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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:

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

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.