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Innovative technological solutions moving towards the realization of a stand-alone biomass boiler with near-zero particulate emissions

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Abstract

The paper describes two innovative technological solutions developed at the University of Bologna and shows a preliminary design on how they can be integrated in a commercial biomass boiler for residential application. The first innovation is a high efficiency and low cost filter for particulate emissions: the first prototype of bubble-column scrubber was tested in University of Bologna laboratory on a 25 kW th and reaches PM2.5 removal efficiency up to 95%. The second innovation is the integration of a thermoelectric generator able to produce electricity directly from heat exchange. A prototype has been realized and tested in University of Bologna laboratory and represents a new approach in the design and application of thermoelectric generator in the field of biomass boiler. The paper will evaluate how these new technologies can be integrated in a residential size biomass boiler from a technological and economic point of view, considering also operation and maintenance costs.

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Keywords: Biomass boiler, PM removal, scrubber, thermoelectric generator.

1. Introduction

Environmental concerns have recently increased the interest in using renewable energy sources (RESs) for the production of thermal and electric energy. In particular, biomass boiler for domestic heating has significantly grown in many countries in the last years. Biomass is considered a RES with a CO_2 neutral balance, which can lead technical, economic and environmental benefits. Nevertheless, biomass boiler spreading has been limited by high particulate matter (PM) emissions and low reliability. The presence of inefficient combustion conditions can lead to

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high PM emissions in biomass boiler plants. Considering that a single small plant produces a low impact, international and national PM emission limits for residential biomass boilers are usually higher than limits for industrial plants, or are not defined at all (i.e. in Italy). On the other hand, small biomass boiler plants density should be taken into consideration since it can really affect air quality [1]. Several PM separation systems are available in the industrial sector, but are not economically sustainable for residential applications. Electrostatic precipitators (ESPs) are one of the most widespread industrial technologies for PM collection. ESPs have a great PM collection efficiency (>95%), but are characterised by high investment and maintenance costs [2]. A more suitable solution for non-industrial applications is the wet scrubber [3]. PM collection efficiency can be greater than 99% with limited costs. Therefore, several prototypes of wet scrubber were tested at the University of Bologna laboratory on a 25 kW th biomass boiler [4]. The highest PM2.5 removal efficiency (about 95%) was reached with a combined Venturi-bubble column scrubber, which consists of the combination of a high pressure pump and a water column. The integration aims to maximize the mixing between flue gas and water. An optimized configuration of wet scrubber is under development in order to reach 99.9% collection efficiency with low specific energy consumption, suitable for domestic applications [5].

Biomass boiler can be integrated with a thermoelectric generator (TEG), which produces electric power from the heat exchange between a hot and a cold surface (Seebeck effect) [6]. The integration aims to increase biomass boiler reliability, since the boiler can produce itself the electric energy needed, thus working also in the event of power failure or sudden stop. The integration with TEG can lead a biomass boiler to become a stand-alone heating system, which can work also in regions where the electric grid is not present or with high connection costs, having a positive effect also on end-user safety [7]. On the other hand, commercial TEGs conversion efficiency (under 5%) and relative high investment have limited the application of TEGs. A wide literature exists about TEGs integration with biomass boiler [8,9]. A TEG prototype has been realized and tested at the University of Bologna laboratory, investigating the nature of the heat exchange between the TE modules and the heat source [10,11], aiming to reach the highest performance of TE modules. The prototype represents an innovative approach in the design and application of TEG in the field of biomass boiler and, after a more detailed cost-benefit analysis, it will be possible to identify the parameter that make the initial investment profitable [12].

The paper shows the integration of two innovative technologies, a wet scrubber and a TEG, both developed by the University of Bologna, on a residential size biomass boiler. A techno-economic assessment and the effective marketability of the two technologies will be deeply analysed, considering investment, energy and maintenance costs, and comparing these new technologies with commercial technologies currently applied in residential sector.

2. Materials and Methods

A typical economic assessment of a technology for electric energy production can be carried out considering the Levelized Cost Of Energy (LCOE) method. The LCOE, measured in €/kWh el, is the ratio between the sum of actualized investment and of operation and maintenance costs with the actualized electric energy produced during a certain technology system life. The LCOE is applied in the paper for the economic analysis of TEG and comparison with other electric energy production systems. A similar parameter has been defined for the comparison of different PM separation systems, wherein the denominator is not the produced electric energy, but the filtered PM, measured in grams, in a certain time interval. This parameter has been defined as "Levelized Cost of Filtration" (LCOF), measured in €/g of filtered PM. The two parameters introduced are defined as in Eq. 1:

$$LCOE/LCOF = \frac{I_0+\sum_{t=1}^{n}\left[C_t^M\cdot(1+e+r_M)^t+C_t^{Energy}\cdot\left(1+e+r_{Energy}\right)^t\right]/(1+i)^t}{\sum_{t=0}^{n}P_t^y/(1+i)^t} \quad (1)$$

where I_0 is the investment cost, C_t^M and $C_t^{Eneregy}$ are, respectively, the operation and maintenance costs and the energy costs evaluated in the t-th year, and P_t^y is the yearly output produced by the system, which is electric energy in the case of LCOE and the quantity of filtered PM in the case of LCOF. Table 1 shows the description and the value of the macroeconomic parameters of the LCOE and LCOF methods, which allow the actualization of the costs.

Table 1. Value of macroeconomic parameters for the LCOE/LCOF indicator.

Parameter	Description	Value
n	Evaluation period, equal to system life [years]	15
i	Discount rate [%]	2.5
e	Yearly inflation rate [%]	1
r_M	Yearly O&M costs escalation rate [%]	1
r_{Energy}	Yearly energy cost escalation rate [%]	1

The two newly technologies are compared with commercial alternatives through the LCOE and the LCOF methods. In particular, TEG LCOE value is compared with the typical LCOE of off-grid applications with photovoltaic and micro-wind generators. Finally, the wet scrubber is compared with a residential ESP through the LCOF method.

2.1 LCOE Calculation

A schematic of the integration of a biomass boiler with a TEG is shown in Fig. 1. The innovative TEG developed by the University of Bologna [11] aims to reach the performances of the TE modules supplied by the manufacturer by realizing the direct contact between the modules surface and the heat transfer fluids. Moreover, the innovative TEG allows the interface of the hot side of the modules with a condensing fluid to reach the best temperature uniformity on the modules array. In particular, glycerol triacetate has been chosen as hot fluid. The system is composed mainly by three subassemblies [11]: i) the TE modules subassembly, which is composed by 2 solid frames and 25 TE modules and guarantees hydraulic and electric insulation between cold and hot side, ii) the cooling system, which uses and pre-heats the water of the boiler, provided by 25 cone flow nozzle, and iii) the evaporator, which heats up and evaporates the glycerol triacetate utilizing the heat of the flue gas from the biomass combustion. The TEG shall produce nearly 17 W el for each TE module with a temperature difference of about 180°C from cold to hot sides, and the water is pre-heated by 0.4 kW th before biomass boiler inlet. Consequently, 25 TE modules produce about 0.5 kW el and the TEG occupies a total occupied volume of about 500x500x500 mm.

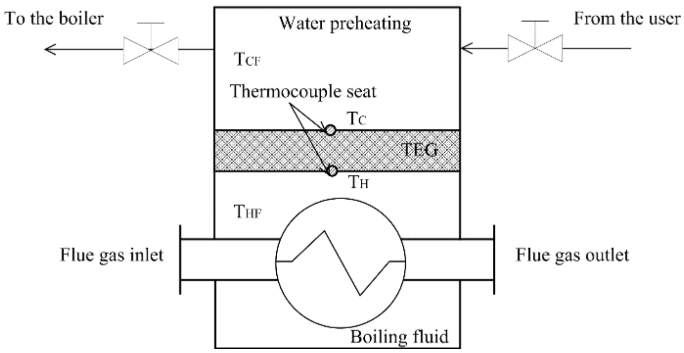

Fig. 1 - Schematic of the innovative TE device.

The investment cost for the realization of the innovative TEG device has been estimated on the basis of prototype costs [5] and is equal to 8600€, being the main cost (70%) made by TE modules and heating/cooling heat exchangers. Possible cost reduction due to scale economy was not considered. The annual maintenance costs of the TEG has been estimated in about 185 €/year and was computed [5] by considering the substitution of 2 thermoelectric modules every five years and the refilling of the evaporator with 1 liter of glycerol triacetate every year. The TEG works in a cogeneration mode, in fact the hot flue gas supplies heat power to the TEG, which produce an electric output and pre-heats the boiler water. Consequently, the energy consumption of the TEG is related to the biomass consumption to produce the 0.5 kW th that the TEG converts into electricity, and are not available as thermal energy. Consequently, the annual energy costs can be evaluated as in Eq. 2:

$$C_t^{Energy} = \frac{P_{el}}{\eta_{Boiler_{YA}} * LHV_{Pellet}} * h * 3600 * c_{Pellet} \tag{2}$$

where the main parameters are reported in Table 2.

Table 2. Main parameter for the calculation of the energy cost of the TEG.

Parameter	Description	Value
Pel [W]	Heat power effectively converted into electricity	500
ηBoilerYA [%]	Seasonal biomass boiler efficiency	75
LHVPellet [J/kg]	Biomass lower heating value	$18.72 \cdot 10^6$
h [hours/year]	Yearly number of utilization hours	2200
cPellet [€/kg]	Pellet cost	0.29

2.2 LCOF Calculation

A new configuration of wet scrubber was designed to obtain a PM removal efficiency greater than 99%, with low specific energy consumption [5]. Removal efficiency is defined as in Eq. 3:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \cdot 100 \quad (3)$$

where C_{in} is the PM mass concentration at the inlet of the filtration system, while C_{out} is the PM mass concentration at the separation system outlet, evaluated in mg/Nm^3, considering NTP conditions (273.15 K, 101.325 kPa) and an oxygen content of 11%. The designed wet scrubber consists of a plexiglas cylindrical tower with a diameter of 0.24 m and a height of 1 m, in which the flue gas passes through a water spray, generated by 40 nebulizers, and is conducted to the chimney by 2 fans. The total water flow is 2 l/min, provided with a pump which guarantees a pressure of 80 bar to generate droplet with a SMD (Sauter Mean Diameter) of 15 µm (Fig. 1). The discharge water has to be filtered since the small diameter of the nebulizers could clog. A prototype has been realized at the University of Bologna laboratory and soon it will be tested with the flue gas produced by a 25 kW th biomass boiler, fed by flint corn, to verify the correspondence between computed (estimated at 99% with a consolidated mathematical model) and real PM collection efficiency.

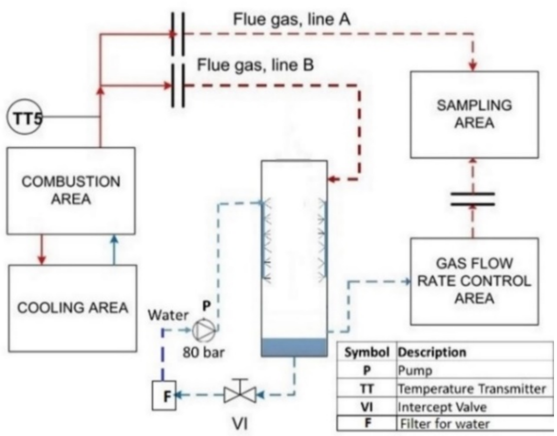

Fig. 2 – Process Flow Diagram (PFD) of the innovative wet scrubber developed by the University of Bologna.

The filter schematized in Figure 2 is compared to the ESP-Carola filter, which is a patented solution designed for domestic heating systems and that is already been used in several application [13]. The ESP was tested on a wood pellet boiler of 20 kW th and reached a PM separation efficiency of 82%.

For a proper comparison, a first assumption is that both the technologies are installed on the same plant. The reference plant has been identified in a domestic wood pellet-fired boiler with a thermal capacity of 22 kW th, for which the PM emissions have been quantify and characterized morphologically and chemically and are available in literature [14]. The main characteristic of the boiler, the generated flue gas and PM emissions are summarized in Table 3. Secondly, it is necessary that the two technologies reach the same efficiency. The estimated PM collection efficiency of the new wet scrubber (99%) is used as reference value. Regarding the ESP, since it does not reach the efficiency of the wet scrubber, it is assumed to install in series two ESPs in order to collect the same quantity of PM as for the wet scrubber.

Table 3. Biomass boiler main data.

Thermal capacity	22 kW th	Flue gas flow rate	70 Nm^3/h
Fuel	Wood pellet	Flue gas O_2 content	15.9%
Thermal input by users	18.4 kW th	Flue gas temperature	186.9°C
Pellets feed rate	3.86 kg/h	PM emissions (13% O_2)	180 mg/Nm^3

With the previous assumptions it is possible to evaluate the costs of two different technologies by considering the same performance in terms of PM collection. The investment costs of the wet scrubber and of the ESP consist of four main parts: the structure of the filter, the flue gas line, the water circuit (if present) and the instrumentation. Wet scrubber cost for the realization has been estimated on the basis of prototype costs [5]. ESP cost estimation results as more complex: the cost of the structure was evaluated in [15], but the technology needs to be adapted to residential applications, and so some arrangements to guarantee system control and safety have to be considered [13]. Table 4 shows the investment costs for the realization of the two technologies, including also installation costs. Since it is necessary to install two identical ESP-Carola to reach an efficiency of 99%, the investment costs must be doubled for ESP LCOF evaluation.

The energy and maintenance costs are evaluated for the two filtration technologies. The total power consumption of the wet scrubber is about 330 W (250 W for the water pump and 80 W for the two fans) [4]. Considering 2200 annual utilization hours of the boiler and a mean cost of electric energy of 0.20 €/kWh (representative of Italian electric energy cost for residential users), the annual cost of energy can be calculated. The maintenance costs of the wet scrubber consider that every year the wastewater filter is replaced and the wastewater is disposed. These operations require the intervention of a technical operator. It is also considered that the water pump is replaced every 5 years. For the two ESPs it is assumed that ESPs auxiliaries consume 250 W and a regular operator intervention is required (for a total of 4 interventions/year) to guarantee the ESPs cleaning and safety, replacement of wear components and ash disposal. Table 5 shows the comparison between energy and maintenance costs of the wet scrubber and two ESPs-Carola.

Table 4. Investment costs for the innovative wet scrubber [5] and the ESP-Carola [13, 15].

Item of investment costs	N° 1 wet scrubber	Cost (€)	N° 2 ESP	Cost (€)
Structure	Plexiglas, grids, intercept valve	114	Electrodes, tension transformer, rectifier, motor and brush	2400
Flue gas line	Pipe and 2 fans	400	Pipe, fan and plant modifications	820
Water circuit	Water pump, wastewater filter and treatment, pipe	956	-	-
Instrumentation	Flue gas flow rate and pressure transmitters	115	Control and safety system and electric panel	1300
Installation	16 h	400	16 h + 16 h (electric panel)	1600
Total (€)		1985		6120

Table 5. Energy and maintenance costs for the new wet scrubber and the ESP-Carola.

Item of energy and maintenance costs	N° 1 wet scrubber	Annual cost (€/year)	N° 2 ESP	Annual cost (€/year)
Energy consumption	726 kWh/year (for water pump and 2 fans)	145	550 kWh/year (for electrodes, fan, motor and electric panel)	110
Maintenance	Wastewater filter and disposal, pump, operator	245	Brush, motor, ash disposal, operator	995
Total		390		1105

3. Results and discussion

3.1 TEG: LCOE and sensitivity analysis

The LCOE of the innovative TEG system described before has been computed in about 0.92 €/kWh el. This value is higher than the LCOE of PV generator, which is in the range 0.08-0.32 €/kWh for European countries [16]. Typical plants for off-grid application with PV need battery and CHP. An example of off-grid CHP plant in literature is composed by 8 kW PV panels, 1 kW CHP module and 1199 Ah deep-cycles batteries, and the whole system has a LCOE of about 0.20-0.31 €/kWh [17]. The LCOE of the TEG system is not too far from the LCOE of a wind generator. For example, a 2.4 kW three blades wind generator (Skystream 3.7) presents LCOE values of 0.29-0.96 €/kWh in function of the wind velocity [18].

So, the innovative TEG has to be optimized from a technological and economical point of view. Its investment cost is referred to the prototype and can be significantly reduced with the production scale effect. Another fundamental parameter that can reduce significantly the LCOE is the hours of operation: in fact, LCOE decreases by increasing the hours of TEG utilization. The effects of several parameters (including pellet LHV, pellet price and TEG efficiency) are investigated with a sensitivity analysis, as shown in Fig. 3.

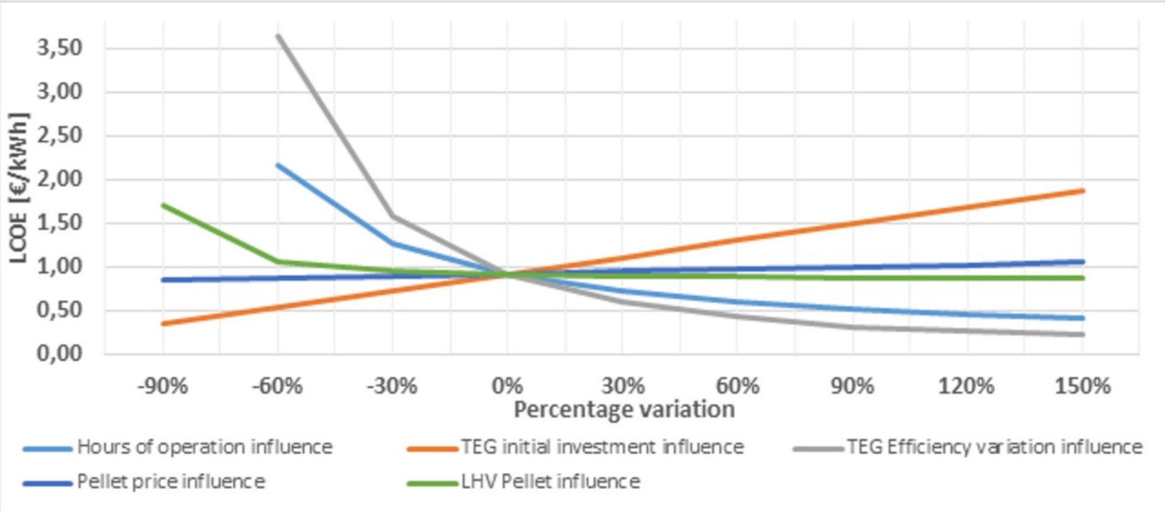

Fig. 3 -Impact of hours of yearly operation, TEG initial investment, TEG efficiency, pellet price and LHV on TEG LCOE.

The results indicate that the most influential parameters on TEG LCOE are the hours of operation, the TEG efficiency and the TEG initial investment. The pellet price and LHV do not significantly affect LCOE value. Consequently, some requirements have to be satisfied to obtain a TEG LCOE comparable with the state-of-the-art off-grid plants. In particular, the cost of investment has to be the 50% or less of the actual cost (considering a possible scale effect) and the hours of operations have to be the 30% or more (> 2800 h/year) of the actual value (typical of norther or cold sites): through this combination the LCOE of the TEG would reach a value of about 0.43 €/kWh el. Moreover, by adding a TEG efficiency 30% or higher than the current values (i.e. though the application of innovative materials or hybrid TE modules), the LCOE would be lower than 0.30 €/kWh, which a sustainable cost.

3.1 PM separation device: LCOF and sensitivity analysis

The LCOF can be evaluated over 15 years by considering the investment, energy and maintenance costs previously estimated. The results show that the LCOF for the new wet scrubber is about 0.02 €/g of removed PM, while the LCOF of two ESP in series is about 0.07 €/g of removed PM. Moreover, a sensitivity analysis has been carried on to verify the effect of some parameters on the scrubber LCOF value. The main parameters which influence the LCOF of the scrubber are the utilization time of the boiler, the investment cost and the energy consumption (Fig. 4). In particular, the LCOF of the scrubber slightly increases with the investment costs: if an investment cost variation from -90% to +150% is considered with respect to the estimated cost of about 2000 €, the LCOF should vary less than ±0.01 €/g PM. Consequently, even if investment costs could increase during the executive design, the LCOF will be similar to the one estimated now. Similarly, the energy consumption slightly influences the LCOF of the wet scrubber. Finally, through the increasing of the utilization time of the biomass boiler, which is related to the external temperature during the cold season, it is possible to reduce the scrubber LCOF. Nevertheless, until a 50% reduction of boiler utilization time (e.g. moderate winter), the scrubber LCOF is still low (< 0.04 €/g PM). Certainly, the PM filtration device becomes more convenient for cold sites where utilization time of the boiler is greater.

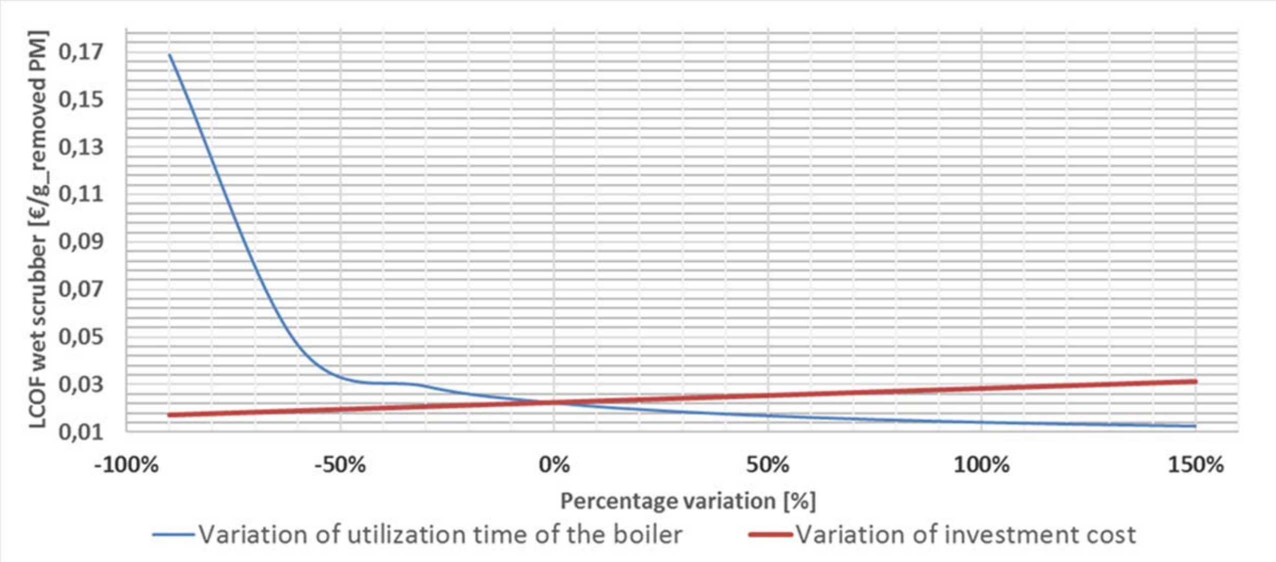

Fig. 4 - Impact of investment costs and utilization time variation of the boiler on the LCOF of the wet scrubber.

4. Conclusions

The paper shows two innovative technologies developed by the University of Bologna, a new configuration of wet scrubber and a thermoelectric generator, and describes how they can be integrated on a residential biomass boiler. From a technological point of view, the two innovative technologies could make the biomass boiler a device with near-zero PM emission and a reliable stand-alone heating system. Consequently, biomass boiler could become more environmental friendly and safety. An economic assessment based on prototypes costs has been realized, including a comparison with commercial competitors.

The wet scrubber prototype results as more convenient than other available technologies for the PM separation in residential application. Nevertheless, further studies and tests are needed to verify the PM removal efficiency and energy consumption.

The LCOE of the TEG results higher than the ones of other available off-grid technologies. On the other hand, TEG LCOE can be reduced through an investment cost reduction (i.e. production scale effect). Moreover, through further research it will be possible to reduce the LCOE thanks to TEG efficiency increase. Finally, the higher is the heating degree days, the lower is the LCOE: so, TEG solution is more sustainable in the northern and/or higher altitude sites.

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