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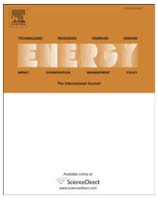

Size optimization of a biomass-fired cogeneration plant CHP/CCHP (Combined heat and power/Combined heat, cooling and power) based on Organic Rankine Cycle for a district network in Spain

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ABSTRACT

This paper presents a methodology to optimize the size (electric power) of a cogeneration plant based on a biomass-fired Organic Rankine Cycle and connected to an existing district heating network, maximizing profitability. First, a model to determine the hourly thermal energy demand profile of a location in Spain has been derived, from open access meteorological data included in Spanish building regulations. Partial load model of an organic Rankine plant has also been obtained to increase the operation hours. These tools have been applied to two locations in Spain with different climatic severities, calculating the optimal size of the plant. The business model does not include subsidies. Calculations show that for population between 10,000 and 20,000 inhabitants the size of the plant ranges from 2 to 9 MWe and the internal rate of return ranges from 6% to 18%. The coverage of the thermal energy demand ranges from 40% to 80%. Regarding the trigeneration mode, it is concluded that cooling is only worth in locations with high summer severity and in full load operation mode, being the optimal size of the plant smaller in trigeneration mode than in cogeneration.

1. Introduction

Nowadays, biomass has become a very interesting fuel for electricity generation because its CO_2 emissions reduction potential and its suitability for small and medium scale energy production facilities [1]. The integration of biomass into cogeneration CHP (Combined heat and power) and trigeneration CCHP (Combined heat, cooling and power) systems has also been revealed as an excellent method of energy supply for buildings [2].

Two different technologies may be applied to biomass power generation: gasification and combustion. Gasification [3] shows a higher efficiency but still entails a high investment; on the other hand, CHP technologies based on biomass combustion are well-proven in this field [4], being the ORC (Organic Rankine Cycle) a mature technology in medium-scale power range (200–2000 kWe) [5], achieving in Europe an overall installed power higher than 120 MWe (more than 120 plants) with an average availability higher than 98% and more than 2,000,000 h of operation [6]. ORC technology is also being proposed for micro-scale power range (lower than 10 kWe) due to its lower investment when compared to Stirling engine [7].

An important issue about CHP/CCHP plants is the operation strategy. Hawks et al. [8] perform a literature review about this topic, finding the heat-led strategy the most usual, especially for micro-CHP at household sector. This means that the thermal demand is exactly followed therefore heat wasting is avoided. Technologies with high heat-to-power ratio (Stirling engine and ORC), found in household sector, exhibit the maximum primary energy savings with this operation mode, although the minimum cost may be achieved with hybrid electricity- and heat-led, depending on the regulatory frame [9]. So, high feed-in tariff systems may lead to situations where oversized CHP plants producing as much electricity as possible and wasting a lot of heat with low fuel prices can be economically feasible [10]. On the other hand, Alipour [11] conclude that profitability of CHP plants at industry and commercial sites can be improved when the excess of heat is sold to close costumers. Regarding the electricity, some strategies lead to self-consume all the produced electricity, using the grid eventually as a storage system [12]. On the other hand, Stoppato [10] compares two scenarios: maximum electricity production with heat rejection and thermal-led strategy with variable electricity production, selling all the produced electricity to the grid in both cases.

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Although the maximum heat recovery (thermal-led strategy) produces the maximum primary energy savings, sometimes the revenues due to it are not included in the cash-flow considered by financial institutions, being this practice a barrier for CHP [1]. This issue agrees with the analysis of barriers found for biomass-fired CHP at United Kingdom by Wright et al. [13]. Another identified barrier is the exigency of high levels of electric self-consumption due to the high heat-to-power ratio found at household sector [14]. Other barriers for CHP and district heating networks deployment in the European Union are depicted by Colmenar-Santos et al. [15].

Several authors have analyzed the economic feasibility of ORC fueled with biomass, and demonstrate that it represents an interesting solution for small- and medium-scale residential applications [16] and district heating [17]. Duvia et al. [18] have focused on cogeneration systems operating as base load supply in existing district heating plants and show that ORC units may have a good feasibility with frame conditions typical for the whole European area. Noussan et al. [19] analyze the inclusion of thermal energy storage in a similar scenario, charging it with the excess thermal production of the ORC; the economic feasibility is evaluated considering the Italian regulation frame. Gebremedhin [20] studies the impact of different levels of biomass prices and emission allowances on the choice of fuels and production technologies in a district heating system in Sweden. A study developed in Austria [17] shows that a medium-scale ORC plant without heat storage is currently viable for annual heat demand higher than 5 GWhth and for biomass prices lower than 17 €/MWh. Algieri et al. [21] demonstrate the economic feasibility of micro-scale plants with the tariff scenario in Italy. Uris et al. [22] conclude that subcritical recuperative ORC systems are technically and economically feasible in district heating systems in Spain when selling electricity to the grid at market prices (without subsidies) and thermal energy to the consumer below market prices.

In order to increase the plant operation hours and thus improve profitability, it is necessary to operate it at partial load conditions [23]. Models to solve the off-design operation have been developed for ORC plants by several authors. Manete et al. [24] employ a global extrapolation model for heat exchangers and dimensional analysis for the turbine, including capacitances to simulate the behavior of the mass in transient periods. Walnum et al. [25] and Gabbrielli [26] use a detailed model for heat exchangers, employing the latter the Stodola equation for the turbine. Patnode [27] proposes the Stodola equation for the turbine and a quadratic extrapolation for heat transfer conductances based on Dittus–Boelter equation for a steam Rankine solar power plant. Other issues about dynamic response of ORC units are analyzed by Ziviani et al. [28] who compare different commercial softwares and develop detailed models able to represent the transient response.

An accurate economic assessment of the CHP and CCHP plant requires an estimation of the thermal load, which presents hourly and monthly variation in a household application. The calculation of the thermal load can be based on hourly average data or load predictions. Xu et al. [29] evaluate the performance of a CCHP system for a data center, by a case study through two-year operational data and transient modeling. Bacher et al. [30] present a method for forecasting the thermal load for space heating in a single-family house using measured data from actual houses combined with local climate measurements and weather forecasts. Gadd et al. [31] perform an analysis of one year of hourly heat meter readings in order to provide heat load patterns. Noussan et al. [19] consider actual heat measurements taken every 6 min over several years of operation and process them to develop a heat demand model. Wood et al. [1] and Michopoulos et al. [32] determine the thermal load using the Energy Plus software (U.S. Department of Energy) [33] for their investigation of the energy, environmental and financial benefits of housing space heating with biomass. Other authors develop load prediction methods based on regression analysis [34] or autoregressive with exogenous time and temperature indexed model [35]. Powell et al. [36] find nonlinear autoregressive models with exogenous inputs as the best methodology between several ones based on artificial neural networks.

The degree-day method has also been used to generate the hourly thermal energy demand profile. Büyükalaca et al. [37] calculate the heating and cooling degree-days with variable-base temperatures for Turkey in order to estimate building energy needs and Martinaitis et al. [38] present the application of degree-days in exergy analysis of buildings. Also the errors in degree-day method have been analyzed in building energy analysis [39]. The degree-day method can be combined with solar radiation data, as done by Carlos et al. [40], comparing several different simplified methodologies for building energy performance assessment during winter. In Spain a combination of degree-days and solar radiation is used to define the climatic severity index [41] which determines the thermal load demand and it is used to divide the country in climatic zones in order to establish building energy performance regulations [42].

Another important issue is the optimization of the size of the plant (usually expressed by its rated electrical power). Algieri et al. [21] propose the use of the MR (maximum rectangle) methodology over the cumulative power thermal load profile, considering only full load operation. Shaneb et al. [43] go in depth in this topic comparing the MR method with a linear programming optimization of profitability with heat-led strategy running the CHP unit from 0% to full load, assuming constant both thermal and electrical efficiencies.

This paper develops a methodology to determine the optimal size and configuration (CHP or CCHP) of a biomass-fired ORC plant that maximizes the profitability for district heating and/or cooling. A model to calculate the hourly thermal energy demand of a location in Spain based on climatic severity index has been obtained. The use of climatic severity data allows to obtain the hourly thermal demand in a simple way, which is the basis to build the cumulative power thermal load profile. This profile is used to calculate the optimal size of a CHP/CCHP plant in two scenarios: full load and partial load operation, always in heat-led strategy. The maximization of the profitability is used as the criterion to determine the size of the plant. The developed methodology is applied to two locations, one with extremely high winter severity and low summer severity and another one with high winter and summer severity.

2. Methodology

2.1. Description of the system

Fig. 1 shows the system layout, based on a typical arrangement for biomass-fired cogeneration plants (CHP/CCHP) based on Organic Rankine Cycle [16]. Biomass is fired in a boiler, where thermal oil is heated and then releases the heat to an organic fluid in the evaporator before entering the turbine where it is expanded. In order to take advantage of the superheated vapor state at the turbine outlet, a recuperator IHE (Intermediate heat exchanger) is used to recover heat from the fluid leaving the turbine. After releasing heat at the IHE the fluid enters the condenser where the useful heat is removed. When the fluid leaves the condenser it is suctioned by a pump which increases its pressure and sends it to the IHE to be heated before entering the boiler. Based on a previous study carried out by authors [22] hexamethyldisiloxane (MM) has been chosen as organic fluid working in a subcritical cycle, being