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Feasibility of small-size biomass-fueled Hirn-cycle cogeneration plants

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Abstract

Biomass utilization seems to be the easiest way to increase the exploitation of renewable energy sources for small and medium scale energy production. In particular, ligneous biomass, thanks to its availability, appears to be the most suitable for cogeneration applications. Among the several technologies available for energy conversion, the most frequently utilized system to generate electric power is still a process based on a Rankine or Hirn cycle with water as a working fluid. This solution seems quite interesting particularly for small size cogeneration plants because of its availability on the market and the analogy with typical applications involving fossil fuels. Many investors (e.g. Energy Service Companies, ESCOs) might be interested in the installation of this type of cogeneration plants in order to reduce the environmental impact of the system and therefore to benefit from governmental incentives. In order to assess the feasibility of this type of plants, it is important to investigate the possible thermodynamic, economic and technologic constraints. An analysis of these factors has been carried out in the present study.

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Keywords: cogeneration; steam; biomass; Hirn cycle; techno-economic feasibility

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1. Introduction

Diffusion of renewable energy technologies is still often limited by plant costs, making these new systems

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economically non-competitive when compared with standard ones. In order to promote their diffusion, many incentive strategies have been proposed by European governments. Concerning biomass, the development of small size plants for local production of thermal and electric energy seems quite interesting in order to increase the diffusion of systems with low environmental impact. Power production from biomass can be carried out through external combustion (e.g. steam cycles, organic Rankine cycles, Stirling engines), or internal combustion after gasification or pyrolysis (e.g. gas engines, Integrated Gasification Combined Cycle -IGCC-). External combustion has the disadvantage of delivering limited conversion efficiencies (max 30–35%) [1], while internal combustion has the potential of higher efficiencies, but the disadvantage of needing thorough and often problematic gas cleaning.

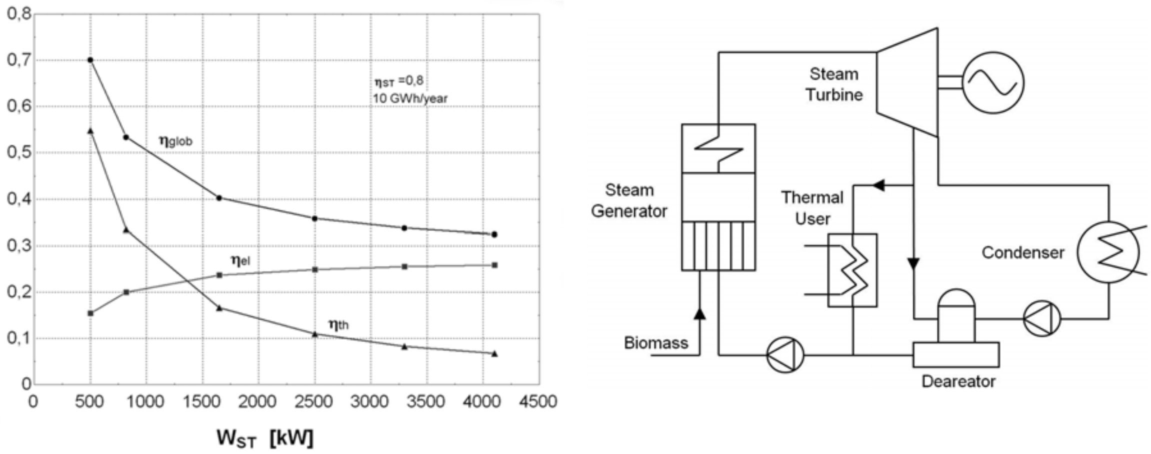
The most common systems to generate electric power are the processes based on the Rankine cycle with water as a working fluid [2]. Most of them use a steam turbine but some examples with reciprocating engines also exist [3]. However, diffusion of Organic Rankine Cycle (especially for low delivering temperature [4, 5]) and internal combustion systems has been strongly increasing in the last years [6, 7, 8]. In particular, power and heat cogeneration by solid biomass is one of the most interesting options for a sustainable and reliable energy supply due to its high availability [9].

Italy, as many other European countries, has an abundant supply of ligneous biomass; primarily wood waste or industrial process waste (such as paper production or wood crafting) [10]. For this reason, the diffusion of small size cogeneration plants working with ligneous biomass to produce locally thermal energy and electric power is a very attractive perspective [11]. In order to promote the diffusion of this type of power plants, the development of tools to investigate their feasibility could be very useful. This aspect was investigated by the authors in a previous study [12] where techno-economic feasibility of ORC, IGCC and steam Hirn cycle technologies was compared for several sizes and thermal requests. The main results were that IGCC and ORC are the best solution for small size applications, but they are affected by strong modularity requirements. For electrical size over 2 MW_{el} the steam Hirn cycle is still the most common solution. In this paper, the authors present the results of a wide-range analysis on superheated Rankine cycle with water as a working fluid.

The thermal requirement was satisfied by a steam extraction from the turbine and no biomass pre-drying system was considered [2]; this solution, compared to the other ones, offers more simplicity, component availability on the market and reference applications. The goal of the present analysis is to understand the influence of incentive availability, working conditions or design choices on the techno-economic feasibility of a small size plant. Whether a cogeneration plant is managed by an Energy Service Company (ESCO) or by other users the most important parameters for an overall design are usually the amount of energy to be produced and the overall annual efficiency. The first is needed to satisfy the user necessity, the second mainly to improve the economic revenue but also to have access to incentives, authorization easing and so on. The first step of design process is the definition of the proper steam turbine size. Once given the request of thermal energy (i.e. steam extraction pressure and mass flow rate) and a reference value of steam turbine efficiency, the overall plant efficiency changes with increasing steam turbine size (Figure 1 sx).

Global efficiency is the sum of electric and thermal efficiencies, which have divergent trends. Electric efficiency increases with the turbine size because the influence of extracted steam mass flow rate decreases. The thermal efficiency, however, decreases with the turbine size because the amount of recovered thermal energy is a constant whereas the consumption of biomass grows. Therefore, in order to achieve high global efficiencies, small size steam turbines seem to be preferred. On the other hand, when reducing turbine size some problems of technical availability and economic feasibility arise, and therefore some configurations, even being thermodynamically possible, could not match a technical or economic feasibility. For this reason a tool to investigate the thermodynamic, technologic and economic feasibility of this kind of cogeneration plant was developed.

Starting from a given thermal energy request and a minimal target for turbine efficiency, the tool allows the analysis of the thermodynamic behavior of the power plant and the definition of the components' size. Since a market check has been carried out by considering several distributors of plant components, it is possible to identify those configurations that are technologically unfeasible. Once a solution is chosen, an economic analysis is carried out to estimate the investment feasibility.



(sx) (dx)

Fig. 1. Trend of global, electric and thermal efficiency for different steam turbine size (sx). Diagram of analyzed cogeneration plant (dx)

2. Thermodynamic model

In Figure 1 (dx), a schematic of the modelled plant is shown. This is a Hirn cycle based power production plant with steam extraction for cogeneration. In this study a no-regenerative cycle was considered in order to be analyzed more easily. Since the regenerative heat exchanging practice allows increasing performance of Hirn steam cycle but implies more complex layouts it is therefore generally avoided for small size plants. The thermodynamic cycle has been simulated by Engineering Equation Solver (EES) using its internal libraries for the evaluation of steam conditions [13].

2.1. Assumptions

Some simplifying hypotheses were assumed. The plant was considered to be working in steady state conditions at the component nominal values without any off-design or transitory conditions. The steam extraction from the turbine occurs at a fixed pressure and both turbine and steam generator efficiencies are constant. A steam extraction, at the minimum pressure allowed by the turbine specifications, was used both for the thermal user and the deareator. The maximum extraction mass flow rates were 10% and 55% of total turbine mass flow rate respectively for the deareator and the thermal user. These values are within the typical operating ranges stated by the turbine manufacturers. Pressure losses, thermal dispersions and pump works were not considered as they lead to result variations lower than the analysis accuracy. The biomass low heating value (LHV) is strongly influenced by its humidity. The model evaluates LHV by means of a correlation as given by the local suppliers, defined as:

$$LHV = -\frac{20.523 \cdot \phi}{100} + 17.700 \tag{1}$$

where *LHW* is the low heating value [kJ/kg] ϕ is the biomass water content [%]. No biomass pre-drying system was considered. Atmospheric conditions have an important influence on the plant performance. Nevertheless this analysis considered only two working conditions depending on the season (hot and cold season) in order to achieve more general and conservative results. During each season the following quantities were considered as constant:

- Temperature of cooling fluid at condenser (the pinch point has been estimated at 10 K);

- Thermal requirements of the user (the different thermal capacities are obtained by varying the mass flow rate of extracted steam);
- Biomass humidity during each season (the low heating value of the biomass depends only on its water content).

2.2. Inputs

The model requires some inputs. They are:

- Plant working period (hours per year);
- Annual thermal requirement of the user and percentage of heat for the cold season.
- Ratio between hours at high thermal requirement (cold season) and those at low thermal requirement (hot season);
- Temperature level needed for the thermal user;
- Seasonal humidity of the biomass;
- Average annual and seasonal plant efficiency (global, electrical and thermal).
- Steam turbine nominal efficiency.

2.3. Technological inputs and constraints

In order to understand the technological constraints of this kind of installation, many manufacturers of steam turbines and biomass steam generators were contacted. Local manufacturers can provide biomass steam generators with a maximum pressure and temperature of 40-50 bar and 400-430 °C respectively with an average efficiency of 90% and 50% maximum allowed humidity of biomass. No biomass pre-drying system is required for standard humidity ranges of lignose biomass. Steam turbine performance depends greatly on its technological level. Its efficiency varies between 60 and 80 % and the minimum steam extraction pressure between 4 and 2 bar respectively. In addition, the steam turbine manufacturers state that the smallest available product size ranges from 900 kW_{el}, for a low technological level (low efficiency), to 1800 kW_{el}, for higher efficiency machines.

2.4. Outputs

The model estimates the steam mass flow rate and the thermodynamic state in every section of the plant, the size of every component, the steam turbine power output, the annual thermal and electrical energy production and the annual consumption of biomass.

3. Economic model

In addition to the previously described model, an economic model was also developed in order to assess the economic feasibility of the plant. The main parameters used in this analysis were the net present value (NPV), the payback period (PBP) and the investment multiplier (M), respectively defined as:

$$NPV = -I_0 + \sum_{k=1}^{n} D_k \cdot (1+i)^{-k} \tag{2}$$

$$PBP \Rightarrow \sum_{k=1}^{PBT} D_k \cdot (1+i)^{-k} = I_0 \tag{3}$$

$$M = \frac{NPV}{I_0} \tag{4}$$

where I_0 is the investment cost, D_k is the net cash flow, n is the plant life (years) and i is the MARR. As input data, the economic analysis requires the following quantities: life period of the plant, purchase price of biomass, sale prices of thermal and electrical energy, amount and typology of available incentives, depreciation period, minimum attractive rate of return (MARR) and taxation profile. If necessary, borrowing of funds can also be taken into account.

The model estimates the plant start-up costs by considering components, piping, electrical connections and installation costs. A survey among suppliers and manufacturers was carried out in order to estimate these costs. Maps representing the size-efficiency-cost relationship for the different components have been thus defined and used in the model. Concerning costs for piping, electrical connections and steam generators, 15%, 10% and 5% of the overall investment were respectively considered. Running costs have been estimated considering biomass, maintenance and employees cost. In particular, employees cost was quantified as approximately 250 k€/year (three people working on the plant); maintenance cost is 0,75 €/MWh_{th} of thermal energy consumed for the steam generator and 7 €/MWh_{el} for the steam turbine.

By knowing the assumed sale prices for electrical and thermal energy it is thus possible to calculate the annual revenues of the plant; if necessary government grants can also be considered. Taxes are taken into account to assess the annual profit and then to calculate the financial parameters for the economic feasibility.

4. Results

By running the model for different values of annual thermal energy delivered and steam turbine efficiency, it is possible to create several maps describing the values assumed by thermodynamic and economic output variables. This approach allows an evaluation of technical and economic feasibility of the plant based on the cogeneration demand and the steam turbine technological level.

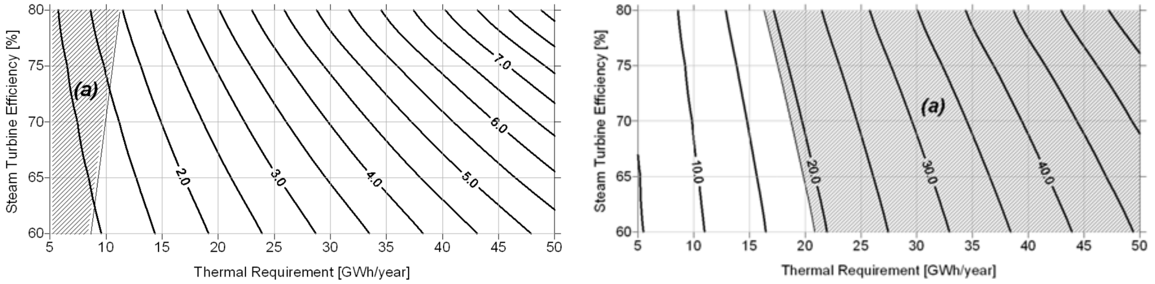
4.1. Case study analysis

The developed model was used to analyze a case study. An Italian wood factory producing plywood and laminated-wood was considered. The factory has approximately 19.000 tons per year of sawdust at 20% of humidity (constant over the year) as waste product. The biomass low heat value is 13.600 kJ/kg in agreement to similar substances [2, 14]. The factory maximum need is 5 MW of electric power and 15 GWh per year of thermal energy for the manufacturing process (water at 90°C). The thermal energy demand is constant during the year because it is only related to the production activity, free from seasonal requirements.

An ESCO could be interested in installing a small-size biomass-fueled Hirn cycle cogeneration plant. The ESCO should buy the biomass from the wood factory and produce electric and thermal energies to satisfy, totally or partially, its energy demand. The ESCO would get proceeds by supplying energy to the factory.

A total of 7.000 working hours per year can be assumed for the cogeneration plant, one-third in the hot season and two-thirds in the cold one. The ambient temperature is fixed at 20 °C during the cold season and 36 °C during the hot one. The required annual average efficiency of the plant is assumed at 45% because this is the minimum value needed to get the facilitations provided for the cogeneration plants (administrative and legal Italian authorizations). Life period of the plant is 20 years. Biomass price can be estimated in 0,035 €/kg and the sale prices for the thermal and electric energy are 0,05 €/kWh_{th} and 0,07 €/kWh_{el} respectively. The incentives for the energy production from renewable source are 0,11 €/kWh_{el}. Depreciation period is 10 years, the MARR 10% and profit tax rate 30%. The analysis does not take into account financing of any type.

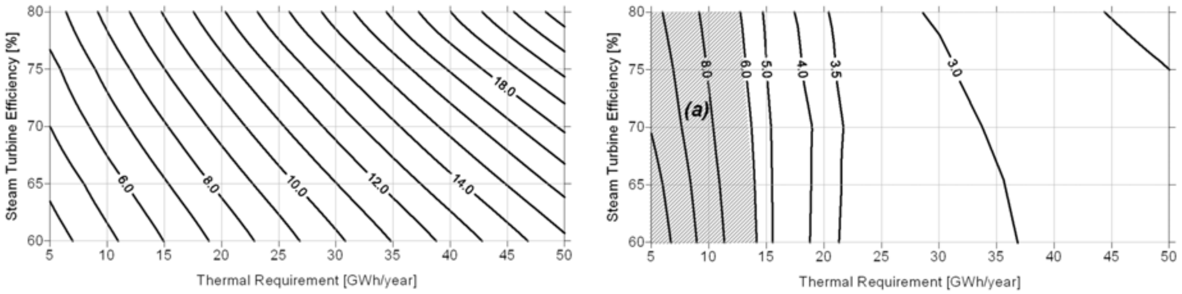
A sensitivity analysis has been carried out by varying steam turbine efficiency and annual thermal requirement. In Figure 2 (sx), calculated steam turbine size is shown. The smallest product sizes available on the market are known and a corresponding technical unfeasibility area can be marked off (a). Once the annual thermal requirement is assigned, different sizes of steam turbine can satisfy the request, depending on the chosen technological level. Many other parameters can influence the final design choice; these will be shown hereafter. Firstly, in Figure 2 (dx) the calculated biomass consumption is reported. Obviously, biomass consumption (ton/year) is influenced by biomass humidity.



(sx) (dx)

Fig. 2. Steam turbine power [MW] at 45% annual global efficiency; (a) technical unfeasibility area (sx). Biomass consumption [ton/year x 1.000] at 45% annual global efficiency; (a) biomass unavailability area (dx).

Available biomass amounts can limit the maximum steam turbine size. Plant start-up costs can be a similar limitation (Figure 3, sx). Maximum acceptable PBP is one of the most important parameters for investment feasibility. In this case study six years was considered as the maximum acceptable PBP. Figure 3 (dx) shows the estimated PBP in case of presence of state incentives, according to Italian regulations.



(sx) (dx)

Fig. 3. Plant start-up cost [M€] at 45% annual global efficiency. Payback period [years] at 45% annual global efficiency; (a) economical unfeasibility area

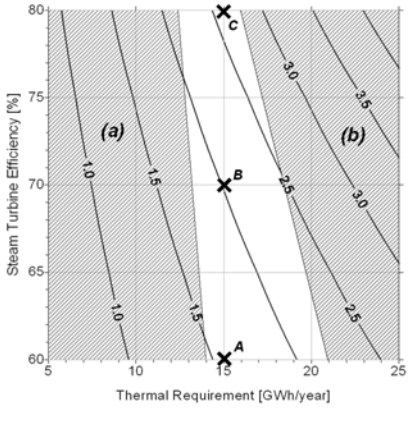


Fig. 4. Different plant configuration at 45% annual global efficiency; (a) technical and economic unfeasibility area; (b) biomass unavailability area; ST power [MW].

By overlaying on Figure 2 (sx) the maximum amount of biomass available (Figure 2, dx) and the six year PBP curve (Figure 3, dx) the area where the plant is feasible under both a technical and economic point of view is detected. This area is shown in Figure 4.

Three possible solutions in the feasibility area are highlighted (A, B, C). In Table 1 the different technical and economic parameters for the three solutions are reported. A different technological level leads to different costs and financial remunerations, thus giving useful data for a design choice.

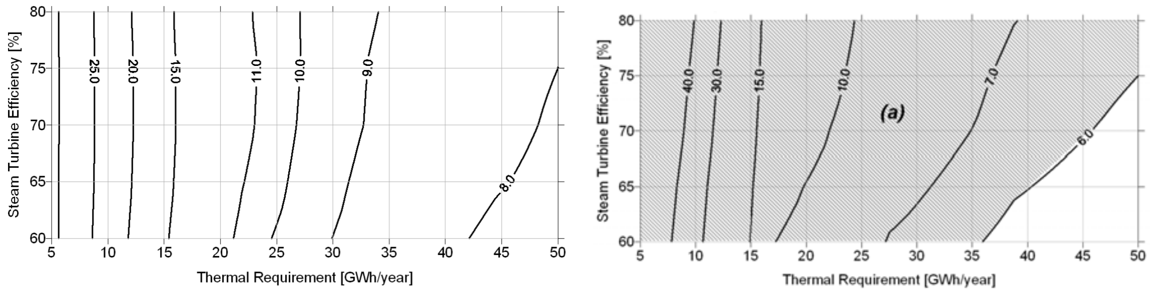
Table 1. Technical and economical parameters evaluated for three different solutions in the feasibility area.

Case	**Eta ST**	**ST_size**	**Cost**	**PBP**	**NPV$_{20}$**	**M**
	[%]	**[MW]**	**[M€]**	**[Years]**	**[M€]**	
A	60	1,6	6,0	5,4	3,7	0,61
B	70	2,0	7,9	5,2	4,9	0,62
C	80	2,6	10,0	4,9	7,0	0,70

Choice among the feasible solutions depends, of course, on several parameters that are up to the investor's discretion. While initial cost and economic revenues are easy to consider, other parameters such as space required for plant installation and biomass storage could be critical. For this reason, the chosen solution could not be that with the greater NPV.

4.2. Case study analysis

As previously mentioned, this analysis was carried out by taking into consideration public incentives. Otherwise, should no public grants be available, the PBP would be very high and the economic feasibility area would not exist with the previously stated conditions. Figure 5 (sx) shows the PBP in this condition.



(sx) (dx)

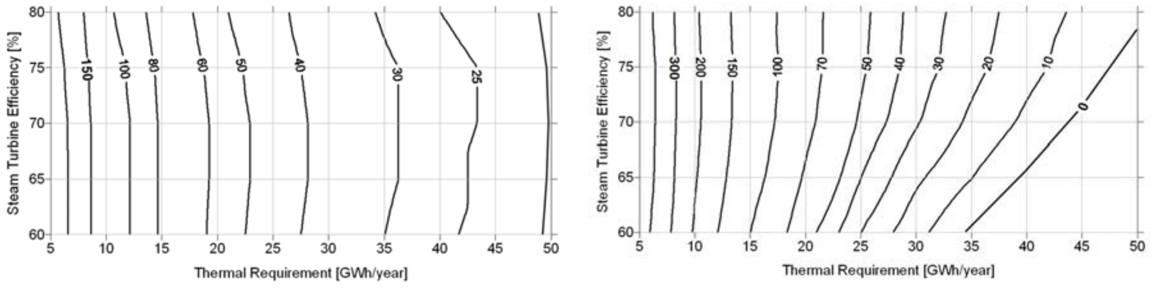
Fig. 5. Payback period [years] at 45% annual global efficiency without public incentives (sx). Payback period [years] at 65% annual global efficiency without public incentives; (a) economic unfeasibility area (dx).

If the annual average efficiency of the plant is assumed as greater, for example 65% (Figure 5, sx), economic feasibility conditions occur, even without public incentives, but at a very high thermal energy requirement.

This is a very difficult condition to be met by a small size plant if considering that 50 GWh/year are roughly the thermal requirements for the district heating of 15.000 people. In this case, by considering a steam turbine efficiency of 70%, the steam turbine size would be 3,5 MW, the biomass consumption 26.000 ton/year and the plant cost approximately 11,5 M€.

If public incentives are not available, high global efficiency of the plant is required. This results in having great thermal requests in order to satisfy an economic feasibility, but these conditions are often hard to find. Currently public incentives seem to be necessary to make a small size Hirn cycle cogeneration plant fueled by biomass feasible.

In order to extend the previous analysis, an investigation of the minimum value of public incentives needed in order to have a Payback Period of 6 years was carried out for different plant configurations. Results are shown in Figure 6 sx and dx for an annual global efficiency of 45% and 65% respectively.



(sx) (dx)

Fig. 6. Value of public incentives [€/MWhel] to have a six years payback period with an annual global efficiency of 45% (sx) and 65% (dx).

Through these diagrams, it is also possible, if the incentive amount is known, to find which size of the plant is needed to have an economic payback in six years. When public incentives are low, big plants with high global efficiency are more economically suitable. When public incentives are high, small size plants can be also realized. Once the type of cogeneration plant that is suitable with the available public incentive has been determined, it is quite important to estimate the sensitivity of the payback period (and then economic suitability) to a public incentive rate variation.

In Figure 7 the payback period for different values of public incentives and thermal request is shown. Large size plants are less sensitive to a variation of public incentive value (small variation of Payback period – right side of the graph). On the other hand, for small size plants, even a slight variation of public incentives value can greatly modify the investment payback period even over the plant life (left side of the graph).

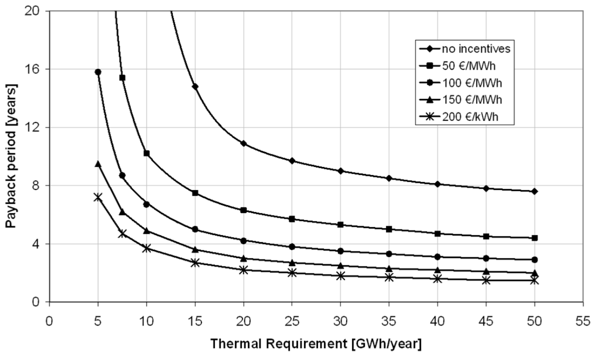


Fig. 7. Payback period [years] for different values of public incentives [€/MWhel] (70% steam turbine efficiency and 65% annual global efficiency).

4.3. Influence of plant efficiency

As previously stated, a high annual global efficiency of the plant could increase the economic feasibility. In Figure 8 the area of technical and economic feasibility is highlighted by considering as in the previous case study, an average efficiency of 65% and public incentives. In this new condition, the feasibility area is not consistent with the thermal requirement of the case study.

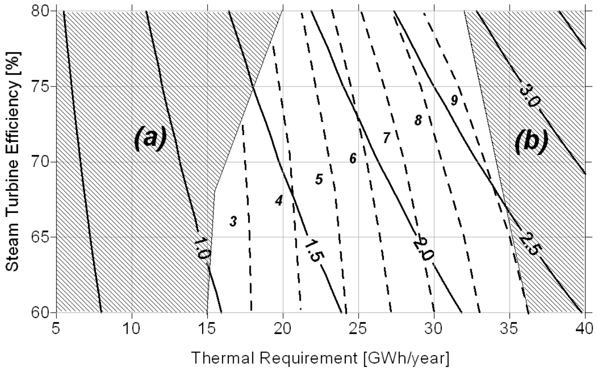


Fig. 8. ST power [MW] (solid line) and NPV [M€] (dashed line) at 65% annual global efficiency; (a) technical and economic unfeasibility area; (b) biomass unavailability area.

As described in Figure 8, by increasing the plant global efficiency the steam turbine size decreases (given an annual thermal requirement). Since the technical limits are directly bounded to turbine size, the technical unfeasibility area spreads to greater thermal requirement conditions. In other words, the same unfeasible conditions are achieved for greater thermal requirement conditions. At the same time, a smaller plant size involves a lower productivity, thus leading to higher PBP. On the other hand, by decreasing the plant size, the limit of biomass availability increases. Thus by increasing the plant global efficiency smaller plant sizes and lower biomass availability are required but the technical and economic feasibilities are more difficult to be achieved for low thermal requirement. Unlike common expectations, the feasibility of small size plants with higher efficiency could be harder than that with lower efficiency.

5. Conclusions

The feasibility of small size Hirn-cycle cogeneration plants fueled with ligneous biomass was investigated from the economic, technologic and thermodynamic point of view. Many constraints can restrict the feasibility of this kind of plant such as component technological limits, economic goals, funds, biomass availability, etc. Once the thermal energy requirement of the user and the annual global efficiency desired are given, a methodology to highlight the feasible plant configurations was developed.

Some interesting considerations on the results can be summarized. First of all, public incentives are needed in order to achieve any feasible solution when the annual global efficiency is low. Without public incentives, high plant efficiencies are necessary to find some feasible configurations but these occur at very high thermal energy requirement. In other words public incentives seem to be necessary to make feasible a small size Hirn cycle cogeneration plant fueled by biomass. When considering the plant size, the incentives' value plays a key role. For small size cogeneration plant, also a small variation of incentive value can move the payback period even over the life time of the plant.

Secondly, annual global efficiency plays an important role in plant feasibility. By increasing the plant global efficiency, smaller plant sizes and biomass availability are required but the technical and economic feasibilities are more difficult to be achieved at low thermal requirement. In such cases the feasibility conditions of small size plants with higher efficiency could be harder to meet than for plants with lower efficiency.

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