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Diffused introduction of Organic Rankine Cycle for biomass-based power generation in an industrial district: a systems analysis

Damiana Chinese*,†, Antonella Meneghetti and Gioacchino Nardin

DiEM, Department of Energy Technology, University of Udine, Via delle Scienze, 208, Udine 33100, Italy

SUMMARY

Specific Organic Rankine Cycle (ORC) units dedicated to biomass-based power production have recently been developed through the introduction of novel organic working media and technology innovation. For small systems, ORC technology appears as an efficient alternative to conventional generation if also process waste heat can be exploited, as resulted in the last few years from the successful operation of several demonstration plants in Austria and Switzerland. The present study aims to investigate the impact of the introduction of ORC units in an industrial context from a system perspective, with particular reference to industrial districts, which are characterized by the concentration in small areas of a large number of medium- and small-sized firms.

The paper focuses on the opportunity of combining ORCs, traditional Rankine cycles and multi-source district heating to meet energy requirements in an industrial district in North Eastern Italy. To this end, a mixed-integer linear programming model oriented to economical optimization of the system is developed and sensitivity analysis is carried out in order to determine the conditions for the expansion of biomass-based power generation in the analyzed industrial district and to evaluate potential for CO_2 emission reduction.

KEY WORDS: district heating; industrial districts; Organic Rankine Cycles; biomass combustion; mixed-integer linear programming; CHP; energy systems modelling

1. INTRODUCTION

Centralized biomass combustion associated to district heating systems is a consolidated technology for heat requirements satisfaction, having a favourable environmental impact, because no emission of greenhouse gases are generally counted for biomass combustion and general low emission can be achieved through controlled combustion. Since biomass is a scarce resource, it should be used as efficiently as possible, in particular through combined heat and power production.

*Correspondence to: D. Chinese, DiEM, Department of Energy Technology, University of Udine, Via delle Scienze, 208, Udine 33100, Italy.
† E-mail: chinese@interfree.it

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The rationale for biomass-based cogeneration also lies in the potential increase of profitability (Obernberger, 1998). Where space or process heat demand is hardly uniform, in fact, 'heat only' district networks can display profitability problems, as can be expected in Southern European countries and as experienced even in Austria, in spite of its alpine climate (E.V.A., 2000).

In mild climates, a major risk of low profitability for district heating can be expected in industrial areas (Chinese and Meneghetti, 2002), since industrial customers are characterized by higher discontinuity in heat consumption and pay lower heat prices than residential clients, due to special prices granted to large consumers by sellers of traditional fuels and to tax reduction. However, potential sources of residual biomass are mainly located in these areas. Considering high investment costs associated to heat transportation and environmental impact of biomass transportation by trucks, it would be sensible to generate and use heat in the same areas where biomass is by-produced. This is especially true in industrial districts, which are geographically determined productive systems, characterized by the concentration, in the same area of few square kilometres, of a high number of small–medium-sized firms, specialized in various stages of the manufacturing process of the same product (Pyke *et al*., 1992).

Previous studies (Chinese and Meneghetti, 2002; Chinese *et al*., 2002) highlighted that, in furniture manufacturing industrial districts, not only wooden residuals are available, but also existing installations, such as traditional hot water biomass-based boilers, which are usually under-utilized and which could form the backbone of multi-source, biomass-based district heating networks. Moving from a traditional district heating network fed by a centralized biomass-based combustion station towards a distributed concept of heat generation, which resembles the same distributed structure of industrial districts, might, in fact, help to enhance the cost effectiveness of biomass utilization. Since, however, such energy networks would mainly serve industrial clients, they could still experience profitability problems. These could be mitigated by the introduction of CHP, as can be argued from the results presented in Chinese and Meneghetti (2002) and Chinese *et al*. (2002). The mentioned case studies, in fact, highlighted that subventions on renewable power wholesale price foreseen in Italy, such as the so-called green certificates, can make power production more profitable than the sale of the corresponding thermal energy to industrial customers. In those cases, for instance, it appeared more favourable to meet the peak load of a district heating network through natural gas boilers rather than using a thermal bleeding from an existing waste-to-energy plant, whose exploitation would have reduced power generation and sale.

In the light of these considerations, the present study aims to investigate whether the diffused introduction of new biomass-based power plants could improve the potential profitability of the system. In particular, our objective is to identify and to analyze a suitable technology for power generation at the small scale of existing boilers. To this end, we focus on a particular technology, namely on ORCs, which are briefly presented in the following section. Thanks to demonstration projects (Obernberger, 2001) and recent market implementations (Duvia and Gaia, 2002), standardization and commercialization of these power generation groups have led to a reduction of investment costs through scale economies in component production. As a consequence, the nominal capacity of $5\,MW_{th}$, which was indicated (Obernberger, 1998) as a lower limit for economic operation of biomass-based CHP plants, could be further reduced and standardized ORC modules from about $1900\,kW_{th}$ are now commercially available. Moving from this background, we identify technology options suitable for furniture manufacturing industrial districts and in particular for a specific case study, presented in Section 3. We develop an optimization model (Section 4) based on mixed-integer linear programming, able to deal with various technologies and with power cogeneration, in order to identify the combination of fuels, boilers and technologies which maximizes system profit. Finally, results obtained by means of the optimization model are discussed in Section 5.

2. ORGANIC RANKINE CYCLES FOR BIOMASS-BASED POWER PRODUCTION

ORC as a process does not represent a new technology, since it has been widely applied in geothermal power generation (see e.g. Desideri and Bidini, 1997). Like in traditional water Rankine cycle, the working fluid is heated at the evaporator and converted into high-pressure vapour, which is expanded through the turbine, thus producing mechanical energy, converted into electrical power through a generator. From the turbine outlet, vapour is cooled through the condenser, where it turns into the liquid phase. If the temperature difference between vapour at turbine outlet and at the evaporator inlet is reasonably large, the compressed liquid can also be pre-heated through a regenerator, thus improving cycle efficiency. Instead of water, opportune organic working fluids or mixtures are chosen, having proper vapour saturation curves. We refer to Angelino and Di Paliano (1998) and Hung *et al.* (1997) for a complete description of the properties and applications of such fluids. Generally, main features of these fluids are critical temperature and pressure lower than the corresponding values at water critical point, and by isentropic or positive slopes of the saturation vapour line on the $T-s$ diagram. This allows to perform phase change, generating vapour for turbine expansion, at a low temperature. By ranges between 60 and 250°C, saturated cycles can be completed with acceptable efficiency, which remains reasonably constant also by moderate variations of turbine inlet temperature. Thanks to the positive slope of the saturated vapour line, ORCs do not lead to condensation throughout turbine exhaust, occurring in similar conditions within saturated water Rankine cycles, which would drop isentropic expansion efficiencies and would lead to blade corrosion. Superheating is also possible and suitable for heat exploitation at comparatively high temperature (e.g. up to 400°C according to Angelino and Di Paliano, 1998), provided that maximum temperature is well below the fluid maximum stability temperature, which would cause deterioration and chemical decomposition of organic working fluids. Other favourable properties of some organic fluids in power generation influence the expansion phase, which can be carried out with higher expansion efficiencies (Duvia and Gaia, 2002) and with smaller turbines, when specific volumes in vapour state are lower than water ones. Owing to the characteristics of ORCs, two main application fields in power generation have been developed over the years: the traditional application, also at large scale, for low temperature (e.g. geothermic) power generation, and the use as a bottoming cycle in the low power range, even at relatively higher temperatures, when an external combustion or heat source should be exploited. The latter group of applications includes commercial ORC modules recently developed for small-scale biomass-based power generation. A complete description of the specific technology is provided by Duvia and Gaia (2002), who highlight advantages related to the chosen working fluid, characterized by environmental friendliness and favourable thermodynamic properties, and technology specific advantages such as high cycle efficiency, very high turbine efficiency, low stress of the turbine and no erosion of the turbine blades, allowing very long operational life. A primary advantage related to ORCs is also the absence of water treatment systems, which would represent a basically size-independent fixed cost, especially significant for small systems.

Working fluid properties also allow a compact size of the energy conversion group, thus reducing required space and investments.

From literature on existing demonstration projects (see e.g. Obernberger, 2001; Duvia and Gaia, 2002), general configuration for a bioenergy cogeneration plant based on commercial ORC module has been derived. As a reference case for the optimization procedures carried out in this study, we assume the configuration represented in Figure 1, consisting in the following sections:

- The biomass combustion section, including an automatic biomass feed mechanism deriving from a storage section, a combustor made according to techniques in use for water boilers, filters, controls, automatic ash disposal systems and all accessories required to perform a safe, reliable and clean combustion, according to national and international directives.
- The boiler and heat transfer section: a thermal oil boiler is used in order to achieve simple and safe control (practically unmanned operation) at a hot side temperature of about 300°C.
- The energy conversion section, consisting in the commercial module described by Duvia and Gaia (2002), includes the evaporator, the turbine, coupled with the included electric generator, the regenerator, the condenser and the circulation system, including pumps, to complete the closed-loop circuit by sending the liquid organic fluid to the evaporator.
- The thermal utilization and dissipation section, including connection to water circuit for internal use or to a district heating system, a by-pass heat exchanger for direct heat transfer from the thermal oil circuit to the water circuit, dry coolers for dissipation of excessive heat flows at the condenser.

As for temperature levels, available thermal and electrical flows related to plant size, we founded our calculations on data provided by constructors, partially through personal communications and mainly through the table reported in http://www.turboden.com (2003).

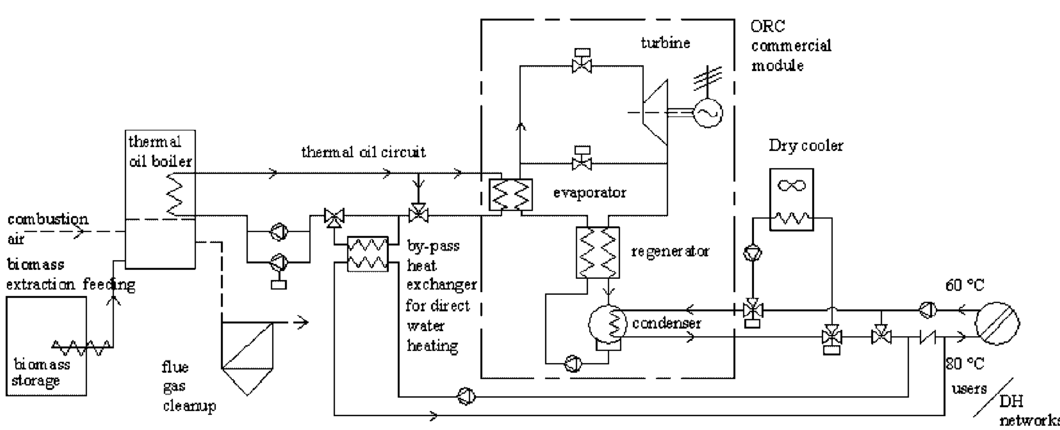

Figure 1. Organic Rankine Cycle for biomass-based power generation.

3. TECHNOLOGY OPTIONS FOR A FURNITURE INDUSTRIAL DISTRICT: A CASE STUDY

As a reference case for systems analysis at an industrial district level, a furniture manufacturing industrial district located in North Eastern Italy was chosen, and in particular an expanding industrial area including about 60 small–medium-sized enterprises and some 80 residential buildings, which was the object of previous investigations (Chinese and Meneghetti, 2002; Chinese *et al*., 2002). A more accurate modelling of the heat demand has been performed for the current analysis. Based on statistical data on local hourly outdoor temperature of 5 years, we subdivided a year in 50 sub periods, taking into account, by identifying opportune time spans of a day, the fact that industrial and civil demand are only partially contemporary. We also assumed that industrial process heat demand is constant over the year, but is related to operation time of the firms, while hot water demand from residential units is considered negligible. During the night, the heating systems work in attenuated regime, maintaining an indoor temperature of 6°C in order to avoid icing. With these assumptions, we obtained the systems duration curve represented in Figure 2, having a peak load of about 18.5 MWh h^{-1}. Residential peak demand is 1.3 MWh h^{-1}, while current biomass users require about 4.6 MWh h^{-1} as a peak load.

Previous studies highlighted that several heat sources are usually available on site to meet single firm requirements and could be considered for integration into a potential ‘heat only’ network.

Table I presents the potential heat sources identified in this case study and their main features. The last column reports actions that should be carried out in order to make heat sources available for integration with a power generation group or into a district heating network. Recent boilers just need a refurbishment to extend their prospective lifetime and to achieve conformity with latest prescriptions on emissions. Older boilers should be substituted, but buildings and storage systems could be maintained. Virtual units represent boilers that could be built on available land plots: investment costs are higher in this case, including also costs of buildings. In the area there is also a waste-to-energy plant, currently burning refuse derived fuel

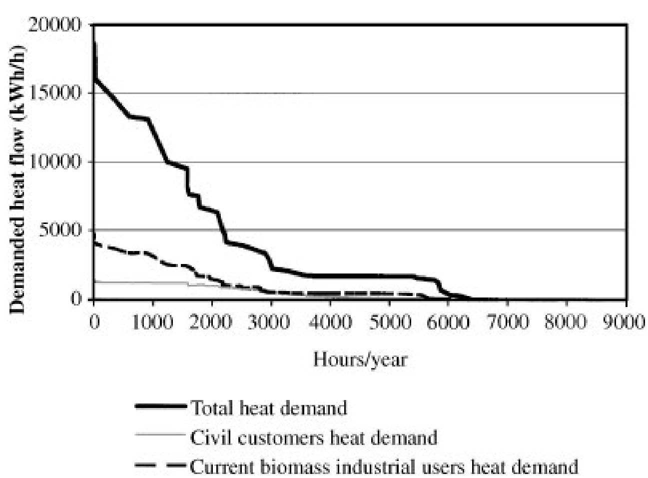

Figure 2. Heat demand of the analyzed system: duration curve.

Table I. Potential heat sources in the analyzed industrial area.

Source	Fuel	Size (kW)	Status/actions
1	Waste wood	2326	Boiler refurbishment
2	Waste wood	1750	Boiler refurbishment
3	Waste wood	1860	Boiler substitution
4	Waste wood	2800	Boiler substitution
5	Waste wood	0–6000	Virtual, to be built on available land plot
6	Waste wood	0–4000	Virtual, to be built in an existing building
7	Waste-to-energy thermal bleeding	6830	Available
8	Natural gas	8000	Virtual, to be built on available land plot

Table II. Technology options for biomass-based CHP and district heating in an industrial district.

	Heat production	
Power production	Independent heat production and consumption (no district heating network)	System heat production and consumption (district heating network)
No power production	'Base status': firms, who by-produce wood residuals, use them to meet their own heat requirements. Surplus is mainly sold, partially disposed of Other firms and civil buildings burn fossil fuels	A district heating network is built. Firms by-producing wood residuals become heat producers and sell heat to the district energy utility. Other firms and civil buildings are connected to the network as users
Power production through Organic Rankine Cycle modules	Organic Rankine Cycles are independently introduced in firms. Waste heat from ORC is either used for space heating by bioenergy producers (heat-driven mode) or dissipated through dry coolers (power-driven mode)	Organic Rankine Cycles are independently introduced in firms, but waste heat from ORC is used to meet space heating requirements of all firms and of civil customers in the area, in heat or power-driven mode

and industrial waste produced in the district, which was designed to make available about 6830 kW_{th} to potential heat users through a thermal bleeding (Meneghetti *et al*., 2002). For every heat source, a further element required for integration into the network is a heat exchanger of proper size.

Various approaches and technology options can be considered when designing energy facilities in industrial districts. A designer can evaluate the feasibility of investments for consumption reduction, heating technology and fuel substitution or even microcogeneration at a single firm level. On the other hand, he can consider the industrial area as a whole, trying to take advantage from mutual proximity of the firms and from interfirm co-operation characterizing industrial districts (Pyke *et al*., 1992).

Aiming at analyzing ORC technology potentiality, suitable options for the examined industrial district are summarized in Table II.

The baseline (upper left quadrant) corresponds to preservation of the current status, maintaining, refurbishing or renewing existing independent biomass or fossil fuel boilers, which satisfy heat requirements of single firms. Size of biomass-based boilers and by-produced wooden waste quantities are such, that potential heat flows exceed heat demand of producing firms.

Surplus wood residuals (about 12 000 tonnes year^{-1} according to previous estimations by Meneghetti *et al.* (2002)) are stored and mainly sold, partially disposed of. The introduction of bioenergy generation at small scale using ORCs could be carried out independently by single firms (low left quadrant). In that case, heat removed at the condenser should either be used to satisfy the firm's heat demand (heat-driven mode) or dissipated through dry coolers (grid-driven mode). Alternatively, network facilities could be designed in a system perspective, trying to meet heat requirements of all firms and residential buildings in the area. In particular, either a heat-only district energy network (upper right quadrant) or a CHP-based district energy network (low right quadrant) could be designed. To identify best solutions among possible options, determining capacities and technologies, an optimization model has been developed in order to design solutions at a system level rather than analyzing single firms independently.

4. SYSTEM MODEL

Linear programming has been adopted for 30 years as a basic optimization tool for energy system planning at national or regional scale. Also, mixed-integer linear programming (MILP) has been used at regional or municipal level (see e.g. Sundberg, 2001), when it is advisable to use integer variables, beside continuous ones, to model inherently discrete phenomena. MILP has often been applied also to optimize energy supply to smaller systems, such as, for instance, single factories (Bojic and Dragicevic, 2002). As highlighted by Mavrotas *et al.* (2003), there is, in fact, a growing trend to implement energy planning models in smaller systems, because of the increasing number of alternative energy technologies, differing in cost, efficiency, environmental performance and thanks to relevant software improvement. At smaller scale, usable data are more precise than aggregate data available for large-scale optimization. Accordingly, more accurate results are expected at this scale: that is why MILP should be used at this level. This is especially true for industrial districts, which can be placed at an intermediate scale between aggregate energy planning (industrial sector planning) and single factory energy optimization. Therefore, MILP was chosen by Chinese and Meneghetti (2002), in order to account for scale economies and fixed parts of investments in optimizing a 'heat only' district energy network for an industrial area. In the present study, to assess and optimize profitability of technology options including separate or system heat production, combined with power production or not, the economic objective becomes designing an optimal energy system rather than an optimal heat distribution network. A decision support tool should be able to:

- identify and dimension boilers and energy carriers to be included into a district heat network to achieve maximum profit;
- to answer yes or no questions on the opportunity of highlighted technology options;
- to support capacity and operation strategy decisions for power generation.

To this end we have developed the following model, aiming at the maximization of annual equivalent profit, which takes into account annual proceeds from heat and power sale, annual variable costs depending on produced energy and fixed costs, represented by equivalent annuities for the amortization, at a given interest rate, of all investments related to installed thermal and electrical capacities and to the district heating system.

4.1. Equation 1: the objective function

The objective function is reported in Equation (1):

$$\max\left\{\begin{array}{l} \sum_{\mathrm{cl}}\sum_t p_{\mathrm{th}}(\mathrm{cl})\,\mathrm{def}_{\mathrm{th}}(\mathrm{cl},t)n_{\mathrm{h}}(t)\mathrm{BIN}_{\mathrm{DH}} + \sum_f\sum_b\sum_t\sum_{\mathrm{tech}}[p_{\mathrm{el}}(f,\mathrm{tech})n_{\mathrm{h}}(t)\,\mathrm{EF}_{\mathrm{el}}(f,b,t,\mathrm{tech}) \\ \quad -\dfrac{c_{\mathrm{fuel}}(f)}{\eta_b(b,f)}\dfrac{\mathrm{EF}_{\mathrm{el}}(f,b,t,\mathrm{tech})+\mathrm{EF}_{\mathrm{th}}(f,b,t,\mathrm{tech})}{(\eta_{\mathrm{el}}(f,b,\mathrm{tech})+\eta_{\mathrm{th}}(f,b,\mathrm{tech}))}n_{\mathrm{h}}(t) - c_{\mathrm{manag}}\,\mathrm{NEF}_{\mathrm{th}}(f,b,t,\mathrm{tech})n_{\mathrm{h}}(t)] \\ \quad -\sum_f\sum_b\sum_{\mathrm{tech}}[(\mathrm{ann}(f,b,a)\,\mathrm{dis}(f,b,a)+c_{\mathrm{man}}(f,b,\mathrm{tech}))(\mathrm{BIN}_b(f,b,\mathrm{tech})c_{b,\mathrm{fix}}(f,b,\mathrm{tech}) \\ \quad +\mathrm{BIN}_{\mathrm{he}}(f,b,\mathrm{tech})c_{\mathrm{he,fix}}(f,b,\mathrm{tech})+c_{b,\mathrm{var}}\mathrm{CAP}_{\mathrm{th}}(f,b,\mathrm{tech})+c_{\mathrm{he,var}}\mathrm{CAP}_{\mathrm{he}}(f,b,\mathrm{tech}))] \\ \quad -\sum_{\mathrm{cl}}[(\mathrm{def}_{\mathrm{th,peak}}(\mathrm{cl})c_{\mathrm{sub,var}}+n_{\mathrm{sub}}(\mathrm{cl})\cdot c_{\mathrm{sub,fix}}\mathrm{BIN}_{\mathrm{DH}}] - (\mathrm{ann}_{\mathrm{DH}}\mathrm{dis}_{\mathrm{DH}}c_{\mathrm{fix,DH}}+c_{\mathrm{man,DH}})L_{\mathrm{DH}}\,\mathrm{BIN}_{\mathrm{DH}} \\ \quad -\sum_t c_{\mathrm{el,aux}}\mathrm{EF}_{\mathrm{th,diss}}(t) \end{array}\right\} \tag{1}$$

Basically, three groups of money flows can be identified:

- proceeds and variable costs, depending on thermal and electrical energy flows ($\mathrm{EF}_{\mathrm{th}}$ and $\mathrm{EF}_{\mathrm{el}}$) produced in each time span, if opportune multiplied by the time span duration expressed in hours $n_{\mathrm{h}}(t)$;
- fixed investment costs related to installed capacities CAP, mainly of thermal generation units (th) and of heat exchangers (he);
- fixed parts of investments and fixed investment costs which are related to yes-no decisions modelled through binary variables BIN.

Energy flows EF are determined by the optimization model for each boiler b and fuel f, for each available technology tech and in each time span t. In comparison with the model presented by Chinese and Meneghetti (2002), the introduction of a general set of technologies adds flexibility and allows to model power production and heat production, separated or combined, with various technologies beside the ORC analyzed in the present case. Fuel costs are proportional to EF, through unit cost c_{fuel} and efficiencies η of boilers (b) and of energy conversion systems (el, th). Net energy flow NEF is introduced to account for management and pumping costs, which are proportional to total thermal energy flowing in the network $\mathrm{EF}_{\mathrm{th}}$ when a district heating system is built and tend to zero when no network exists. $\mathrm{EF}_{\mathrm{th,diss}}$ is a continuous variable representing the thermal power which is dissipated at the dry cooling units in case of lowered heat demand by the users, especially in the power-driven model, consuming electrical energy to feed ventilators and circulation pumps. Relevant costs are assumed to be proportional to dissipated thermal energy amounts through the $c_{\mathrm{el,aux}}$ unit cost per $\mathrm{kWh}_{\mathrm{th}}$.

Investment costs of boilers, of heat exchangers and of ORC modules including all elements required for operation (dry cooling, grid connection, etc.) grow linearly with installed capacity CAP. For each technology there is a size-independent part of the investment, leading to decreasing specific investment costs, which is modelled through binary variables BIN_b (for boilers, even with ORC unit) and $\mathrm{BIN}_{\mathrm{he}}$ (for heat exchangers) equalling 1 if a component is included into the system, 0 otherwise. Equivalent annuities are obtained by multiplying total investments by an annuity factor ann(f,b,a), which is a function of interest rate and of expected duration of the units, and by a discount factor dis(f,b,a), accounting for discounts by manufacturers and public subventions. Maintenance costs are also assumed to be proportional to total investment costs through coefficient $c_{\text{man.}}$ A new binary variable BIN_{DH} is introduced to model the district heating option. BIN_{DH} equals 1 if a district heating network is built, 0 otherwise. Thereby, we impose that thermal energy sale proceeds, proportional to thermal energy flow $\text{def}_{\text{th}}(\text{cl},t)$ demanded by various clients cl in each time span t, can only be earned if investments in a district heating network ($c_{\text{fix,DH}}L_{\text{DH}}$) and in client heat exchange substations, expressed by a linear function of the peak demand $\text{def}_{\text{th,peak}}$ and of the number of substations n_{sub}, are undertaken and relevant maintenance is performed.

4.2. Equation 2: constraints

By Equation (2) constraints are introduced into the optimization model.

Alternative constraints, modelled by means of an arbitrary large constant M, are Equations (2) and (3), imposing that energy flow is either large enough to satisfy total heat demand by all potential clients (distribution heat losses—about 14%—are properly introduced) when a district heating network is built, or that each heat source meets its own requirements in the other case. Constraint 2.3 expresses the relationship between electric and thermal flows through the constant α. Assuming that electric efficiency of ORC modules is constant and equals 17.8% (Duvia and Gaia, 2002) α is 22.4% for ORC.

$$\sum_{\text{tech}}\sum_{f}\sum_{b}\text{EF}_{\text{th}}(f,b,t,\text{tech})\eta_{\text{dis}} \geqslant \sum_{\text{cl}}\text{def}_{\text{th}}(\text{cl},t) - M\ \ (1-\text{BIN}_{\text{DH}})\ \ \forall t \tag{2a}$$

$$\sum_{\text{tech}}\text{EF}_{\text{th}}(f,b,t,\text{tech}) \geqslant \text{def}_{\text{th,source}}(f,b,t) - M\,\text{BIN}_{\text{DH}}\ \ \forall b,\forall f,\forall t \tag{2b}$$

$$\text{EF}_{\text{el}}(f,b,t,\text{tech}) = \alpha(\text{tech})\,\text{EF}_{\text{th}}(f,b,t,\text{tech})\ \ \forall b,\forall f,\forall t,\forall\ \text{tech} \tag{2c}$$

$$\text{EF}_{\text{th}}(f,b,t,\text{tech}) \leqslant \text{CAP}_{b}(f,b,\text{tech})\eta_{\text{th}}(f,b,\text{tech})\ \ \forall b,\forall f,\forall t,\forall\ \text{tech} \tag{2d}$$

$$\text{EF}_{\text{th}}(f,b,t,\text{tech}) \leqslant \text{CAP}_{\text{he}}(f,b,\text{tech})\eta_{\text{th}}(f,b,\text{tech}) + M(1-\text{BIN}_{\text{DH}})\ \ \forall b,\forall f,\forall t,\forall\ \text{tech} \tag{2e}$$

$$\text{CAP}_{b}(f,b,\text{tech}) \leqslant \text{BIN}_{b}(f,b,\text{tech})\ \text{max cap}(f,b)\ \ \forall b,\forall f,\forall\ \text{tech} \tag{2f}$$

$$\text{CAP}_{\text{he}}(f,b,\text{tech}) \leqslant \text{BIN}_{\text{he}}(f,b,\text{tech})\ \text{max cap}\ (f,b)\ \ \forall b,\forall f,\forall\ \text{tech} \tag{2g}$$

$$\sum_{\text{tech}}\text{CAP}_{b}(f,b,\text{tech}) \leqslant \text{max cap}(f,b)\ \ \forall b,\forall f \tag{2h}$$

$$\text{CAP}_{b}(f,b,\text{tech}) \leqslant \text{max mark(tech)}\ \ \forall b,\forall f,\forall\ \text{tech} \tag{2i}$$

$$\text{CAP}_{b}(f,b,\text{tech}) \geqslant \text{BIN}_{b}(f,b,\text{tech})\ \text{min mark(tech)}\ \ \forall b,\forall f,\forall\ \text{tech} \tag{2j}$$

$$\sum_{\text{tech}}\sum_{f}\sum_{b}\sum_{t}\frac{\text{EF}_{\text{el}}(f,b,t,\text{tech})+\text{EF}_{\text{th}}(f,b,t,\text{tech})}{(\eta_{\text{el}}(f,b,\text{tech})+\eta_{\text{th}}(f,b,\text{tech}))}\frac{n_{\text{h}}(t)}{\eta_{b}(f,b,\text{tech})}\text{woodfract}(f) \leqslant \text{woodavail} \tag{2k}$$

$$\mathrm{EF}_{\mathrm{th,diss}}(t) = \sum_{\mathrm{tech}} \sum_{f} \sum_{b} \mathrm{EF}_{\mathrm{th}}(f, b, t, \mathrm{tech}) - \frac{\sum_{\mathrm{cl}} \mathrm{def}_{\mathrm{th}}(\mathrm{cl}, t)}{\eta_{\mathrm{dis}}} \mathrm{BIN}_{\mathrm{DH}} - \sum_{\mathrm{tech}} \sum_{f} \sum_{b} \mathrm{def}_{\mathrm{th,source}}(f, b, t)(1 - \mathrm{BIN}_{\mathrm{DH}}) \quad \forall t \tag{2l}$$

$$\mathrm{EF}_{\mathrm{th,diss}}(t) = 0 \quad \forall t \tag{2m}$$

Constraints (2d) and (2e) require that generated heat flow is lower or equal to installed capacity of thermal units and, only if the network is built, of heat exchangers transferring heat to the system. Equations (2f) and (2g) set actual capacity of existing boilers, empowered capacity for new ones or potential capacity for virtual ones, as an upper bound to capacities that can be assigned by the optimization system, thereby forcing the binary variables accounting for fixed investment parts to equal 1 if a capacity higher than zero is installed. Equation (2h) allows various conversion technologies to be associated to a given thermal unit, provided that their total capacity does not exceed the upper bound set. Equations (2i) and (2j) avoid capacities to be out of ranges available on market, while Equation (2k) establishes estimated available wood waste quantities as an upper bound to consumption of wood as a fuel. Finally, additional constraints (2l) and (2m) are used to model the heat-driven operation mode of the system, computing dissipated thermal flows as difference of generated and demanded flows in each time span for various technology options and setting this value to 0.

5. RESULTS AND DISCUSSION

The model has been developed in a dedicated language (AMPL) and solved with a commercial solver (CPLEX). Simulations have been performed for the case study described in Section 2, using client profiles represented in Figure 2. Investment costs of ORC modules and industrial wood residual burners and boilers are shown in Figure 3, representing cost interpolation curves obtained by fitting data derived from (E.V.A, 2000), as for building and storage costs, and made available by various suppliers of biomass boilers and by the constructor of ORC compact modules specific for biomass-based power generation (http://www.turboden.com 2003).

Cost functions for heat exchangers and house substations as well as management and pumping costs have been mainly derived from (Winkens, 1998). We have estimated at 6450 m the total length of the district heating network to be built in order to connect all potential sources and customers in the area: a specific grid cost of 210€ m^{-1} was derived from (E.V.A, 2000). Discounts and subventions are assumed to reduce investment costs for renewable energy and district heating of 20% (approximately corresponding to an abatement of V.A.T.). Economic and technical parameters adopted for the calculation are reported in Appendices A and B.

Following scenarios are investigated:

- 'Heat only': ORC technology is excluded. Wholesale price of thermal energy is established based on direct competitors, i.e. natural gas sale price to different classes of customers (industrial and civil). Upper limits assumed for calculations are 0.088 € $\mathrm{kWh}_{\mathrm{th}}^{-1}$ for civil customers, 0.046 € $\mathrm{kWh}_{\mathrm{th}}^{-1}$ for industrial clients.

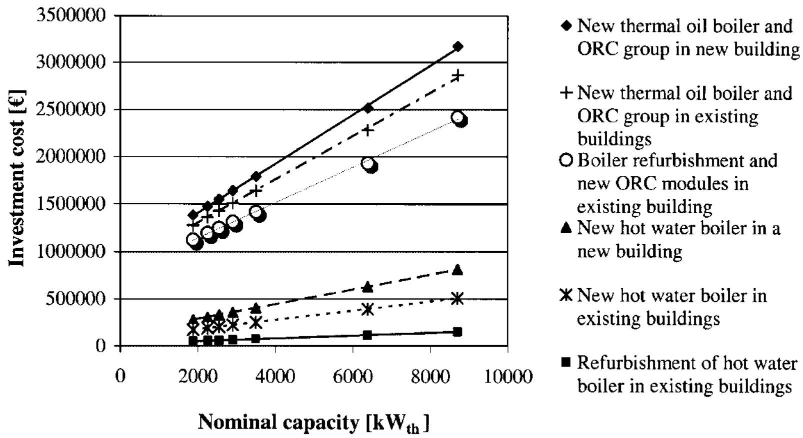

Figure 3. Investment costs of ORC modules and biomass boilers.

- 'ORC in heat-driven mode'. ORC is included as a technology option. The system operates only in presence of heat demand and heat dissipation is excluded‡.
- 'ORC in grid-driven mode'. Dissipated thermal flow may be larger than zero, the main constraint remaining quantities of wooden waste, scraps and chips available in the district. All generated power is assumed to be put into the grid and sold. The model can deal with time-dependent tariffs for both heat and power; however, constant average values have been assumed by ranges between 0.042 € kWh_{el}^{-1} without green certificates and 0.125−0.142 € kWh_{el}^{-1} with these subventions.

To deal with such wide ranges, sensitivity analysis has been carried out in every case, first of all by varying sale price of heat and power. Figures 4 and 5 show, respectively, variation of annual net profit and simple pay back time at varying thermal energy sale prices for different electricity price levels in the ORC heat-driven scenario. Heat price is expressed in the graph as ratio to price of natural gas for various groups of clients.

We have also conducted a sensitivity analysis by varying the demanded thermal energy flow in proportion to maximum heat demand, which corresponds to the connection of all potential customers to the network. So we can assess the opportunity of designing smaller systems to satisfy a reduced demand. Results of this analysis, carried out at maximum achievable heat and power price, are represented in Figures 6 and 7, focusing, respectively, on environmental and economic performance.

For every scenario, emissions of carbon dioxide equivalents have also been calculated, according to the Intergovernmental Panel on Climate Change (IPCC, 1996), as the product of gas emissions and the global warming potentials (GWPs), used as a quantified measure of the globally averaged relative radiative forcing impacts of the greenhouse gases emitted by the analyzed energy system, assuming CO_2 as the reference gas. Revised 100-year GWPs from IPCC's 3rd Assessment Report were adopted (IPCC, 2001), thus taking for nitrous oxide a value

‡Dry coolers are always included in the power generation units for safety reasons.

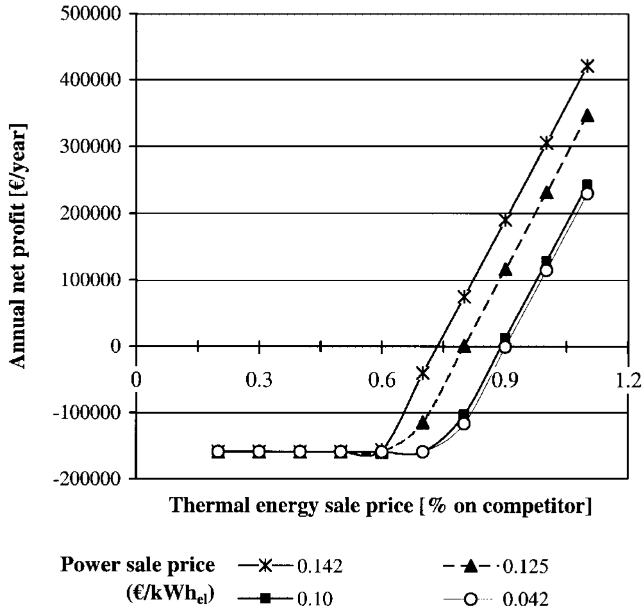

Figure 4. Sensitivity to heat and power sale prices: net annual profits.

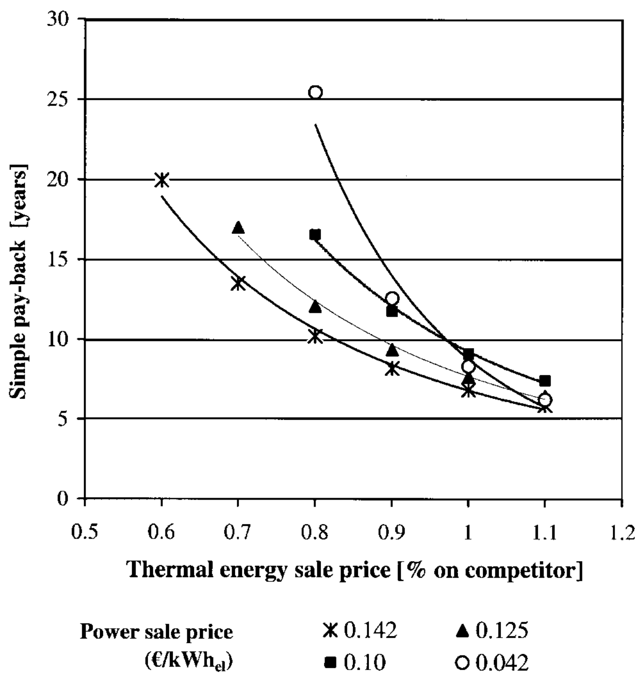

Figure 5. Sensitivity to heat and power sale prices: simple-pay back time.

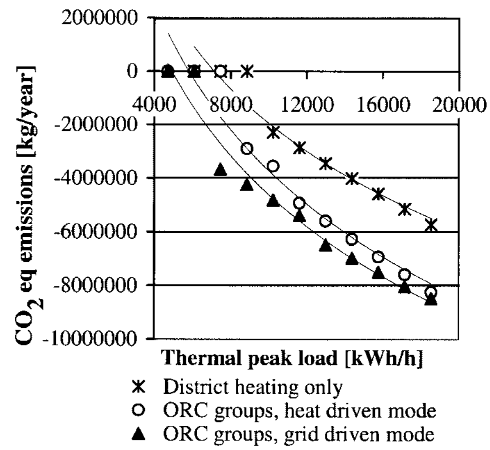

Figure 6. Sensitivity analysis with respect to demanded energy flows: CO_2 equivalent emissions.

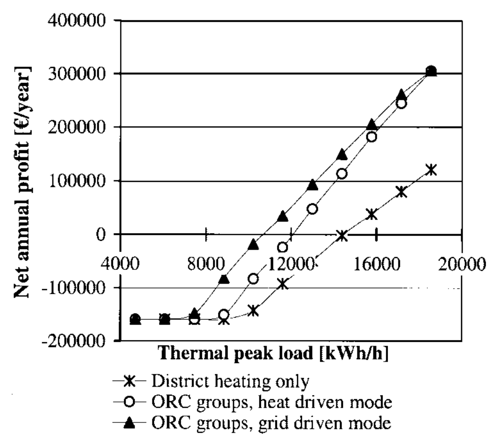

Figure 7. Sensitivity analysis with respect to demanded energy flows: net annual profits.

of 296 and for methane a value equal to 23. Emission factors for each type of combustion source involved into the model and an estimate of the average emission factor of power generation in Italy were taken from (EPA, 1995), (IPCC, 1997), (EEA, 2001),(ANPA, 2002), or, in the case of the waste-to-energy plant, were calculated from actual measurements (Meneghetti *et al.*, 2002).

Heat price has great influence on district heating feasibility. Figure 4 shows that, by heat price ranges lower than 60% or 70% of natural gas price, at high or low power price, respectively, system profit remains negative and constant. In this case, in fact, no district heating network is built and the negative constant profit represents total expenses met by potential heat suppliers, i.e. firms having large biomass boilers, to satisfy internal heat demand. If heat price increases, a district heating network is built, including also ORC groups only if power price is higher than $0.10\,€\,kWh_{el}^{-1}$.

Hence, since current prices of biomass-based power in Italy are higher than this threshold, the introduction of ORCs is economically advantageous, because it leads to:

- higher net profits than heat only networks, as shown in Figure 4;
- shorter simple pay back time: at full heat price, 8.19 years estimated for the heat only network become 6.86 years with ORC groups (see Figure 5);
- less intense dependence of pay back of heat price: Figure 5 shows that at low power price, i.e. for 'heat only' district networks, the pay-back time curve is steeper;
- economical feasibility at lower heat price of a district heating network, which, compared with the baseline configuration, brings about environmental benefit.

Environmental benefits are highlighted by Figure 6, representing avoided emissions of CO_2 equivalents as a function of heat demand, expressed on the horizontal axis through corresponding peak load. Allowing early transition to district solutions also at lower heat demand, the introduction of ORC modules fosters significant reductions of GHG emissions in the analyzed district. Furthermore, biomass-based power generation leads to larger emission reduction than district heating alone, because it increases efficiency in biomass utilization and, generating higher margins, it leads to higher installed biomass combustion capacities. Diagram in Figure 6 highlights that introduction of ORC-based power generation enables a further emission reduction compared with the 'heat only' scenario, which can be explained partially by the marked dependence of Italian power generation system of fossil fuels, leading to significant values ($0.578\,kg\,CO_2\,eq\,kWh_{el}^{-1}$) of the equivalent GWP for power generation, and partially by higher capacities installed and higher efficiency in biomass utilization.

Emission reduction is even larger when the system is operated in grid-driven mode. As for profitability, grid-driven operation yields better results than heat driven operation if system heat demand is low, while at full demand there is practically no difference. This is mainly due to the limited biomass availability in the district, which bounds the increase of installed biomass combustion capacity. This constraint also leads the model to design systems in similar way, including almost the same boilers, both in the heat and in the grid-driven mode. As can be observed in Figure 8, in fact, the configuration of the grid-driven mode differs from the heat driven one only by the introduction of a larger natural gas peak load boiler, in order to divert biomass to more profitable power generation through ORC groups rather than to heating purposes. Base loads are covered in both modes through the integration of the same boilers within the system.

In both cases, the optimization procedure determines the boiler capacity to the minimum value covering the heating demand. It can be noticed, however, that, when the biomass availability constraint is removed, larger power generation capacities are installed in the grid-driven mode even though waste heat cannot be recovered. Hence, taking into account biomass scarcity avoids, to some extent, such energetic paradoxes, which would arise when aiming only at profit maximization or even at maximum emission reduction and when allowing an energetically inefficient operation mode such as the grid-driven one. However, while the system should be dimensioned on heat demand, in view of the pursued efficient use of biomass, grid-driven operation could be an effective strategy to improve profitability when heat demand

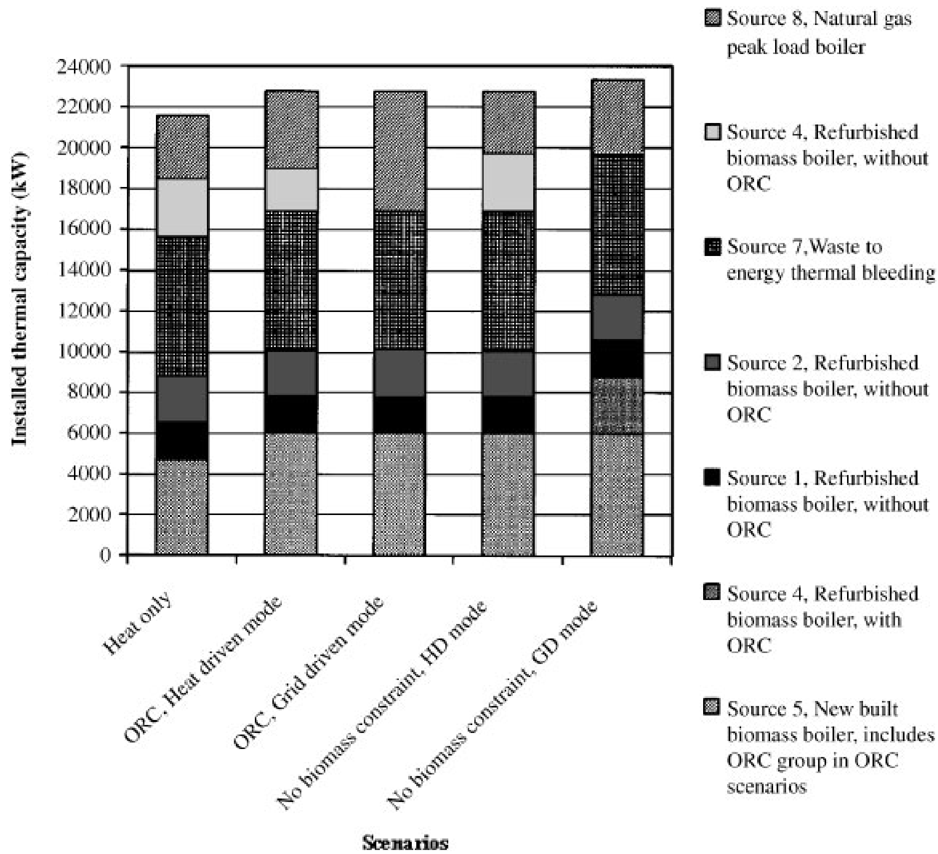

Figure 8. Installed capacities to meet a 18.5 MW heating demand.

is low, for instance when only a part of potential customers is already connected to a new built district heating network.

Looking at Figure 7 it can also be noticed that profits increase more rapidly by growing heat demand in presence of ORC modules than for heat only networks, mainly because larger heat demand allows to amortize larger, new built centralized cogeneration plants, having lower specific costs. In most cases, a centralized power plant appears preferable to multiple small CHP units, while integrating existing boilers into the network is economically more favourable than building centralized plants for the purposes of pure heat generation. This can be explained considering that savings, achieved through the exploitation of existing boilers and facilities, represent a consistent proportion of boiler costs, but are negligible when compared to investments in ORC groups.

Finally, it should be observed that, if heat demand is too low, the district heating network is not chosen by the optimization procedure, not even in ORC scenarios and in grid-driven mode. Owing to the small size and low thermal demand of single firms, if current biomass users remain independent and no district heating network is built, ORC based power generation is not introduced in the system by the analyzed heat and power price ranges.

Hence, it can be concluded that, in the analyzed system, district heating and ORC-based power generation are interdependent: on one hand, ORCs foster the introduction of district heating, on the other hand, building a district heating network is a necessary condition for the introduction of ORCs. To achieve energy and environmental efficiency, as well as satisfactory economic performances, it is therefore extremely important to design energy facilities considering industrial districts as systems, rather than focusing on single firms as independent units.

6. CONCLUSIONS

In order to design an energy system able to exploit the features of industrial districts, characterized by the concentration in a restricted area of a multitude of similar, small-sized firms having correspondingly small boilers and facilities, we have investigated the inclusion of ORC for biomass-based cogeneration into a multi source industrial district heating system. To this end, we have developed a mixed-integer linear programming model and have applied it to a case study from the furniture industry. Results show that a distributed heat generation system, integrating existing biomass fed boilers into a district heating network, is the optimal configuration to meet the heterogeneous heating requirements of industrial and civil buildings in the area if the heat demand is large enough. As for power generation, on the other hand, a new centralized cogeneration plant based on ORC, rather than a number of uneconomical small cogeneration units, would bring about economic advantage in presence of a district heating network. This confirms that, in the case of IDs, facilities and plants should be conceived and designed in a district oriented perspective, both with centralized and distributed solutions. In fact, as highlighted in Meneghetti and Chinese (2002), innovative technologies, such as ORCs, may be out of reach for single small enterprises but may be affordable if firms co-operate, accepting to connect to a district heating network, acting as sources or as clients, and, as the case may be, to invest in shared centralized or distributed facilities. Hence, increased inter-firm cooperation fosters higher innovation and technology levels, which may enhance profitability and environmental affordability of industrial district energy systems, as demonstrated in the analyzed case for ORCs.

APPENDIX A

Economic data used for calculations are shown in Table AI.

APPENDIX B

Technical parameters and efficiencies are shown in Table BII.

Table AI

Investment costs (including installation)	Estimated lifetime (years)	Size-independent cost component $c_{b,\text{fix}}(f,b,\text{tech})$	Size-dependent cost component $c_{b,\text{var}}(f,b,\text{tech})$
Biomass boiler refurbishment, no ORC (sources 1–4)	15	23 962 €	14.821 € kW^{-1}
New biomass boiler, to be built in an existing building (source 6), no ORC	20	79 874 €	49.403 € kW^{-1}
New biomass boiler and new building on available land plot (source 5), no ORC	20	127 798 €	79.045 € kW^{-1}
Biomass boiler refurbishment and ORC cogeneration group	15	765 145 €	188.2 € kW^{-1}
New biomass boiler in an existing building with ORC group	20	838 457 €	231.16 € kW^{-1}
New biomass boiler on available land plot, with ORC group	20	886 381 €	260.8 € kW^{-1}
Waste-to-energy heat exchanger	15	28 818.29 €	18.29 € kW^{-1}
Natural gas boiler (source 8)	20	23 852.70 €	43.14 € kW^{-1}
Heat exchangers	15	6213.3 €	13.534 € kW^{-1}
District heating pipeline	30	210 € m^{-1}	Negligible
Substations (costs sustained by DH, taking into account customer contribution)	15	3727.9 €	8.120 € kW^{-1}

Variable costs		
Fuel costs	Biomass	0.01040 € kWh^{-1}
	Natural gas	0.04287 € kWh^{-1}
	Thermal bleeding (lost revenues from power sale, calculated as a function of renewable power sale price)	$0.13p_{\text{el}}$ (waste, all tech)
Maintenance (yearly expenses estimated as % of investment costs)	Biomass boilers (new or refurbished)	7% Of investment cost
	Natural gas boiler	3% Of investment cost
	Waste-to-energy installations pertaining to district heating	5% Of investment costs
	Biomass boilers with ORC groups	9% Of investment costs
	District heating network	5% Of investment cost
Operation and Management	3.11×10^{-3} € kWh^{-1}	
Pumping	0.45×10^{-3} € kWh^{-1}	
Auxiliary electricity	$0.0292p_{\text{el}}$ (biomass, orc)	

Table AI *Continued.*

Estimated energy sale price ranges	Minimum price	Maximum price
Thermal energy to civil customers	0.0592 € kWh_{th}^{-1}	0.0882 € kWh_{th}^{-1}
Thermal energy to industrial customers	0.0275 € kWh_{th}^{-1}	0.0459 € kWh_{th}^{-1}
Thermal energy to boiler owners	0 € kWh_{th}^{-1}	0 € kWh_{th}^{-1}
Renewable electrical energy	0.042 € kWh_{el}^{-1}	0.142 € kWh_{el}^{-1}

Interest rate 6%.
Subventions on investments: 20%.

Table BII.

District heating network length 6450 m	
Boiler efficiencies:	
New and refurbished biomass boilers efficiency	0.75
Natural gas boiler efficiency	0.92
Waste-to-energy thermal bleeding heat exchange efficiency	0.90
Thermal efficiency of ORC group	0.794
Electrical efficiency of ORC groups	0.178
α Ratio for ORC groups	0.224
Dissipation ratio for thermal energy dissipation	0.0292 $kWh_{el}\,kWh_{th}^{-1}$
Heat losses through the DH network	0.14
Minimum boiler capacity for ORC installation	1500 kW_{th}
Maximum boiler capacity for ORC installation	8700 kW_{th}
Low heating value of wooden biomass	14.3 kJ kg^{-1}

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