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Energy performance and profitability of biomass boilers in the commercial sector: A case study in the UK

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Abstract

Commercial buildings or shopping malls are characterized by large thermal and electrical energy consumptions with high variability of energy demand. Therefore, there is a large interest to explore novel renewable energy generation systems for these applications. A novel flexible configuration of biomass-fired CHP system with organic Rankine cycle (ORC) is here proposed and applied to the case study of food retail buildings in the UK. The proposed configuration adopts a molten salt (MS) circuit to transfer heat from the biomass furnace to the ORC plant. A thermal Energy Storage (TES) is proposed to improve the flexible operation of the plant and reduce the size of the biomass boiler. Molten salts have been preferred to thermal oil as they have no fire risks and low environmental impact and can be used as medium for a Two Tank TES with a “direct heating” scheme. The plant has been analysed using real input data from a biomass boiler installation, conversion efficiency and heat demand from the store. The model is informed by hourly energy costs and electricity feed in tariff in order to define optimal size and operation of the bottoming ORC for the specific case study of large commercial energy end user in the UK. The results show that the use of thermal storage in a biomass-fired ORC plant can improve the boiler efficiency and reduce the biomass consumption in thermal-load following operating mode and increase the investment profitability.

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1. Introduction

Commercial buildings represent an important thermal and electrical energy demand segment, characterized by highly variable energy demand. To satisfy their energy demand and reduce primary energy consumption, small size combined heat and power (CHP) generation systems are possible solutions [1]. These cogeneration units form a large segment of the distributed generation (DG) market [2], presenting several advantages from environmental and economic point of view.

Biomass boilers are suitable technologies to reduce greenhouse gas emissions and increase the share of renewable energy sources. The use of biomass as substitute to fossil fuel in small-scale CHP plants has been widely investigated in literature. Available technologies for small-scale CHP (from 100 kWe to 1 MWe size) using lignocellulosic biofuel include: (i) biomass pre-processing through gasification coupled to both Internal Combustion Engine (ICE) [3] and Micro Gas Turbine (MGT) [4], included pyrolysis [5], and (ii) direct combustion in grate or fluidized bed boilers to feed externally-fired MGT [6] or Stirling [7] also for trigeneration application [8]. Another commercially available solution for biomass CHP is represented by Organic Rankine Cycle (ORC) engines [11]. ORCs are similar to the steam-driven Rankine turbine cycle, except that they are able to exploit low-temperature heat sources because of the use of an organic working fluid as medium for the turbine instead of water. The biomass ORC plants market has grown thanks to the reliability of the technology but also thanks to the policy mechanism of incentives available in many European countries [10]. A review on application of ORC in small and micro scale biomass CHP is presented in ref. [11]. In ref.[12], an assessment of the energy performance of biomass boilers coupled to an ORC under real operating conditions is showed.

Biomass boilers are generally characterised by difficulties when requested to be operated during rapid transients for load following: a longer time period to ignite the fuel and reach rated output respect to gas or oil boilers [13], lower performances and higher emissions at part load [14]. A thermal energy storage (TES) connected to a biomass boiler could allow decoupling boiler operation and thermal energy output modulation for load following. In the recent years, the development of energy storage technologies has increased the interest on this option [15]. Thermal energy can be stored as latent heat, sensible heat or thermochemical energy. Sensible heat storage (SHS) is the most common store method. For low-temperature SHS water appears to be the best liquid available because it is inexpensive and has a high specific heat, but in case of temperature higher than 100°C diathermic oil, liquid metals or molten salts (MS) are preferred[16]. In particular, MSs show a number of advantages for applications at temperature higher than 250°C such as in the case of concentrating solar plants [17]. At these temperatures, MSs have the advantages of a high heat capacity, high density, high thermal stability, relatively low cost and low vapor pressure. The low vapor pressure results in storage designs without pressurized vessels [17]. Moreover, MSs represent also a good alternative as heat transfer fluid (HTF) to thermal oil as they have no fire risks and low environmental impact.

In this paper, a cogenerative plant composed by a biomass boiler connected to an ORC generation system and a TES selected to compensate the energy fluctuations has been analysed as possible solution to satisfy a supermarket heat demand. Real heat demand patterns in UK have been used. The main novelty relies on the biomass boiler decoupling from the load by means of a two-tanks MS TES that provide the required heat to ORC, avoiding part load operation. An economic assessment has been carried out to compare this solution to: (i) a standard configuration, where the biomass boiler is directly coupled to the ORC, (ii) a scenario where only the biomass boiler and the TES are considered and (iii) the baseline scenario where the heat is supplied to the store through the hot water produced by the boiler (currently adopted solution).
2. TES and ORC technology description

The layout of the plant is shown in Fig.1. The plant is composed by a biomass boiler, an intermediate circuit that uses Molten salts as HTF directly connected to a Two Tank thermal storage, an ORC operated as cogeneration unit because the heat flux discharged from the condenser is directly supplied to the thermal end users of the commercial building. The considered biomass boiler is a moving grate furnace fed by wood pellets. Unlike normal biomass boilers that produce steam or hot water, the proposed boiler heats molten salts by means of flue gases exiting the combustion chamber flow in a heat exchanger where MS are heated up to the temperature of the hot tank. The MS selected is a mixture of lithium, sodium and potassium nitrates that can operate up to 500°C without chemical decomposition and reach 120°C without freezing [18]. MSs have been used not only as HTF but also as energy storage medium. In this work, considering the high temperature of the flue gas, a temperature of 450 °C has been chosen for the Hot Tank, while a temperature of 200°C has been chosen for the cold tank to avoid excess work for the circulating pump. Thanks to the relatively high temperature interval (450-200=250°C), the energy stored per mass unit is relatively high with savings for the costs of tanks and storage medium. The ORC analyzed receive the thermal input from molten salts. Since the temperature of the hot tank is relatively high, a recuperative configuration has been selected for the system.

![Fig. 1 Layout of the system configuration](image)

According to the characteristic of the thermal source, Toluene proves to be a suitable working fluid because it is chemically stable in the range of temperature considered [19], [20] and meets environmental and safety requirements. It is a “dry fluid” with a dry expansion in the turbine, thus avoiding the drop generation that can damage turbine blades. The main thermodynamic properties of the ORC are summarized in Table 1 while a T-s diagram can be found in Fig.2. The condenser temperature has been selected to match the water temperature requested by the thermal users. Other parameters used in the thermodynamic simulations are: biomass boiler efficiency = 88%; mechanical/isentropic efficiency all turbines = 90/75%; electrical genset efficiency = 92%.

3. Thermal energy storage: sizing and operating conditions selection

The food retail sector interest in sustainability goals is fast increasing, and a number of operators in the UK is keen to decarbonize its business and to reduce energy consumption [21]. To pursue these goals, several biomass boilers have been installed in different stores to supply the required heat, also motivated by the introduction of the non-domestic renewable heat incentive (RHI)[22] by the UK government. These boilers are constantly monitored and data on electric and thermal demand are recorded every half hour. In this paper heat demand patterns of three days, in summer, winter and mid-season shown in Fig.3, have been used to size the TES and carry out the economic assessment. All the calculations have been done under the hypothesis of heat load following condition.
### Table 1. Thermodynamic properties of the ORC

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic fluid</td>
<td>Toluene</td>
</tr>
<tr>
<td>Evaporating pressure</td>
<td>25 bar</td>
</tr>
<tr>
<td>Inlet turbine temperature</td>
<td>330°C</td>
</tr>
<tr>
<td>Condenser Temperature</td>
<td>85 °C</td>
</tr>
<tr>
<td>Net electric efficiency</td>
<td>((\eta_{el}))</td>
</tr>
</tbody>
</table>

TES has been sized when heat demand is maximum, during winter, as represented in Fig. 3. The ORC efficiency is known from the thermodynamic parameters of the cycle (see table 1 and Fig 1.), therefore it is possible to evaluate, from the store heat demand, the amount of heat required by the biomass boiler to feed the ORC through the TES. The assumed hypothesis is that the heat demand of the store is completely satisfied by the heat discharged by the ORC. The peak heat demand is 350 kW, and it matches the maximum heat required from the ORC (\(Q_2\)). A thermal input \(Q_1\) of 455 kW is required by the ORC, in order to satisfy this demand. Thus, the size of the ORC, \(W_{el}\), selected for this application results of 85 kW, evaluated as follows:

\[
W_{el} = \frac{Q_1}{\eta_{el}} \quad 1)
\]

The average ORC heat demand results 317 kW (\(Q_{mean,ORC}\)), and a biomass boiler of 350 kW has been chosen. Assuming a furnace operation in baseload conditions, the cumulative heat sent to the TES at time \(t\) \(E(t)\) gives

\[
E(t) = \int_0^t (Q_{prod} - Q_{req}) dt \quad 2)
\]

where:
- \(Q_{prod}\) is the thermal power produced by the biomass boiler;
- \(Q_{req}\) is the thermal power required by the ORC.

Integral in Eq.(2) has been evaluated in the range \(0 < t < T = 24\) h and TES size has been computed as

\[
V_{TES} = \max(E) - \min(E) \quad 3)
\]

The TES capacity, obtained from this simplified procedure is 550 kWh, as shown in Fig. 4.

Once the TES has been sized, it is possible to analyze the operating strategy of the biomass boilers coupled to the TES and the ORC in summer and mid-season conditions. A preliminary optimization has been done by a trial and error strategy. The choice of the furnace operating mode has been done according to the following principles, to reduce the emissions and increase the efficiency:
- the furnace should be turned off at part load lower than 20%;
- between two ignition cycles a time interval of at least one hour should be considered.

Several combinations of boiler part-load values and ignition cycle have been considered to select best performing operation mode. Thermal efficiency of the ORC is calculated as function of the working condition as in [23]. In Fig.5(a) and (b) is shown the dynamic behavior of the heat power produced by the boiler \(Q_{bb}\) and thermal energy stored in TES \(Q_{TES}\) respectively in summer and mid-season.
During summer, the ORC works the whole day constantly at minimum part load, see Fig. 5(a). Under these conditions the boiler is switched on at 100% of part load, supplies heat to the TES and the store and fills the TES. Once the TES is full, biomass boiler is switched off and $Q_{req}$ is supplied through the TES. By doing so, biomass boiler works for 7 h per day at maximum load in an average summer day. In mid-season, ORC requires more heat in the first half of the day, Fig. 5(b), thus the time interval between two furnace ignitions is smaller than the one required after midday. TES integration allows, especially in the afternoon when the heat required is lower, to switch off the furnace for several hours. Boiler operates at 80% of part load for 13 h per day.

4. Techno-economic assessment

In the economic assessment the following cases have been compared:

- **CASE 1**: a configuration with a biomass boiler of 350 kWt connected to a TES having a capacity of 550 kWh and an ORC of 85 kW e. The operating conditions of this case and the selection of the components have been described in the previous section;
- **CASE 2**: a conventional biomass boiler of 520 kWt is installed, and heat demand is satisfied by the hot water produced by the biomass boiler. This case represents the present store configuration;
- **CASE 3**: a boiler with the same size of CASE 2 but coupled to an ORC of 85 kW e, that supplies heat to the store through the condenser. This case has no TES and MS circuit is used only as HTF to the ORC;
- **CASE 4**: biomass boiler and TES as in CASE 1 but no ORC is included. The heat demand is directly supplied to the store and the TES compensates the heat demand fluctuations.

The main cost items and biomass consumption values for the techno-economic analysis are reported in Table 4.
been considered also in CASE 2, 3 and 4. The energy production has been computed under the hypothesis that the biomass boiler and the ORC operate following the thermal load in CASE 2 and 3, while the same operating condition of CASE 1 has been considered for CASE 4. The turnkey investment cost and operational costs are estimates from manufacturers’ information [24][25]. The operation and maintenance (O&M) costs are 5% of investment cost and include the handling and maintenance of the biomass furnace, personnel and biomass storage cost [26]. Biomass ash discharge costs are accounted for assuming unitary cost of 70 Eur/t of ash (10% content in the biomass). Following additional input data are assumed: lower heating value (LHV) of biomass of 4.18 kWh/kg; cost of biomass of 80 Eur/t [27]; electric internal consumption for operation of the CHP plant equal to 5%; avoided cost of electricity from on-site ORC generation of 160 Eur/MWh; heat selling price of 80 Eur/MWh [28].

Table 4. CAPEX, OPEX and biomass consumption for the selected case studies.

<table>
<thead>
<tr>
<th>Case study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass consumption (t/year)</td>
<td>371</td>
<td>637</td>
<td>710</td>
<td>371</td>
</tr>
<tr>
<td>Total upfront cost (kEur) of which:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ORC generator</td>
<td>165</td>
<td>0</td>
<td>165</td>
<td>0</td>
</tr>
<tr>
<td>- Biomass boiler, HEX, gas treatment</td>
<td>158</td>
<td>185</td>
<td>185</td>
<td>158</td>
</tr>
<tr>
<td>- HTF circuit and MS system</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>- Engineering, development., insurance</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

The financial appraisal of the investment is carried out assuming the following assumptions: (i) an operational lifetime of 20 year with no 're-powering' over this lifetime and zero decommissioning costs; (ii) the maintenance and fuel supply costs, and electricity and heat selling prices are held constant of the lifetime (in real 2018 values); (iii) the capital assets depreciate linearly over 20 years; and (iv) the cost of capital (net of inflation) is equal to 5%, corporation tax are neglected, and the capital investments and income do not benefit from any support. The equivalent operating hours for electricity production, assuming a thermal load following operating mode, are 1,864 per year in all the cases CASES 1 and 3. The analysis has been done assuming one typical day in each season, hence the number of days considered are 75/76/161 respectively in winter, summer and mid-seasons.

5. Results

The levelized cost of electricity is 230 Eur/MWh (CASE 1 and 3, calculated allocating the ORC investment and operational costs to the electricity production) while the levelized cost of heat is 38 Eur/MWh in CASE 1 and 4 and 52 Eur/MWh in CASE 2 and 3 (allocating the remaining system costs to the heating production). In all cases, the fuel costs are allocated to the heat generation. The adoption of a TES reduces the levelized cost of heat. The energy dissipated in CASEs 2 and 3 is 18% of the total energy produced by the biomass boiler (due to the assumed minimum output of 20% rated power for the furnace, even when the heating demand is lower than this limit) while in CASE 1 and 4 the amount of wasted heat is 9% of the total energy produced. This reduced value is due to the TES, which reduces the dissipated heat and allows to turn off the boiler when the demand is low, since the heat stored can supply the energy required.

The net present value (NPV), in Fig. 5, is the lowest in the CASEs 2 and 3. In CASE 2, the low NPV is due to the low part load at which the biomass boiler operates in summer and mid-season conditions, which increases the biomass consumption (see table 4) due to the reduced combustion efficiency. The traditional solution in this case is a back-up gas boiler to satisfy the peak demand but this is not viable since a full renewable system was required. In CASE 3 the reason of the low NPV is the low number of operating hours of the ORC in comparison to its high investment cost. The low profitability of the configuration with an ORC is due to the assumption of thermal load-following operation, which limits electricity production and determinates a levelized cost of electricity higher than the electricity unitary cost (hence making unprofitable the investment in the ORC). A more profitable strategy for the ORC would have been a baseload mode, operating the ORC at rated power to maximize the electricity production, despite of the discharged heat when it exceeds the thermal demand of the store. The economic indices are reported in Fig 6-8. The internal rate of return (IRR) in Fig. 6 and the Profitability Index of Fig 7 confirm the considerations done for the NPV: in a thermal-
load following mode, considering the low amount of electricity produced, coupling an ORC to a biomass boiler does not increase the investment profitability. On the other hand, considering a TES in biomass boiler/ORC layout can decrease the IRR compared to the baseload case, CASE 2. The profitability index of the CASE 1 is also more profitable than CASE 3, since this allows higher global conversion efficiency due to the peak shaving effect of the thermal storage buffer. The Payback time of fig. 8 confirms the advantages of a TES in biomass-fired ORC plant since payback time is lower than the CASE 3. CASE 4 presents the lowest PBT and highest profitability.

6. Conclusions

In this paper, an energy analysis of a biomass-CHP configuration with a biomass boiler and an ORC with TES is proposed. The options with and without the ORC unit and with or without the TES are compared. The energy demand profile of a supermarket has been used to size the TES, the biomass boiler and to select the operating conditions of the plant. Based on the results of the thermodynamic simulations and upfront and operational costs estimate, the investment profitability is evaluated, for each configuration. The main conclusions are: (i) coupling the biomass boiler with a TES allows the boiler to work at higher part load conditions and at a higher global energy efficiency, with a lower biomass consumption and reduced emission; (ii) the hypothesis to supply heat to the store only by means of cogenerated heat from the ORC unit, and operate this generation system in heating load following mode, is not profitable in comparison to baseload operation to maximize electricity generation (and discharge excess heat). This work highlights that the profitability of ORC installation could increase if a more flexible plant, where the heat demand is satisfied also by the TES, is considered; in this case, a smaller ORC size could be selected, increasing equivalent operating hours and reducing investment costs. An electricity-load following operating mode could also be investigated for the ORC unit, as proposed in previous researches by the same authors. Further simulations to investigate the optimal ORC working fluid, size and thermodynamic parameters could be also carried out, in order to investigate the trade-off between electric efficiency and temperature of heat delivered to the demand.
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References

[24] Technical data from biomass furnace manufacturer Uniconfort and Sainsbury’s biomass boiler performance
[25] Data from ORC generation system manufacturer Enertime (www.enertime.com)