# Fostering sustainable micro district heating: A tool for biomass boiler design



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# Fostering sustainable micro district heating: a tool for biomass boiler design

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**Abstract**: Biomass micro district heating networks can represent an opportunity for small communities to comply with European directives and achieve a sustainable energy supply. To foster their adoption, a facility management provider should rely on methods and tools to properly size the biomass energy conversion system, so that it can better suit the local community characteristics and requirements. To this end, the concepts of partial and complementary degrees-hour are introduced in order to partition energy flows along the whole heating season between the biomass boiler and the fossil fuel peak load one for each possible biomass boiler size. Basing on such division, the operational profile of the plant and related costs as well as carbon dioxide equivalent emissions can be evaluated. The methodology is embedded in a decision support tool, which provides the minimum cost solutions as well as the more environment-friendly ones. Results from the application of the tool to a real case of a mountain village are discussed.

**Keywords**: Sustainable energy supply, renewable energy, facility management, biomass district heating, biomass boiler design.

## 1. Introduction

The use of local wooden biomass as a sustainable energy supply source for space heating through small sized district heating networks represents one of the solutions to comply with EU 2020 objectives of reducing fossil fuel adoption and greenhouse gases emissions (Panoutsou, 2016). Biomass is recognized as a viable chance to increase the share of renewable sources in energy systems with environmental, economic and social benefits, since its adoption is $CO_2$ neutral, while providing a low-cost fuel and local promotion for rural population. In mountain areas, for example, biomass is available from forest maintenance and as process waste of wood transformation along the furniture supply chain. Its exploitation for micro district heating can make local communities self sufficient for heating requirements of public and residential buildings, as well as enhancing their image of green conscious locations for touristic promotion. To foster biomass energy conversion systems, Facility Management (FM) providers should rely on tools to develop solutions that better suit local communities resources and requirements.

The design of a biomass boiler for micro district heating only networks is affected by the particular characteristics of the fuel in comparison to fossil ones and the significant investment required for the biomass energy conversion plant. Two main approaches are commonly adopted by practitioners for boiler sizing, based on peak load and base load design, respectively.

By the former, boiler heat capacity is set to match the peak thermal load over the whole heating season, since biomass fuel is very cheap and leads to low operational costs. This oversizing leads to higher capital costs, but also to operational issues, since the boiler should work at partial loads for most the time, with an inefficient combustion, fouling at heater exchangers, and increased pollutant emissions (Masa and Vondra, 2015).

To overcome these issues, according to the base load design principle, a smaller capacity can be chosen, in order to make the boiler working at near nominal conditions, but with the installation of an additional fossil fuel burner in order to meet peak loads. In this case lower investments are required for the biomass boiler, but a portion of energy demand should be covered by traditional fossil fuel systems with related costs and emissions. A common practice is to set boiler thermal capacity at 50% of the peak load, which is typically able to meet a significant amount of the total thermal energy requirements depending on demand profile, and to match the base load when operating at its minimum output (Palmer et al., 2011). Another way is to select as boiler capacity the average thermal power on the whole heating season. Given the total annual thermal energy demand and the annual operating hours, the required average thermal power to be provided to the district heating network can be easily obtained and the boiler sized consequently by introducing the global efficiency of the system (biomass plant + district heating network) (Vallios et al., 2009).

Both the above mentioned approaches lead to suboptimal solutions, while the biomass energy conversion plant should be designed in order to minimize the total costs incurred by a FM provider, so that economic benefits can in turn be reflected on the local community. Biomass availability, energy efficiency, and pollutant emissions should also be taken into account in order to foster more and more sustainable solutions. This study proposes a new approach to properly sizing the biomass boiler for micro district heating system, i.e. for thermal power less than 1 MW as typical of small communities. A tool has been developed, which links the selection of the biomass boiler capacity to the analysis of the operational profile of the biomass energy plant during the whole heating season, taking into account the specific features of the community to be served.

The paper is structured as follows. In section 2 the new approach embedded in the design tool is described. Its application to a case study is analysed in section 3, while conclusions about its potential and future enhancements are derived in section 4.

## 2. A new approach for biomass boiler design

In order to overcome issues described in the previous section, the total yearly cost of the biomass energy conversion plant should be calculated as a function of the possible biomass boiler nominal heat capacity $P_{bio}$, by developing the expected system operational profile along the whole heating season. For a given $P_{bio}$, in facts, energy flows to be provided to the micro district network basing on the expected outdoor temperature can be partitioned between the biomass boiler and the fossil fuel one, allowing to calculate related operational costs. Thus, a curve of total costs (investment and operational ones) to be minimized can be derived for $P_{bio}$ in the range ($P_{min}$, $P_d$), where $P_{min}$ represents the minimum heat capacity available in the market and $P_d$ the design heat load, i.e. the heat peak load referred to the outdoor design temperature as defined in the European Standards (EN 12831:2003).

To suit the operational profile to the local community to be served, the following input data should be acquired:

- Required indoor temperature $t_{id}$ and daily heating period for each building type (e.g. residential buildings, swimming pools, sports centres) served by the micro district heating network. These values are generally set by law; the decree DPR 412/93, for example, classifies Italian building types into eight main classes, each with a nominal indoor temperature. Moreover, it associates the allowed maximum heating hours per day and the duration of the heating season on the basis of the climate zone the analysed location belongs to. These values can be adapted whenever particular requirements of the local communities should be introduced;
- Global heat loss coefficients $H_w$ for each building $w$ and the average overall efficiency $\eta_{glob}$ of the district heating network. The former data are commonly available at the municipal office, where all facilities projects are recorded. For the latter, instead, we can refer to literature values (e.g. Vallios et al., 2009);
- The average hourly temperature distribution of a typical year, which is easily provided by the local meteorological agencies;
- Local supply cost and availability of biomass and fossil fuel cost for the peak boiler.

In the following subsection 2.1 the methodology to develop the heating system operational profile is introduced. In section 2.2 the cost evaluation embedded into the proposed tool is described.

### 2.1 Developing the system operational profile

For sake of simplicity, the case of one single building will be initially analysed. Given the building structure global heat loss coefficient H (EN 12831:2003), the overall heating system efficiency $\eta$ and the building indoor design temperature $t_{id}$, the minimum value of the outdoor temperature $t_{o,bio}$ covered by a biomass boiler of heat capacity $P_{bio}$ can be obtained from Equation (1):

$$P_{bio} \cdot \eta = H \cdot (t_{id} - t_{o,bio}) \quad [kW] \tag{1}$$

If the actual outdoor temperature in a given hour exceeds $t_{o,bio}$, then the biomass boiler is able to satisfy the whole thermal requirements of the building in that time span. This operating condition is represented in Figure 1, assuming a linear function of the heat load with the outdoor temperature, as well as steady-state condition of the heating system.

On the contrary, when the hourly outdoor temperature is lower than $t_{o,bio}$, the biomass boiler should operate at its nominal power $P_{bio}$ while the traditional fossil-fuelled boiler covers the remaining energy demand (see the yellow area C in Figure 1).

The variable $t_{o,bio}$ allows to partition the annual thermal energy demand between the two different kinds of boilers. To this end, analogously to the Degrees-Day methodology (UNI 10349), the Partial Degrees-Hour $DH_{h-P}$ and the Complementary Degrees-Hour $DH_{h-C}$ can be defined, as follows:

$$DH_{h-P} = \sum_{j=1}^{S} \left( t_{id} - t_{o_{h,j}} \right) \quad \forall h : t_{o_{h,j}} \geq t_{o,bio} \quad [K \cdot h] \tag{2}$$

$$DH_{h-C} = \sum_{j=1}^{S} \left( t_{id} - t_{o_{h,j}} \right) \quad \forall h : t_{o_{h,j}} < t_{o,bio} \quad [K \cdot h] \tag{3}$$

where $t_{o_{h,j}}$ , represents the average outdoor temperature during the hour h of the j-th day, and S is the total amount of days within the analysed heating season.

By introducing the daily period $T$ of operations for the biomass energy conversion plant, the hourly values $DH_h$ can be aggregated into the related global value $DH_T$ as follows:

$$DH_T = DH_{T-P} + DH_{T-C} = \sum_{h \in T} DH_{h-P} + \sum_{h \in T} DH_{h-C} \tag{4}$$

On the basis of Equations 1-2, the following quantities can also be defined:

- $N_1$ as the total amount of hours within the heating season when $to_{h,j} \geq to,bio$
- $N_2$ as the total amount of hours within the heating season when $to_{h,j} < to,bio$

The quantities $DH_{T\text{-}P}$, $DH_{T\text{-}C}$, $N_1$ and $N_2$ allow a more detailed estimation of the seasonal thermal requirements of a building and how they should be divided between the biomass and fossil fuel boilers, considering the actual heating period and the specific climate data of the location.

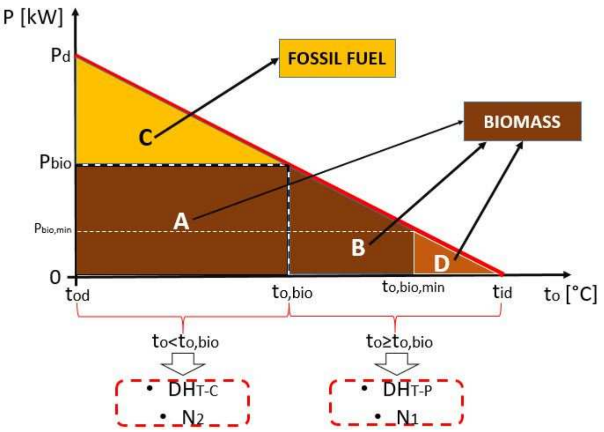


**Figure 1 – Thermal load partition between the biomass boiler and the fossil fuel one as function of the temperature to,bio.**

The overall thermal energy requirement of the heating season is conceptually related to the sum of the areas A, B, C, and D in Figure 1, once heat losses H have been introduced. The thermal energy, entirely supplied by the biomass boiler during the whole heating season (i.e. for $N_1$ hours) by operating in partial load mode, is related to the area B of Figure 1 and can be obtained from the quantity $DH_{T\text{-}P}$.

The thermal energy supplied to the building thanks to the combined operation of both the biomass and the fossil fuel boiler is represented by the areas A and C in Figure 1, respectively, and can be obtained through the quantity $DH_{T\text{-}C}$. Finally, the area D represents the thermal energy demand supplied by the thermal storage tank, provided with the biomass energy conversion module, to avoid operational conditions of the boiler under its minimum load.

The methodology can now be extended to the case of multiple buildings served by a district heating network. In this case, the design heat load of the biomass energy conversion system should take into account the cumulative thermal energy requirements of all the buildings in the network.

Concerning the allocation of the thermal energy requirements between the two different kind of boilers, an hourly-based approach is needed, since the set of buildings to be heated can change hour by hour depending on their requirements. This means that the partition shown in Figure 1 should be generated for each hour h of the period T. The related temperature $to,bio,h$ can be evaluated by the following relation:

$$to,bio_h = \hat{t}id_h - \frac{P_{bio} \cdot \eta_{glob}}{\sum_{w=1}^{K_h} H_w} \qquad \forall h \in T \qquad (5)$$

where w represents a building among the $K_h$ out of K total utilities in the network, which generate a heat load during h. The hourly indoor design temperature $\hat{t}id_h$ is obtained as the weighted average of indoor temperatures for all the buildings $K_h$ and the related $H_w$ coefficients.

The Partial Degrees-Hour $DH_{h\text{-}P}$ and $DH_{h\text{-}C}$ can be calculated as shown in the following Equation 6 and 7:

$$DH_{h-P} = \sum_{j=1}^{S} \left( \hat{t}id_h - to_{h,j} \right) \quad \forall h : to_{h,j} \geq to,bio_h \quad [\mathrm{K \cdot h}] \quad (6)$$

$$DH_{h-C} = \sum_{j=1}^{S} \left( \hat{t}id_h - to_{h,j} \right) \quad \forall h : to_{h,j} < to,bio_h \quad [\mathrm{K \cdot h}] \quad (7)$$

The global metrics $DH_{T\text{-}P}$ and $DH_{T\text{-}C}$ can then be calculated by Equation 4.

### 2.2 Costs evaluation

Once the operational profiles of the energy conversion plant for each possible heat capacity of the biomass boiler have been generated as described in the previous subsection, total annual costs as function of $P_{bio}$ only can be easily accounted.

The investment costs for the commercially available biomass boilers suitable for micro-district heating networks (heat power range approximately lower than 1 MW) have been collected, leading to the interpolation function represented in Figure 2. All the auxiliary equipment needed for the operation of the biomass energy conversion system has been accounted, including the container/housing structure, the fuel storage container and the automatic handling system, the hydraulic system, pumps and skid pump, stack, electrical system, and the insulated thermal storage tank usually coupled with the boiler for buffering function.

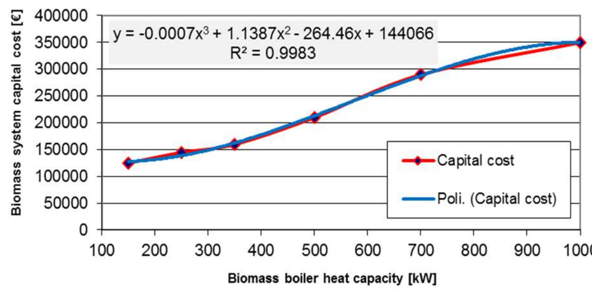


**Figure 2 – Capital cost as function of the biomass boiler size**

When the micro district heating system should cover also domestic hot water (DHW) requirements, which can represent a significant amount of heat demand depending on building use (e.g. swimming pool), then the related thermal power $P_{DHW}$ should be introduced. $P_{DHW}$ can be considered as a constant value along a year, independently of outdoor temperature. Therefore, it can be added to $P_{bio}$ to associate the final size of the biomass boiler with the proper investment cost in the optimisation process.

As concerns operating costs, we consider the fuel costs and the maintenance costs. The personnel costs have not been included since no dedicated operators are needed for such small size plants. District heating network costs (pumps, heat exchangers,..) have been also neglected since they are independent of $P_{bio}$. The economic estimation of fuel costs to cover the seasonal thermal energy requirements is then based on the energy partition previously discussed, since different supply costs should be accounted for the biomass and natural gas. The maintenance costs are set as a percentage of the energy cost (commonly 0,15%).

The tool has been developed using commonly available spreadsheets, in order to enhance its adoption by practitioners.

## 3. A case study

The Sustainable Energy Action Plan (SEAP) of a small mountain village in Northern Italy gave us the opportunity to actually apply the proposed tool. The analysed case study consists of a micro-district heating network potentially serving three existing public utilities located at short distance, in particular two school buildings and the municipal gymnasium, which are currently supplied individually by natural gas boilers, for a total design heat load of about 1 MW. DHW requirements are negligible for the school buildings, while they are currently satisfied by a dedicated facility for the gymnasium; therefore, they have not been considered. The proposed intervention consists of the installation of a biomass energy conversion system to feed the micro-district heating network, while maintaining the existing natural gas boilers as peak loads and backup boilers. The latter solution has been chosen due to the limited available financial resources of the local community; in the future, a more efficient fossil fuel solution can be sized.

As highlighted in section 2, average hourly values of temperature distribution along a typical year have been calculated by averaging historical data of the last decade provided by the local meteorological agency. An energy audit for the collection of heating requirements in terms of internal desired temperature and heating duration, heat loss coefficients and heating overall efficiencies $\eta_{glob}$ for the 3 buildings has been performed. The resulting thermal energy demand of the micro heating network is reported in Figure 3. In particular, in Figure 3a the hourly demand profile of a given day (namely March the 15th) can be analysed (see the blue coloured line), while in Figure 3b the resulting daily duration curve along the whole heating season is provided.

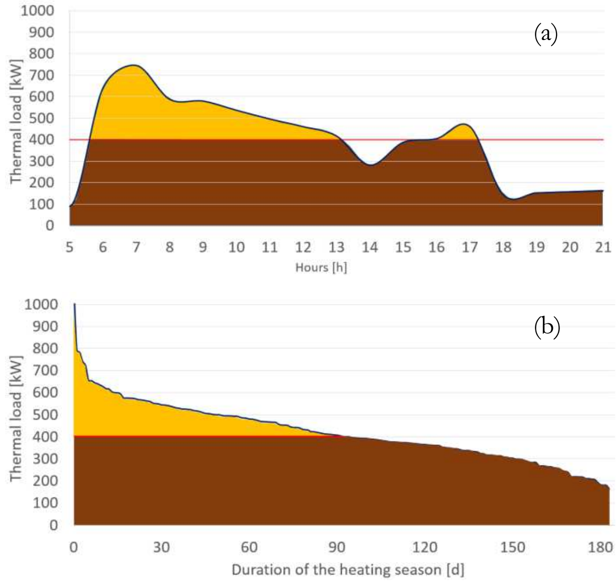


**Figure 3 – The operational thermal profile: hourly (a) and daily duration curve (b)**

Basing on the capital cost curve shown in Figure 2 for the biomass boiler, the total investment has been calculated and related to one year by the annuity factor, considering a capital lifetime of 10 years and an interest rate of 5%; no additional investment is accounted for peak boilers, since they are already available. As concerns operative costs, the partition of energy flows associated with each potential boiler size is generated as described in section 2 and reported for a 400 kW $P_{bio}$ in Figure 3 (see yellow and brown coloured areas). Related fuel costs have been evaluated by considering a supply cost of 0.10 €/kg for wooden chips from forest maintenance and process waste of local firms (30% water content, Lower Heating Value 3.4 kWh/kg) and a local natural gas cost equal to 0.74 €/$Sm^3$ (from the bills). A maintenance cost of 0.1 c€/kWh has been accounted. The resulting total yearly cost for each potential $P_{bio}$ has been calculated and shown in Figure 4 (see the red line), where also $CO_2$ equivalent emission savings have been highlighted (see the green line).

The optimal value of the biomass boiler capacity is nearly 400 kW for a total yearly cost of 46,620 € and emission savings of 127.7 $CO_2$ eq ton/year. The cost curve in Figure 4 as well as the duration curves in Figure 3 provided by the tool can be used to assess the impact of different decisions by the FM provider. If the peak load approach is chosen, leading to a $P_{bio}$ of 1000 kW, then a related cost increase of about 22% is encountered (see Figure 4) with respect to the optimal solution. With the base load approach of 50% of the peak load, $P_{bio}$ should be set to 500 kW with a cost increase of 1.1% if compared to the minimum. A different perspective can also be adopted when choosing the best biomass boiler size; a FM provider can be forced to select a more green-conscious solution, in order to make the local community compliant with the European Directives. In the proposed case study, the emission curve stabilises at around $P_{bio}$ = 650 kW, which corresponds to a cost increase of 7.3% with respect to the minimum cost solution. In this way the FM provider can better set the thermal energy cost to be proposed to its clients.

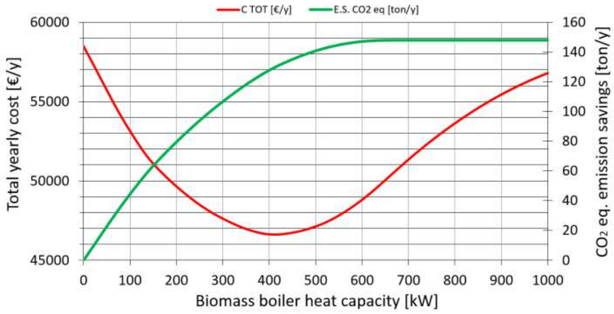


**Figure 4 – Total cost and emissions curves**

## 4. Conclusions

A new approach to properly size a biomass energy conversion plant for micro district heating networks has been proposed and embedded in a tool. The method allows to create the operational profile of the plant along the whole heating season for each potential thermal power of the biomass boiler, by partitioning the required energy flows between the biomass and the fossil fuel boiler serving as integration and backup. In this way, both capital and operative costs can be better evaluated and minimized, while adhering to local community characteristics in terms of specific heating requirements, as highlighted by the analysed case study.

Future research will be devoted to introduce thermal heat storage in order to better exploit the biomass renewable source. Moreover, the biomass boiler can be coupled with other renewable energy sources such as solar panels to satisfy DHW requirements. The methodology can be then extended to medium district heating networks, by introducing biomass-based CHP facilities.

## References


Panoutsou, C. (2016). The role of sustainable biomass in the heat market sector for EU27. *WIREs Energy and Environment*, 5, 430-450.

Nikodinoska, N., Buonocore, E., Paletto, A., Franzese, P.P. (2016). Wood-based bioenergy value chain in mountain urban districts: An integrated environmental accounting framework. *Applied Energy*. Available at http://dx.doi.org/10.1016/j.apenergy.2016.04.073

Masa, V., Vondra, M. (2015). Operational problems: biomass boilers with oversized output. *Chemical Engineering Transactions*, 45, 331-336.

Palmer, D., Tubby, I., Hogan, G., Rolls, W. (2011). *Biomass Heating: a Guide to Medium Scale Wood Chip and Wood Pellet Systems.* Biomass Energy Centre, Forest Research, Farnham.

Vallios, I., Tsoutsos, T., Papadakis, G. (2009). Design of biomass district heating systems, *Biomass and Bioenergy*, 33 (4), 659-678.

EN 12831:2003, Europeans Standard, *Heating Systems in Buildings. Method for calculation of the design heat load.*

UNI 10349. *Riscaldamento e raffrescamento degli edifici. Dati climatici*, in Italian