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Techno-economic Analysis of Different Plant Configuration for Thermoelectric Cogeneration from Biomass Boiler

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Abstract- Thermoelectric modules integration within biomass boiler for the direct conversion of heat into electricity is a possibility to increase efficiency and to realize a stand-alone biomass boiler. Due to the low conversion efficiency (up to 5%) of commercial thermoelectric modules, the aim of the integration shall not be the electricity production for external power supply, but the energy self-consumption of biomass boiler electric auxiliaries. The paper describes and analyses four different options for the integration of thermoelectric modules within a biomass boiler: in the combustion chamber, in the convective tubes, in the chimney and with a condensing fluid circuit to be realized outside the biomass boiler. Five quantitative and qualitative key performance indicators have been defined to assess how the integration strategy can influence the electric yield of thermoelectric modules, the ease of maintenance, the operation continuity, the need of auxiliaries systems to be added as well as the impact on biomass boiler redesign or retrofit. The analysis shows that the realization of a circuit with a condensing fluid allows reaching the best combination of key performance indicators. On the basis of this result, the paper also shows the preliminary design of a new test facility to test Glycerol Triacetate as condensing fluid to produce electricity by thermoelectric modules.

Keywords Thermoelectric modules, Biomass boiler, Cogeneration, Key performance indicators, Test facility.

1. Introduction

In the last decades environmental impact and energy efficiency concerns have become more relevant in the development and design of power plant systems. Fossil fuel-based technologies are the main sources of emissions of air pollutants, such as CO_2, CO and NO_x. Moreover, uncertainties associated with fossil fuel prices and resources have led to an increased interest in the development of new strategies and policies for energy saving as well as for the use of renewable energies.

Therefore, the application of ThermoElectric Generators (TEGs) in energy systems has become more interesting, since TEG may represent a relatively low cost technology for the direct conversion of low enthalpy thermal energy into electricity, even if characterized by low conversion efficiency [1,2,3,4]. In particular, TEG becomes market competitive if applied in the recovery of waste heat, which can be produced in civil and/or industrial processes. Another opportunity is to integrate TEGs with thermal renewable sources. A wide literature exists about TEG applications in different fields, including, among others, integration with fuel cells [5], solar concentrators [6], internal combustion engines, both for stationary electric generation and for automotive [7,8], refrigeration plants [9], photovoltaic modules [10,11], geothermal [12].

Biomass is one of the earliest sources of renewable energy, especially in rural areas. Biomass is a versatile fuel that can be used as biogas, liquid fuel or solid fuel. However, further technological improvements are needed to overcome critical issues that up to now have limited biomass use spreads, thus increasing the share of energy produced from biomass plants. These critical issues are (i) environmental impact [13], (ii) difficulties and/or high costs of connection to the electric grid, especially in the case of isolated installations, and (iii) security system reliability in the event of power failure or sudden stop [14]. By appropriate dimensioning, the integration of TEGs with a biomass boiler makes it possible to produce the electrical energy required for boiler auto-consumption, so making it unnecessary to connect it to the grid and ensuring greater reliability of the system even in the case of black-out. A reliable integration between TEG and a biomass boiler can be achieved only through a power electronic circuit to regulate the output voltage and to boost it to a battery level [15]. The battery, which is charged by the modules during standard operation, can be used to feed the boiler auxiliaries during start-up time, when the hot temperature is not high enough to produce power for the boiler auxiliaries feeding.

A wide literature exists about TEG application in biomass stove [15-23]. These studies involve the installation of the TEG directly on the casing (i.e. external side) of a biomass stove and foresee the clamping of a heat sink in the cold side of the module, while an air fan is often used to allow TEGs reaching higher cooling rate on the cold side. Few studies analyse the opportunity of integrating TEGs with biomass boilers. In 2006 Moser et al. designed a 15 kWth pellet biomass boiler integrated by a TEG prototype located around the flame in the combustion chamber. Some tests were carried on at laboratory scale, and it was found that relevant problems were produced on piping resistance and heat exchange capacity by, respectively, hot flame temperature and fouling [24]. In 2013 Bradzil and Pospisil designed and realized an external TEG to be located in the flue gas duct of a 25 kWth biomass boiler. The TEG was made by four commercial modules connected electrically in series, each one with a nominal power output of 9.6 W. The cooling water of the thermoelectric modules was maintained between 25°C and 27°C, while the temperature of the output flue gas reached a maximum temperature of 185°C. The chimney draught during operation was also measured to be 29±2 Pa. The maximum measured output power from commercial TEGs reached 8.5 W [25]. In 2014 Alanne et al. conceptualized a micro-cogeneration system where thermoelectric material is directly integrated in the heat transfer surface of the combustion chamber of a 20 kWth conventional domestic wooden-pellet-fired boiler [26]. The combustion chamber was considered as either coated with thermoelectric modules or designed so that the heat transfer surface itself builds up one single water-proof thermoelectric structure. It was found that temperature differences up to 660°C can be achieved with Alanne et al. configuration, the hot side temperature reaching the level of 750°C. The electrical output of the plant is 1.9 kW el at most, and the electrical efficiency of 8.9% can be obtained (i.e. by considering alloys of lead telluride and silicon germanium), when the figure of merit of the thermoelectric material is unity. Naturally, lower performances can be reached if commercial TEGs' characteristics are taken into account, due to both lower electrical efficiency and lower maximum allowable hot temperature [26]. In 2015 Barma et al. estimated the amount of electrical power which can be produced by TEG placed between flue gas duct and fresh air duct of a 14 MW th industrial thermal oil heater fed by biomass. Average flue gas temperature was around 300°C. Also Barma et al. took into consideration innovative TEG materials, since commercial Bi_2Te_3 based commercial module (like HZ-2 model) produce 3.7 W, where new module, based on p-type $(Bi,Sb)_2Te_3$ and n-type hot forged Bi_2Te_3 generate 4.4 W, at the same operating condition [27].

So, literature researches have been focused on experimental and/or theoretical assessment of peculiar solution, but it is missing an analysis of which kind of integration strategy can be identified as the winning one, taking into consideration different parameters such as initial investment, reliability, maintenance costs and efficiency. In fact, before the modules installation it should be important to study where the installation of the TEG is more suitable or rather where the temperature is higher and uniform. A preliminary assessment was realized by carrying on a theoretical and experimental analysis which highlights relevant criteria for designing TEG integration within thermal power plant [14]. In particular, it was shown that the search for uniformity of heat distribution on TEG surfaces through the inclusion of additional materials does not introduce real benefits, as it is offset by the conductivity factor decrease. On the other hand, when more TEGs are connected in series, heat uniformity across TEGs surfaces becomes a relevant issue because the difference in TEG voltage output needs to be avoided in order to guarantee the highest performance. Therefore, to really obtain the benefits of the uniform heat distribution and its steadiness, without reducing TEG temperature difference between hot and cold surfaces, fluid characteristics become relevant.

The aim of the paper is to complete the analysis by considering five key performance indicators (KPIs), that are (i) Seebeck modules performance, (ii) ease of maintenance, (iii) modules reliability, (iv) additional auxiliaries and accessories and (v) structural changes in the boiler, which measures efficiency and effectiveness of TEG integration with a biomass boiler plant. Moreover, the paper analyses different kind of process fluid to be adopted, thus optimizing TEG integration performance.

2. Material and Methods

2.1. Thermoelectric module identification

The thermoelectric modules that will be considered in the paper as technological reference is the HZ-20 module, manufactured by Hi-Z Technology. HZ-20 has been chosen since Hi-Z Technology modules have been tested in several researches and under different conditions [14,16-19,22,25]. The main technical specifications of the HZ-20 are presented in Table 1. As shown in Table 1, the maximum allowable temperature on the hot surface of the HZ-20 module is 250°C. New kind of materials are under investigation to increase both TEG efficiency and allowable temperature on the hot side, but their application are now limited only for lab test scale. So, the temperature of 250°C can be considered as a technological limit in TEG application and will be the basis for the identification of the optimized fluid to be used in the integration process with a biomass boiler.

Table 1. Main specifications and properties of the HZ-20 module.

Thermoelectrical material	Bismuth Telluride
Weight (g)	115
Module dimensions (mm)	75 x 75 x 5.08
Number of Couples	71
Max hot operating temperature T_H (°C)	250
Thermal Conductivity λ (W/mK)	2.4

2.2. Biomass boiler characteristics and TEGs integration options

The paper considers as biomass boiler reference the Ariterm Biomatic 20+, which is a common pellet fueled boiler with nominal thermal output of 20 kW th. Moreover, the Ariterm Biomatic is the biomass boiler tested in [26]. Biomass boiler characteristics are summarized in Table 2.

Table 2. Main characteristics of the Ariterm Biomatic 20+ boiler

Nominal power output (kW th)	20
Thermal efficiency (%)	91
Water volume inside the boiler (lt)	140
Weight (kg)	245
Dimensions (mm)	1,555 x 608 x 935

On the basis of literature analysis and the characteristics of thermoelectric module and biomass boiler, four different options (O1, O2, O3 and O4) have been identified for the TEG modules integration with the boiler (Figure 1).

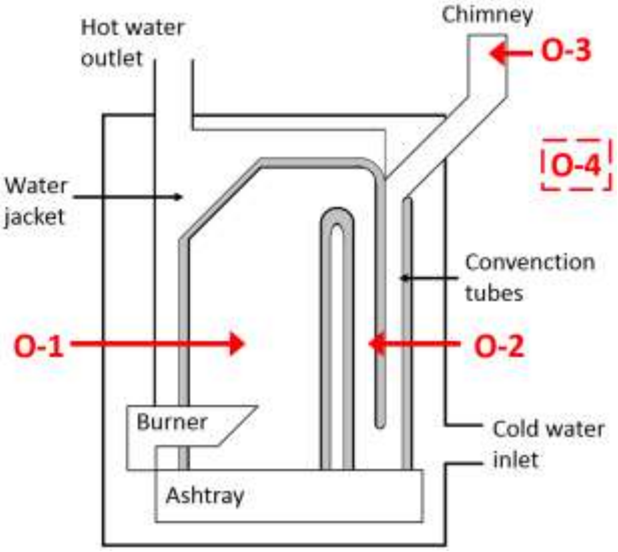

Fig. 1. Installation options of thermoelectric modules into biomass boiler.

The options are: O1 - installation of the TEG modules in the combustion chamber wall; O2 - installation of the TEG modules in the convection tube; O3 - installation of the TEG modules in the wall of the chimney; O4 - installation of the TEG modules in an external system, with a condensing fluid on the hot side of the modules.

The identification of the temperature at the hot side, T_H, and to the cold side, T_C, is necessary to estimate the performance of the HZ-20 modules in each installation alternatives. In [25] the temperatures of the exiting flue gas were determined through a thermodynamic model: the results for both the combustion chamber and the convection tubes are, respectively, 592.5°C and 104°C for the nominal (100%) operation. In these conditions, the combustion chamber, which is made of 5 mm of steel, reaches a surface temperature of 125°C, while convection tubes are at a surface temperature of 90°C. If TEGs are installed within the biomass boiler, in the combustion chamber or in the convection tubes, the flue gas will leave the boiler at a relatively high temperature, since TEGs work as insulation between the combustion chamber or convection tubes and the water envelope. So, if TEG thicknesses (including Seebeck module, aluminium and ceramic films and steel plate) of 1 cm for the combustion chamber installation and of 4 cm for convection tubes are considered, working conditions will change and temperature on hot and cold side of TEGs can be estimated as in Table 3 [26]. If TEGs thickness is increased up to 4 cm also in the combustion chamber, the heat flow to the water is reduced, with a reduction in thermal efficiency of the biomass boiler [26]. Flue gas temperature at the chimney was estimated on the basis of results: flues gas temperature may be higher than 200°C, but with the installation of TEGs a hot side temperature not higher than 185°C was reached, with a temperature difference between hot and cold side of about 113°C [25]. Finally, the last option was developed on the basis of [14] and foresees the realization of an external circuit which includes on the hot side an evaporating-condensing fluid at ambient pressure, while on the cold side there is the water coming from the end-user heating circuit (temperature of about 70°C in the worst case). A preliminary layout of the option O4 is shown in Figure 2.

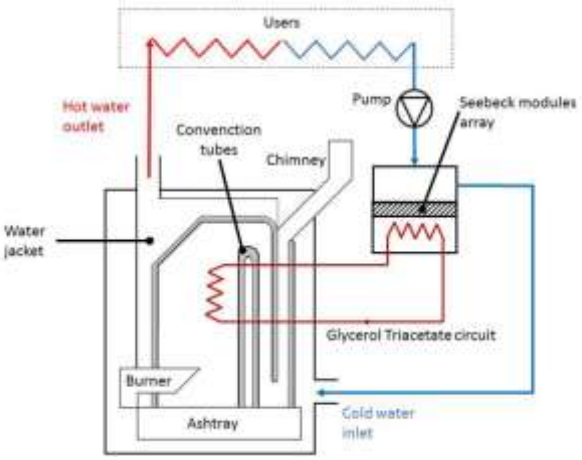

Fig. 2. Preliminary layout of option O4: the Glycerol Triacetate serpentine is placed in the combustion chamber.

The Glycerol Triacetate steam generator is realized through a serpentine flow tube placed in the combustion chamber (as showed in Figure 2) or in the convection tubes area of the boiler. The Glycerol Triacetate steam may reach the Seebeck modules array through natural circulation. Otherwise, a circulation pump and a thermostatic valve should be added to the circuit. In the Seebeck modules array, the Glycerol Triacetate steam condensates and transfers heat to the cooling fluid. The cooling circuit of the Seebeck modules array should utilize the cold water coming from the boiler users, thus realizing the preheating of the boiler water and avoiding any thermal losses. The main temperatures of the TEGs integrated in the Ariterm Biomatic 20+ are summarized in Table 3.

Table 3. Assumed temperatures for the comparative analysis

	Hot side fluid	Cold side fluid	T_H [°C]	T_C [°C]
O1	Flue gas (plus irradiation)	Water	282	116
O2	Flue gas	Water	260	76
O3	Flue gas	Water	185	72
O4	Condensing fluid	Water	258	72

2.3. Evaporating-condensing fluid

Option O4 foresees the realization of a prototypal evaporator-condensing closed loop. So, the fluid to be used in this kind of application shall present a boiling point near to 250°C and at the atmospheric pressure. This fluid shall be also non-toxic, non-corrosive and as cheap as possible. After a preliminary survey on the Nist database, 18 fluids with a boiling point between 220°C and 280°C at atmospheric pressure (1 bar) were found. The 18 fluids have been then deeper analysed taking into consideration the following parameters: the boiling temperature, the melting point/solidification temperature, the auto-ignition temperature, the flash point temperature, the approximate cost (€/litre), common uses and all related EU Hazard Statements, considering the Regulation (EC) No. 1272/2008. Table 4 summarizes fluid selection process, taking into consideration the following requirements: (i) a boiling point (BP) between 220°C and 280°C, (ii) a melting point (MP) lower than 10°C, (iii) a self-ignition temperature (SIT) higher than 300°C and (iv) no EU Hazard statements (not hazardous, NH). Accordingly to Table 4 analysis, Glycerol Triacetate and 1,5 Pentanediol have all the characteristics required. The further selection was based on the cost of the fluid: Glycerol Triacetate has a market cost of about 45 €/lt, while the 1,5-Pentanediol costs about 90 €/lt. So, Glycerol Triacetate was chosen as potential fluid.

Glycerol Triacetate is used in pharmaceutical products as a humectant, a plasticized and as a solvent. Glycerol Triacetate can also be used as a fuel additive as an antiknock agent which can reduce engine knocking in gasoline, and to improve cold and viscosity properties of biodiesel [28]. In Table 5 the main characteristics of Glycerol Triacetate are summarized.

Table 4. Analysis of 18 fluids: if the requirement is satisfied, the cell contains an X; if no information was available, the cell contains n.a. (not available)

Fluid	**BP**	**MP**	**SIT**	**NH**
Anisaldehyde	X	X	n.a.	X
Cinnamaldehyde	X	X	n.a.	
Cinnamyl alcohol	X		n.a.	
N,N-Dibutylaniline	X	n.a.	n.a.	
1,6-Dimethylnaphthalene	X	X	n.a.	X
Diphenylmethane	X		n.a.	X
Geraniol	X	X	n.a.	
Glycerol triacetate	X	X	X	X
Lauryl alcohol	X			
Linoleic acid	X	X	n.a.	X
Methyl caprate	X	X	n.a.	
Methyl cynnamate	X		n.a.	X
1-Methylnaphthalene	X	X	n.a.	
Methyl salicylate	X	X	n.a.	
Nicotine	X	X	n.a.	
1,5-Pentanediol	X	X	X	X
Quinaldine	X	X	n.a.	
Tetradecane	X	X	n.a.	

Table 5. Glycerol Triacetate main characteristics

Boiling point (°C)	258
Self-ignition temperature (°C)	430
Flash point (°C)	138
UE Hazard Statement	none
Cost (€/lt)	45
Heat of vaporization (kJ/kg)	393
Liquid density (kg/m^3)	1,160

2.4. Definition of Key Parameter Indicators (KPIs)

In order to realize the best integration between thermoelectric modules and the biomass boiler, during the designing phase other Key Performance Indicators (KPIs) shall be evaluated in addition to the TEG performances. In industrial plants KPIs are mainly used to understand if the whole system or some single equipment present some issues or possibility of optimization. The main KPIs in industrial plants are related to energy efficiency, maintenance, operation, direct costs (i.e. use of new or more raw materials) and indirect costs (i.e. needs of structural redesign and/or retrofit of the biomass boiler) [29]. By considering the design of a prototypical device for the thermoelectric generation to be integrated in a biomass boiler, these KPIs can be contextualized as follow: KPI-1, Seebeck modules electric yield; KPI-2, ease of maintenance; KPI-3, Seebeck modules reliability and operation continuity; KPI-4, additional auxiliaries and accessories required; KPI-5, structural redesign and/or retrofit of the biomass boiler.

A maximum score of 5 and a minimum score of 0 is assigned to each KPI, with a minimum variation of 0.5. If the KPI can be evaluated by a measurable quantity, the score is assigned through a normalization process which is based on the maximum value observed. A score of 5 point is assigned to the maximum value. If the KPI can be evaluated also or only by qualitative parameters, a fully justification of scores has been included in the paper (see paragraph 3).

The first indicator (KPI-1) is influenced by temperature difference between hot and cold surfaces of the Seebeck modules. So, once an electric power target is fixed, the integration options which are characterized by lower Seebeck modules performances in terms of electric power output will also result in a higher number of Seebeck modules needed to produce the requested electric yield. More Seebeck modules means more heat exchange surface needed, and also more investment costs.

Regarding the maintenance indicator (KPI-2), the ease of maintenance is of great importance. Seebeck modules should be easy to check and, in case of faults or failure, to be repaired or substituted. Moreover, maintenance should be realized with biomass boiler running, thus allowing continuity to the heat production and delivery to the users. As consequence, the Seebeck modules array should be easily accessible and be also repairable without compromising biomass boiler operation continuity.

In general, the operation KPIs (KPI-3) concern the overall equipment effectiveness, measured for example by the percentage of operation time over a time period. Consequently, operation and maintenance are strongly connected [29]. In this case, the TEG is the element to be considered as critical for both biomass boiler and TEG itself operation. TEG fouling or exposure to high temperature and/or contaminated fluid (like flue gas) can produce negative impact on TEG operation reliability. Nevertheless, as demonstrated by [26], the application of TEGs in certain position of biomass boiler can produce a penalization on thermal performance of the boiler (i.e. lower hot water temperature), thus limiting biomass boiler operation capacity.

The integration between the thermoelectric modules and the biomass boiler requires auxiliaries and accessories that are different in each installation option (KPI-4): heat exchangers, pipes, fluid pumps, instrumentations, electric battery and electronic control for battery charge regulation. Depending on kind and number, an increasing in auxiliaries and accessories can have relevant impact on integration costs, as well as in the complexity of the whole system, thus requiring further improvement of the biomass boiler (for example, a more structured monitoring-control system).

The last KPI (KPI-5) considers how TEGs and biomass boiler integration may impact on biomass boiler structure. In fact, the redesign as well as the retrofit of existing biomass boiler should be as simple as possible in order to reduce the final cost of the integration.

3. Results and Discussion

3.1. KPI-1: Seebeck modules electric yield

The Seebeck modules electric yield can be computed by utilizing the estimated hot and cold temperatures of Seebeck module surfaces (Table 3) and by using the datasheet of HZ-20 and the performance calculator (provided by the module manufacturer). Table 6 shows the results obtained in each integration option (defined as in paragraph 2.2). The score has been assigned coherently with paragraph 2.4 definition.

Table 6. Results of the performance calculations of HZ-20 module for each integration option

	T_H [°C]	T_C [°C]	Max Power [W]	Score
O1	282	116	12.43	3.5
O2	260	76	16.78	5
O3	185	72	6.91	2
O4	258	72	16.66	5

Table 6 shows that O2 and O4 could give the best performances in terms of electric yield, while O3 results as the worst solution. An interesting comparison can be made between two solutions (O1 and O2) which integrate the TEGs within the biomass boiler, and two solutions (O3 and O4) which integrate the TEGs outside the biomass boiler. The integration of TEGs in the convection tube (O2) is preferable to the one in the combustion chamber wall (O1) due to the relatively lower temperature that can be reached on the cold surface of the Seebeck module. Conversely, the adoption of a condensing fluid (O4) instead of flue gas (O3) as hot fluid can produce high benefit since a relatively higher temperature can be reached on the hot surface of the Seebeck module.

3.2. KPI-2: Ease of maintenance

The ease of maintenance has been qualitatively assessed by considering the possibility to easily access to the Seebeck modules for maintenance. In the first two cases (O1 and O2), it is necessary to stop and disassemble the biomass boiler before doing maintenance: so, in these cases the maintenance operations seem to be onerous in terms of both time and costs, including also the biomass boiler shut-down. In the last two cases (O3 and O4), thanks to the fact that TEGs integration has been implemented outside of the biomass boiler, the boiler would not be disassembled. Anyway, O3 option interfaces with flue gas, so a more complex solution should be identified (i.e. a by-pass duct on the chimney) when TEGs maintenance is necessary. For those reasons, 5 and 4.5 points were assigned, respectively, to option O4 and O3, while for both O1 and O2 only 1 point has been assigned (Table 7).

3.3. KPI-3: Seebeck modules reliability and operation continuity

The Seebeck modules should maintain a certain grade of uniformity in cleaning to avoid drastic reductions of the heat exchange capacity. Furthermore, the exposition to too high temperature can irreparably damage the Seebeck modules. In the first two cases, the TEGs can be exposed to both high temperature and uncleaned flue gas. Due to the fact that the installation of TEGs in the convection tubes (O2) should face fewer problems in terms of flue gas temperature, a higher score with regard to TEGs installation directly in the combustion chamber (O1) has been considered. If the installation of TEGs on the chimney (O3) is analysed, the risk of reaching higher temperature than allowed should be avoided. On the other hand, the presence of flue gas may play a negative role in the heat exchange capacity through the hot surface of TEGs due to fouling problem (even if less important than in O2). Finally, the option O4 seems to be the best one, since it does not involve the presence of high temperature or aggressive/dirty fluid (flue gas). Coherently with the analysis exposed above, the maximum score of 5 points has been attributed to O4, followed by O3, O2 and O1 with, respectively, 4, 3 and 2 points.

3.4. KPI-4: Additional auxiliaries and accessories required

The additional auxiliaries and accessories required have been qualitatively assessed by considering which and how many components are needed to complete the integration of TEGs within the biomass boiler. For each integration option considered, a minimum impact on costs is produced by the need of realizing a charge-discharge regulation of an electric battery, to be used as storage element between TEGs modules and biomass boiler's electric auxiliaries. In the case of TEGs integration within the biomass boiler (O1 and O2), the main accessory required is an adequate thermal insulation to protect the Seebeck modules from the high temperatures of flue gas. On the other hand, in these cases the heat flows directly to the hot water produced by the biomass boiler: so, no additional cooling circuit needs to be installed. In the O3 case, a cooling circuit for heat recovery from the chimney needs to be realized. It has been supposed that the biomass boiler produces hot water at 90°C, and that the water returns from users with a temperature of about 70°C. So, before being sent to the biomass boiler, the cooled water can pass through the TEGs in the chimney. An hydraulic circuit (including pipes, water pump, valves and instrumentations) may be added to the system. In the last option O4 the most complex solution is needed, since a Glycerol Triacetate steam generator needs to be designed, realized and installed within the biomass boiler. Moreover, a cooling circuit needs to be added as in O3. The maximum score of 5 points has been attributed to the less invasive solution, which is O2, while a score of 4.5 has been given to option O1. Option O3 reaches a medium positioning with a score of 3. Finally, option O4 reaches the minimum score of 1.

3.5. KPI-5: Structural redesign and/or retrofit of the biomass boiler

The structural redesign and/or retrofit of the biomass boiler have been qualitatively assessed by considering which kind of modifications are needed on the biomass boiler to be integrated with TEGs. If option O3 and O4 are considered, no relevant modification or redesign of biomass boiler is needed, since TEGs are installed outside of the biomass boiler. In the case of O3 application, a modification of the chimney is needed, while in the case of O4 application a serpentine flow tube for the production of Glycerol Triacetate steam. Instead, in the first two cases (O1 and O2) a redesign should be included for new biomass boiler to optimize heat flow across TEGs and to identify the optimal place for Seebeck modules installation. In the same way, if O1 and O2 applications are implemented on existing biomass boiler, a deep modification of combustion chamber and convection tubes, respectively, may be needed to allow TEGs installation. Coherently with the analysis exposed above, option O3 results as the most suitable with a score of 5 points, immediately followed by option O4 with a score of 4.5 points. Then, we have options O1 and O2 with, respectively, 3.5 and 3 points reached.

3.6. KPI summary

Table 7 shows the summary of the previous discussed KPIs scores: the integration option 4 (O4) presents the best KPI score.

Table 7. KPI summary of the five installation options.

KPI	**O1**	**O2**	**O3**	**O4**
1	3.5	5	2	5
2	1	1	4.5	5
3	2	3	4	5
4	4.5	5	3	1
5	3.5	3	5	4.5
Total	14.5	17	18.5	20.5

In fact, this solution allows reaching the best Seebeck modules performances with no structural changes of the boiler, ease of maintenance and high reliability and operation of the TEGs. The integration option 3 (O3) has similar qualitative characteristics of O4, but it is highly penalized by the low electric yield of the Seebeck modules due to the relatively low hot temperature that can be reached on the hot surface of the TEG. Finally, both options O1 and O2, that have less impact from the point of view of additional auxiliaries and accessories required and that can guarantee a satisfying electric yield, are penalized in terms of structural changes to be implemented on the biomass boiler and on the ease of maintenance and operation continuity. On the basis of this preliminary analysis, a new test facility has been designed to evaluate the reliability of O4 and to allow a better estimation of installation, operation and maintenance costs. Since the integration of Seebeck modules may have positive impact also on security system reliability in the event of power failure or sudden stop, the development of this kind of technology could be seen also as an investment in the increasing of safety and health of the final end-user. So, after a more detailed cost-benefit analysis, it will be possible to identify incentive needs to be applied to make the initial investment more profitable [30,31].

3.7. Design of a new test facility for Seebeck modules

A new test facility for Seebeck modules has been designed and realized at the University of Bologna to verify the efficiency and effectiveness of option O4 at real scale. The scope of the test facility is to verify if the system developed is able to reach the performances provided by the HZ-20 manufacturer, which is nearly 25.5 W for each module with a hot temperature of 258°C and a cold temperature of 25°C. Figure 3 shows the test facility layout. The test facility is composed mainly by three assemblies: i) the Glycerol Triacetate steam generator, ii) the water cooling system and iii) the Seebeck modules array.

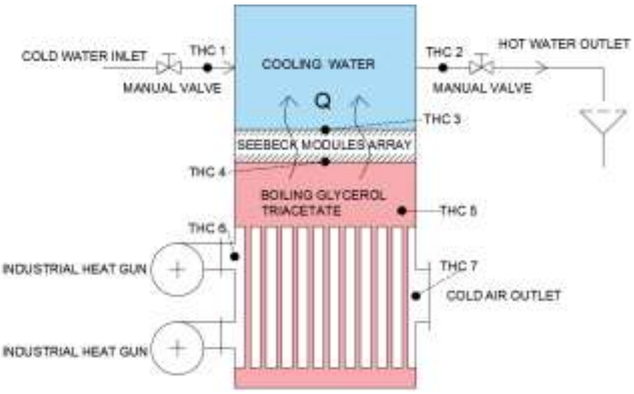

Fig. 3. Schematic of the new test facility.

The Glycerol Triacetate steam generator is made by a heat exchanger with a total surface of about 0.8 m^2, made with 1/8” vertical tubes. The Glycerol Triacetate is heated up to the boiling point at atmospheric pressure by six industrial heat guns. Each heat gun presents the possibility to set the air outlet temperature form 50°C to 600°C and it is characterized by an absorbed electric power of about 2000 W at the maximum operating conditions, which are outlet air temperature of 600°C and air mass flow of 1.5 kg/s. The air mass flow is measured through a vane anemometer. The glycerol triacetate within the heat exchanger is moved by natural convection in a closed loop: firstly the fluid evaporates in the vertical tube bundle, then the steam moves in the upper part of the steam generator where it condensates on the Seebeck modules; finally, the liquid returns to the tube bundle. The evaporated/condensed mass flow of Glycerol Triacetate has been sized nearly 30 kg/h (25.9 lt/h).

The water cooling system is an open loop circuit: the water is feed directly from the aqueduct, is heated up by Seebeck modules cooling and, finally, it is discharged. The water mass flow, measured through a weighing method, can be regulated by a manual valve installed in the cold water inlet pipeline.

HZ-20 modules are compressed between two aluminium frames which allow the direct contact between the Seebeck module surfaces and the fluids and, consequently, optimize the heat transfer from the hot to the cold side of the modules.

As shown by Figure 4, the Seebeck modules array is composed by nine HZ-20 modules. The HZ-20 modules are connected in series in group of 3 and the 3 series are connected in parallel. The target total power generated by the array is 230 W with an output current of 29 A and with a total equivalent internal resistance of 0.27 Ω.

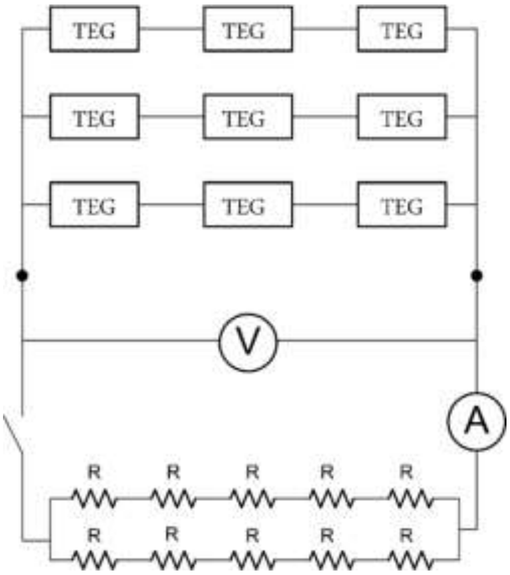

Fig. 4. Schematic of the electric circuit of the new test facility.

The TEG load circuit is made by 10 electric resistors, each characterized by a 0.1 Ω resistance with maximum allowable wattage of 50 W each. The resistors are installed in two branches in parallel; each branch is composed by 5 resistors electrically in series. In the circuit is installed a voltmeter and an ammeter in order to monitor the power generated. The electric circuit shown in Figure 4 allows to (i) maximize the performances of the modules array because of the total resistance similar to that of the TEG array (0.25 Ω vs. 0.27 Ω), (ii) dissipate all the electric power generated by the TEG array and (iii) measure the electric power generated and the open circuit voltage.

The test facility is equipped with seven thermocouples (Figure 3) which monitor the following temperatures: inlet water temperature (THC1), outlet water temperature (THC2), cold surface temperature of HZ-20 array (THC3), hot surface temperature of HZ-20 array (THC4), Glycerol Triacetate temperature (THC5), inlet air temperature (THC6) and outlet air temperature (THC7). By THC1 and THC2 monitoring it is possible to calculate the thermal power Q flowing through the HZ-20 array (once water flow rate has been set and measured). Through the monitoring of THC3 and THC4 it is possible to verify if the electric performance of the HZ-20 array is consistent with the theoretical one. The monitoring of THC5 allows evaluating the effectiveness of the heat exchange between the hot air and the Glycerol Triacetate, while through the monitoring of THC6 and THC7 it is possible to evaluate the heat given by the heat guns to the system.

Figure 5 shows the new test facility described previously which has been designed and realized in the Department of Industrial Engineering at the University of Bologna. The system is 475 mm tall and with a rectangular base of about 255x220 mm, all the dimensions has been optimized to guarantee the operability reducing the space occupied by the system. The test facility is now under commissioning to reach the best performances as possible, and the results of the experimental campaign will be presented in a following paper.

Fig. 5. The new test facility designed and realized at the University of Bologna.

4. Conclusion

Four possible plant configurations for the integration of thermoelectric modules with a biomass boiler, starting from state of the art analysis. Five key-performance indicators have been defined to identify the best theoretical configuration, including parameters concerning thermoelectric modules efficiency, operation continuity and reliability, ease of maintenance, additional auxiliaries and accessories required, need for structural redesign and/or retrofit of the biomass boiler. The realization of an external circuit with a condensing/evaporating fluid results as the most interesting solution. So, a preliminary design of a new test facility has been realized: the test facility will be used to test nine HZ-20 thermoelectric modules and will use water as cooling fluid and Glycerol Triacetate as hot fluid, since it can evaporate at ambient pressure at a temperature of about 250°C. On the basis of experimental results it will be possible to demonstrate the techno-economic feasibility of this innovative idea.

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