standard heating period of 4368 hours from the 15th of October to the 15th of April. The maximum thermal power demand is about 25 kW and the total energy required for heating the building is 60429.2 kWh. This energy needs to be provided through the HVAC system. Results concerning the simulation with diesel oil are summarized in Table 4. Emission, regulation and distribution losses afflict the global thermal energy efficiency that it is about 54%. The maximum thermal power required to the boiler is lower than the nominal thermal power of the diesel-oil boiler. The Trnsys simulation estimates an annual diesel consumption of 11342 liter very similar to the value given by the building owner of 11757 liter. This result validates very well the Trnsys building model.

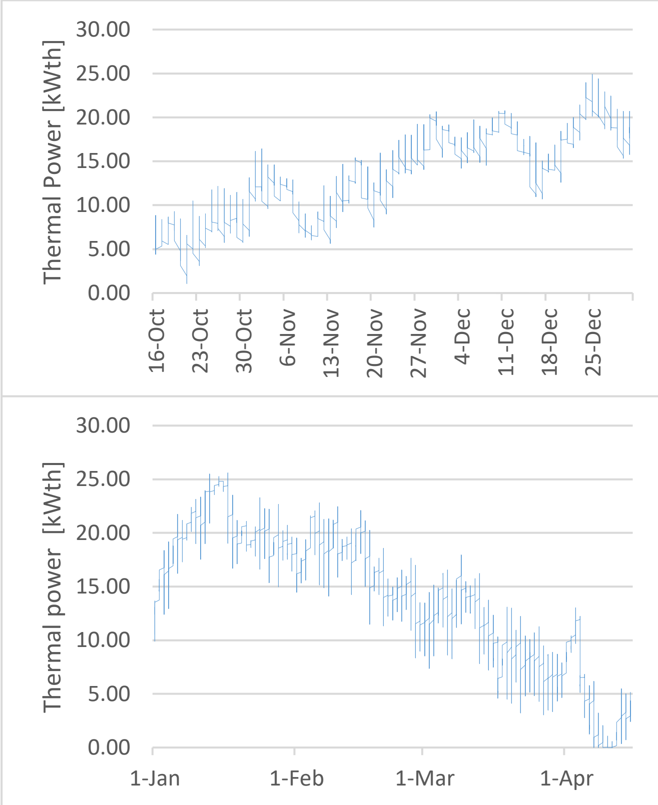

Figure 3. Building thermal power demand during the heating period

Table 4. Simulation results with diesel oil boiler as thermal generator

Global thermal energy efficiency	53.86 %
Maximum boiler thermal power	40.40 kW
Annual boiler energy consumption	112322 kWh
Annual diesel-oil consumption	11342 lt.
Annual diesel-oil cost	10775 €

Results of the simulation with biomass boiler as heat source are reported in Table 5. The global efficiency is 57.80%, this value is higher in comparison to the value obtained using the diesel oil. This is due to the higher biomass boiler thermal efficiency of 91.3% respect diesel oil boiler. Therefore, the maximum boiler thermal power required is 40.4 kW, slightly higher than the nominal thermal power of the biomass thermal boiler of about 38 kW. This difference is low and it can be neglected. About 23 tons of biomass are consumed during this period with a cost of 3532 €. This is about 1/3 of the cost of the diesel-oil.

Table 5. Simulation results with biomass boiler as thermal generator

Global thermal energy efficiency	57.80 %
Maximum boiler thermal power	40.40 kW
Annual boiler energy consumption	104572 kWh
Annual wood logs consumption	23238 kg
Annual wood logs cost	3532 €

The electrical energy consumption is depicted in Figure 4. These data are back calculated using a load curve typical of a residential building [23] and the monthly electrical consumption reported in the invoice of the electrical service company. For every month, a typical daily electrical load was simulated using the method suggested by Caffarelli et al. [23]. In the figure, the minimum, maximum and average daily electrical load is reported for the whole simulation time. The building electrical load is completely covered by the gasifiers. Figure 5 reports the electrical power not self-consumed by the building and injected into the grid. This happens because the gasifiers set-points is heat demand driven and the electrical power consumption is much lower than the thermal power consumption. Anyway, the subsidies for renewable electrical power production are calculated considering the injected electrical power, so high electrical injection increase the revenues of this kind of plant.

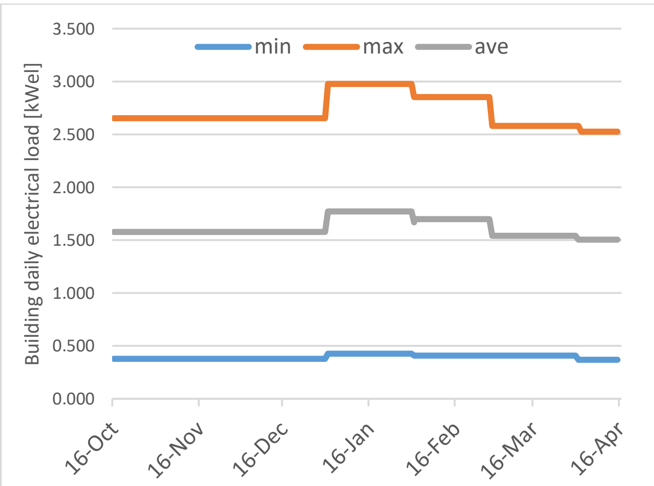

Figure 4. Building daily electrical load during the heating period

Table 6 resumes the results of the simulation with the micro-CHP gasifiers. The global thermal efficiency is low as results of the low thermal efficiency of the gasifier (24.6%). Thermal and power maximum electrical powers are similar to the maximum powers of two gasifiers that work in parallel. The electrical power production is huge (71868 kWh) and 5 times higher than building electrical consumption. This is due by the heat demand driven and by the low thermal efficiency of the machine. In fact, the thermal heat recovery is applied on the engine coolant, the heat of the exhaust it recovered internally in order to pyrolyze the biomass that enters in the reactor. This permits to use biomass with a maximum moisture of 30%.

The annual biomass consumption is greater (about 4 times) than the scenario with the biomass boiler, anyway the specific cost is lower and the fuel feeding annual cost is 2 times the cost of biomass boiler scenario and half the cost of the diesel-oil scenario.

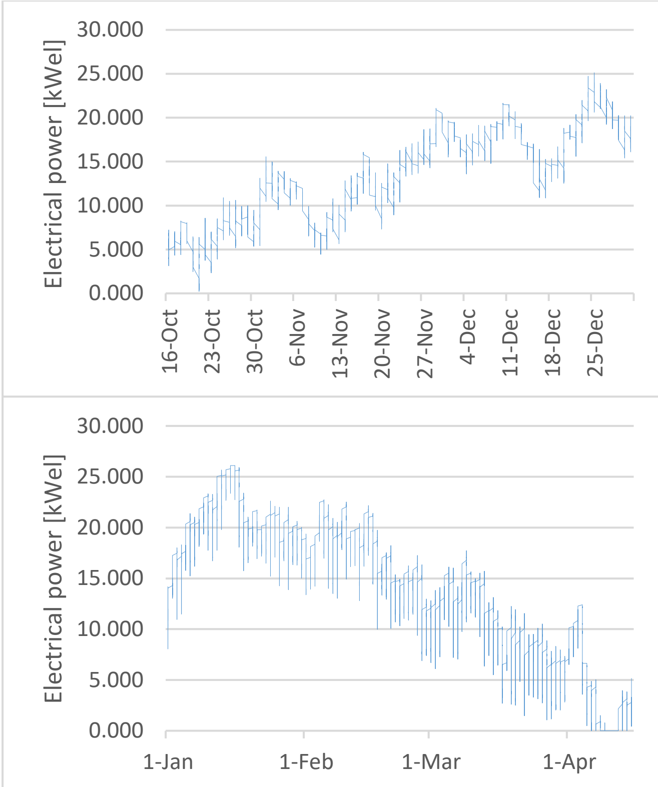

Figure 5. Electrical power injected into the grid

Table 6. Simulation results with micro-CHP gasifiers

Global thermal energy efficiency	15.58 %
Maximum gasifiers thermal power	40.40 kW
Maximum gasifiers electrical power	30.41 kW
Annual gasifier energy consumption	388105 kWh
Annual electrical energy production	71868 kWh
Annual electrical energy self-consumption	7069 kWh
Annual electrical energy injection	64800 kWh
Annual wood chips consumption	86245 kg
Annual wood chips cost	6900 €

3.2 Economical analysis

The study compares the existing diesel boiler system with two retrofitting solution:

Case 1) *Installation of two micro-CHP gasifiers that covers the thermal and electric energy demand and foresee the sale of the electrical energy production excess*. The economic analysis compared two cases: the sale of electrical energy exploiting public subsidies (0.21 €/kWh [11]) and without them (electric price 0.0923 €/kWh [24]). Net present value curves are depicted in Fig. 6-7-8.

Case 2) *Installation of Biomass Boiler*. The economic analysis compared two cases: the benefit with deduction of 65% from initial cost in 10-year time and the benefit without deduction. Net present value curves are depicted in Fig. 9-10-11.

All the analysis is estimated with a discount rate "r" that change between 1% at 5%.

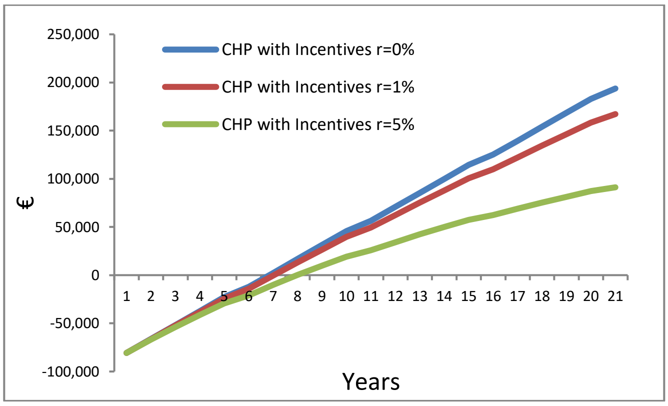

Figure 6. NPV Micro-CHP with subsidies

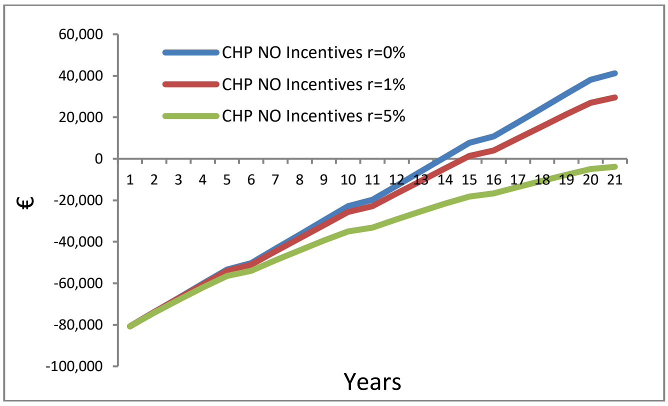

Figure 7. NPV Micro-CHP without subsidies

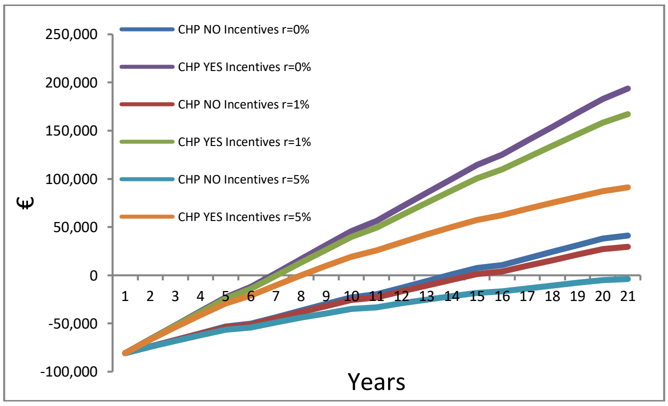

Figure 8. NPV Micro-CHP with/without subsidies

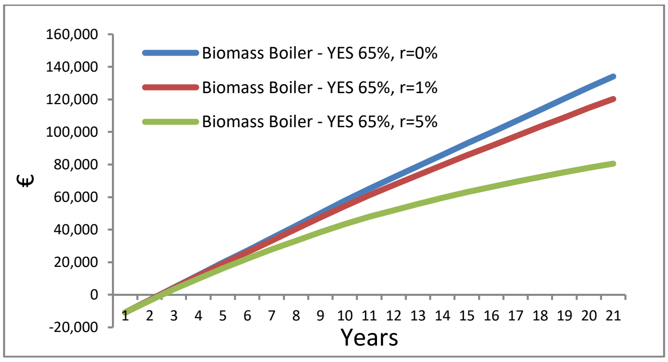

Figure 9. NPV Biomass Boiler with 65% Tax Deduction

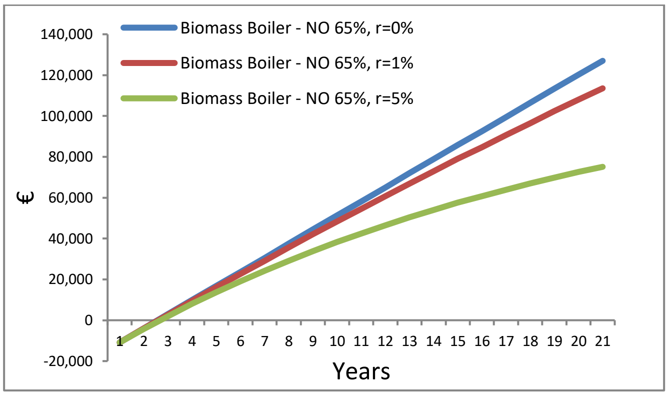

Figure 10. NPV Biomass Boiler without 65% Tax Deduction

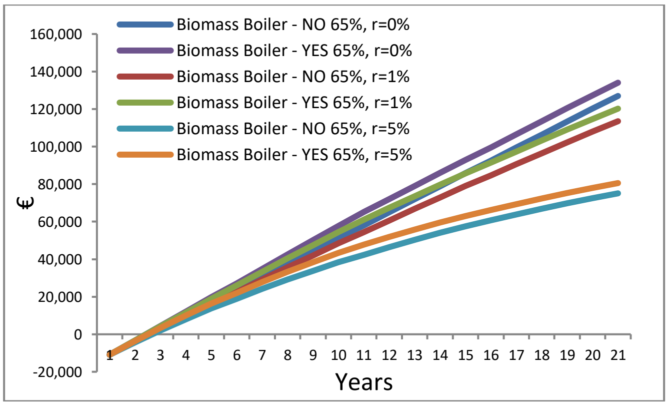

Figure 11. NPV Biomass Boiler with/without Deduction 65%

Table 7. Simulation results with micro-CHP gasifiers

Generator	r=0%	r=1%	r=5%
CHP – YES Inc.	5.84y	6.02y	6.94y
CHP – NO Inc	13.44y	14.3y	>20y
Biomass B.-YES 65%	1.42y	1.44y	1.52y
Biomass B.-NO 65%	1.57y	1.59y	1.59y

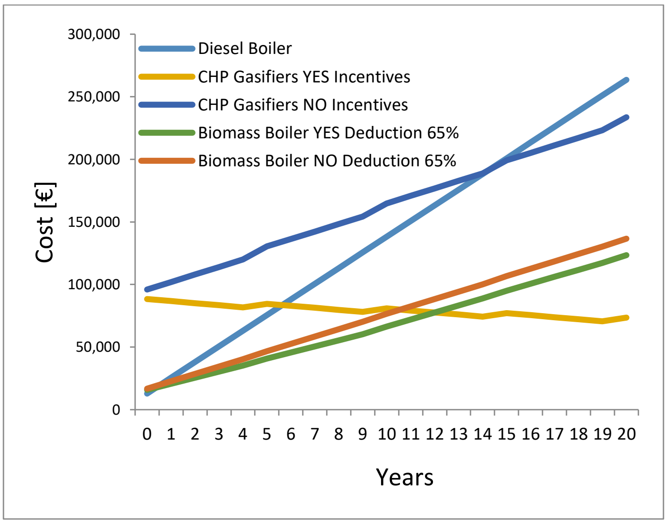

Figure 12. Comparison of cumulative costs trend

Table 7 shows the investments return time (years). Biomass boiler has the faster payback time, therefore the NPV of this solution at 20 years is about 140000 €, lower than the micro-CHP solution that has a NPV at 20 years of about 200000 €.

Figure 12 shows the comparison of cumulative costs trend, in particular the investments return time can be individuated where the line of diesel boiler crosses the other lines.

4. CONCLUSION

The results obtained from this study shows that the replacement of the existing diesel boiler with a biomass boiler is very convenient in the short period compared with the micro-CHP gasifier. In the first case the investments return time is about 1.5 years (considering public subsidies), while using the micro-CHP system it is approximately 6.5 years).

However, in the long period (in this case after 13 year time from installation of the new system of generation), the CHP is more convenient than Biomass Boiler. On the other hand, by using Micro-CHP Gasifier System there is the possibility to gain money from the electricity sales as well as heating the house without any other cost. Both the biomass boiler and the micro-CHP Gasifier system are therefore interesting retrofitting solutions for buildings in locations where natural gas is not available.

REFERENCES

[1] Bilgili F., Koçak E., Bulut Ü., Kuşkaya S. (2017). Can biomass energy be an efficient policy tool for sustainable development, *Renewable and Sustainable Energy Reviews*, Vol. 71, pp. 830-845. DOI: 10.1016/j.rser.2016.12.109

[2] Cutz L., Masera O., Santana D., Faaij A.P.C. (2017). Switching to efficient technologies in traditional biomass intensive countries: The resultant change in emissions, *Energy*, Vol. 126, pp. 513-526. DOI: 10.1016/j.energy.2017.03.025

[3] Saidur R., Abdelaziz E.A., Demirbas A., Hossain M.S., Mekhilef S. (2011). A review on biomass as a fuel for boilers, *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 5, pp. 2262-2289. DOI: 10.1016/j.rser.2011.02.01

[4] Prando D., Patuzzi F., Pernigotto G., Gasparella A., Baratieri M. (2014). Biomass gasification systems for residential application: An integrated simulation approach, *Applied Thermal Engineering*, Vol. 71, No. 1, pp. 152-160. DOI: 10.1016/j.applthermaleng.2014.06.043

[5] Prestipino M., Palomba V., Vasta S., Freni A., Galvagno A. (2016). A simulation tool to evaluate the feasibility of a gasification-I.C.E. system to produce heat and power for industrial applications, *Energy Procedia*, Vol. 101, pp. 1256-1263. DOI: 10.1016/j.egypro.2016.11.141

[6] Allesina G., Pedrazzi S., Sgarbi F., Pompeo E., Roberti C., Cristiano V., Tartarini P. (2015). Approaching sustainable development through energy management, the case of Fongo Tongo, Cameroon, *International Journal of Energy and Environmental Engineering*, Vol. 6, No. 2, pp. 121-127. DOI: 10.1007/s40095-014-0156-7.

[7] Allesina G., Pedrazzi S., Tebianian S., Tartarini P. (2014). Biodiesel and electrical power production through vegetable oil extraction and byproducts gasification: Modeling of the system, *Bioresource Technology*, Vol. 170, pp. 278-285. DOI: 10.1016/j.biortech.2014.08.012

[8] Pedrazzi S., Allesina G., Tartarini P. (2012). Aige conference: A kinetic model for a stratified downdraft gasifier, *International Journal of Heat and Technology*, Vol. 30, No. 1, pp. 41-44.

[9] Allesina G., Pedrazzi S., Tartarini P. (2013). Modeling and investigation of the channeling phenomenon in downdraft stratified gasifiers, *Bioresource Technology*, Vol. 146, pp. 704-712. DOI: 10.1016/j.biortech.2013.07.132

[10] Patuzzi F., Prando D., Vakalis S., Rizzo A.M., Chiaramonti D., Tirler W., Mimmo T., Gasparella A., Baratieri M. (2016). Small-scale biomass gasification CHP systems: Comparative performance assessment and monitoring experiences in South Tyrol (Italy), *Energy*, Vol. 112, No. 1, pp. 285-293. DOI: 10.1016/j.energy.2016.06.077

[11] DM 23 giugno 2016: Incentivazione dell'energia elettrica prodotta da fonti rinnovabili diverse dal fotovoltaico, Ministero dello Sviluppo Economico, Italia.

[12] Basu P. (2013). *Biomass Gasification, Pyrolysis and Torrefaction*, second ed., *Elsevier*, Amsterdam, pp. 249-311.

[13] Wetterlund E., Söderström M. (2010). Biomass gasification in district heating systems – The effect of economic energy policies, *Applied Energy*, Vol. 87, No. 9, pp. 2914-2922. DOI: 10.1016/j.apenergy.2009.11.032

[14] All power labs official website, from www.allpowerlabs.com accessed 28 Mar, 2017.

[15] TRNSYS – transient system simulation tool, version 17 – user manual. (2012). Thermal Energy System Specialists, LLC, Madison, WI.

[16] LEGGE 11 dicembre 2016, No. 232: Finanziaria 2017, Presidente della Repubblica, Italia.

[17] Evaluation of primary Energy need and of system efficiencies for space heating and domestic hot water production. (2008). UNI-TS 11330/2, Rome, Italy.
[18] Unical Unical Exocell 2-41 datasheet, from www.unicalag.it accessed on 28 March 2017.
[19] Cengel Y. (1997). Appendix, introduction to themo dynamics and heat transfer, 1st (Eds.), *Mc Graw-Hill*, New York.
[20] Mescoli GLUP 38 HT LP/200 datasheet, from www.mescolicaldaie.it, accessed on 28 March 2017.
[21] Sassatelli M. (2016). Interventi di efficientamento energetico e produzione d’energia da fonti rinnovabili in complessi agricoli delle comunità montane, M.S. Thesis, Dept. Of Engineering Enzo Ferrari, University of Modena and Reggio Emilia, Modena, Italy.
[22] Pedrazzi S. (2013). Modeling and optimization of advanced systems for electrical energy production from wood biomass, Ph. D. dissertation, Dept. Of Engineering Enzo Ferrari, University of Modena and Reggio Emilia, Modena, Italy.
[23] Biocombustibili solidi, specifiche e classificazione del combustibile - parte 4: Cippato di legno per uso non industriale. (2012). UNI EN 14961-4, Rome, Italy.
[24] Manuale Simulare 12.1. (2017). from www.ingalessandrocaffarelli.com, accessed on 28 March 2017.
[25] Modalità e condizioni tecnico-economiche per il ritiro dell'energia elettrica. (2007). Delibera AEEG n.280/07, Rome, Italy.