ORC TECHNOLOGY FOR WASTE-WOOD TO ENERGY CONVERSION IN THE FURNITURE MANUFACTURING INDUSTRY

by

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Exploitation of low and medium temperature thermal sources, in particular those based on biomass combustion and on industrial residual heat recovery, has been increasingly investigated in the last decades, accordingly to the growing interest towards reduction in primary energy consumption and environmental issues. Organic Rankine cycle technology allows designing power plants that are less demanding in terms of auxiliaries, safety systems, maintenance and operating costs when compared to conventional water steam power plants.

To support the preliminary technical and economic design of this kind of plants in different contexts, a simulation code of part load and off-design operation of an organic Rankine cycle unit for combined heat and power has been developed. In the paper, taking the real situation of a furniture manufacturing factory as a starting point, it is shown how all energy flows occurring all year long inside the combined heat and power plant, can be estimated on the basis of the thermal user duty time profile, the available biomass flow rate and the adopted operation strategy. This information is the basis in order to correctly evaluate the energetic, economic and environmental advantages of the proposed technical solution, with respect to a particular context, as it is shown in the concluding part of the paper.

Key words: *biomass, organic Rankine cycle, co-generation, waste-to-energy*

Introduction

Biomass to energy conversion can lead to important advantages from both energetic and environmental point of view. In fact, as it is well known, biomass is a renewable energy source (RES), so that, its energy usage allows fossil fuels recovery, and it is a CO_2-neutral source of energy too. In addition, a further limitation of polluting emissions, as acids, dust and NO_x, can be obtained if biomass is used instead of other solid or liquid conventional fossil fuels [1-3].

Besides biomass available from agriculture or forest residues and energetic cultivations, an important source of biomass can be obtained from industrial waste also. This option is worth to be specially considered when various factory of the same kind operate inside a small area.

As a general rule, biomass to energy conversion can lead to actual energy saving and polluting emissions reduction if biomass sources are concentrated in a small area, so that a major part of energy consumption, emissions and economic costs related to collection and transport can be avoided.

This is the case of the Italian furniture manufacturing industry that is highly concentrated inside few small areas, named "industrial districts" located in the North-East part of the country. Each one of these industrial district actually produces a huge amount of waste wood, not suitable for recycling inside the furniture production process. In most cases waste wood is simply burned to obtain thermal energy, otherwise it has to be disposed.

A research realized in Italy by Federlegno-Arredo in 1997 [4] shows that the furniture manufacturing sector produced $4.7 \cdot 10^6$ t of waste virgin wood and $1.4 \cdot 10^6$ t of waste processed wood, a half of which is actually used to produce about $0.9 \cdot 10^6$ toe (ton of oil equivalent) of thermal energy from renewable energy sources (RES). This situation justifies the interest in the usage of waste wood for combined heat and power (CHP) production. In fact an extensive usage of co-generated heat is a key point to reach energetic and economic benefit, taking account of the low electrical energy conversion efficiency typically affecting small biomass power plants.

The ORC (organic Rankine cycle) technology seams to be very well suited to this kind of application, allowing interesting electrical and total conversion efficiencies to be achieved with small CHP plant too, like those that could be fed with waste wood from one big factory only, or from a consortium of smaller ones.

ORC technology allows designing power plants that are less demanding in terms of auxiliaries, safety systems, maintenance and operating costs when compared to conventional water steam power plants. Moreover the ORC working fluid does not participate to the combustion process, but combustion (for instance, of waste wood) occurs in a separate furnace (see *The ORC technology*), where fouling phenomenon can be confined and more simply managed. As a consequence, maintenance and component fouling problems are much less important when compared to different biomass to energy conversion systems, based on biomass gasification and internal combustion cycles.

The electrical efficiency of actual ORC units, referred to biomass low heating value (LHV), is approximately 15-20%, depending on the boundary condition of CHP system. Anyway, each installation has to be considered independently, and the energetic and economic analyses have to be carefully tailored. To support the preliminary design of new plants in the considered industrial district, or in different contexts, a simulation code of part load and off-design operation of an ORC unit for CHP, of about 1000 kW_e, has been developed on the basis of Aspen-Plus modular simulation software.

In the paper, taking the real situation of a furniture manufacturing factory as a starting point, it is shown how all energy flows occurring all year long inside the CHP plant, can be estimated, having as input data the thermal duty time profile, the available biomass flow rate and the adopted operation strategy. This information is the basis in order to correctly evaluate the energetic, economic and environmental advantages of the proposed technical solution, with respect to a particular context, as it is shown in the concluding part of the paper.

A typical furniture manufacturing factory

A recent study ordered by the regional government [5, 6], focus on the waste wood to energy option for the furniture manufacturing factories, located inside an industrial district of regione Friuli Venezia Giulia. That study takes into account about 260 factories and includes a detailed analysis of energy recovery options for a selected sub-set of 39 factories. The results about fuels utilisation in the actual plant configurations are shown in fig. 1. Note that 43% of considered factories use biomass (waste wood) as a fuel for their thermal plants. This percentage grows up to 80% when bigger factories only (with 60 workers, or more) are taken into account, so that the latter have to be regarded as the first candidates for adopting a waste wood to energy co-generation system.

Maximal electrical and thermal demands for factories of this kind are shown in fig. 2. Note that the former is below 2000 kW_e, while the latter can reach a value of 8000 kW_t, with an electrical-to-thermal power ratio in the range 0.15-0.40.

In the present paper a factory has been selected as a "typical furniture manufacturing factory" of the district, than the energetic, economic, and environmental advantages of the suggested CHP technology have been evaluated in different operating conditions by means of the ORC unit simulation code. The reasons of the choice can be found essentially in the high thermal energy demand, smaller but not negligible in summertime also due to pressing and painting phase of the industrial manufacturing process, and in the high west wood availability, such that an excess of waste wood is actually sold to the market.

The present thermal plant of the selected "typical furniture manufacturing factory" (fig. 3) consists of two waste wood boilers in parallel, having a nominal output power equal to 2.5 and 4.7 MW_t, respectively, the high and low temperature collectors and a couple of boiler feed pumps. Natural gas also can be used in both boilers, as integration fuel.

Super heated water (7-8 bar) inside the high temperature collector is shared out among

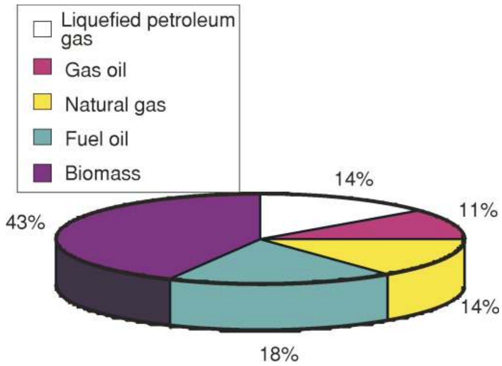

Figure 1. Fuels utilisation in the actual plants for 39 factories in a furniture manufacturing district of region Friuli Venezia Giulia, Italy

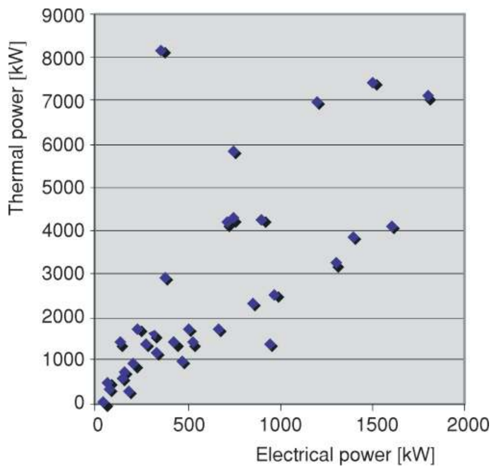

Figure 2. Maximal thermal *vs.* electrical demand for factories in the same furniture manufacturing district of fig. 1

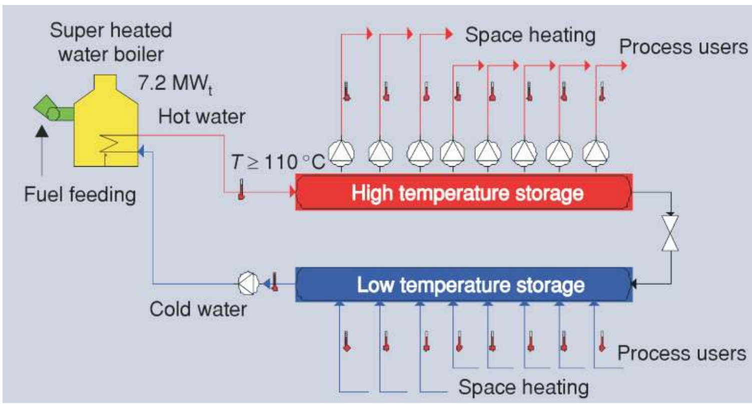

Figure 3. Present thermal plant of the selected "typical furniture manufacturing factory"

all thermal users through 9 pumps in parallel. Industrial presses need super heated water at a temperature not below 110 °C, so that a typical temperature inside the high temperature collector is about 115 °C. Note that super heated water at this temperature is sent to all other users too, even if this is not strictly necessary. In order to avoid important lay out modification of the thermal plant, co-generated heat also will have to be generated at such a temperature, that is higher than nominal design temperature for CHP ORC units, where the thermal vector enter the condenser at about 60 °C and is heated up to about 80 °C.

The first step in order to evaluate the energetic, economic, and environmental advantages of the suggested CHP technology has been an energy audit of present electrical and thermal consumptions. Taking into account the periodical operation course in this kind of manufacturing, the whole year has been modeled through three typical days:

- a typical winter day (104 days/year), when the factory operates 15 hours per day and the space heating system is always on,
- a typical spring-autumn day (45 days/year), when the factory operates 12 hours per day and the space heating system is on 6 hours per day only, and
- a typical summer day (100 days/year), when the factory operates 8 hours per day and the space heating system is always off, so that the industrial process only consumes heat.

The results of electrical and thermal energy audit are shown in figs. 4 and 5.

The simplified year model, based on three typical days only, has been validated by comparing the actual energy consumption of the factory in the last years, and the ones resulting from the simplified model, obtaining a difference smaller than 1.5%. These results support the option of evaluating energetic, economic, and environmental advantages of the west wood to energy technology

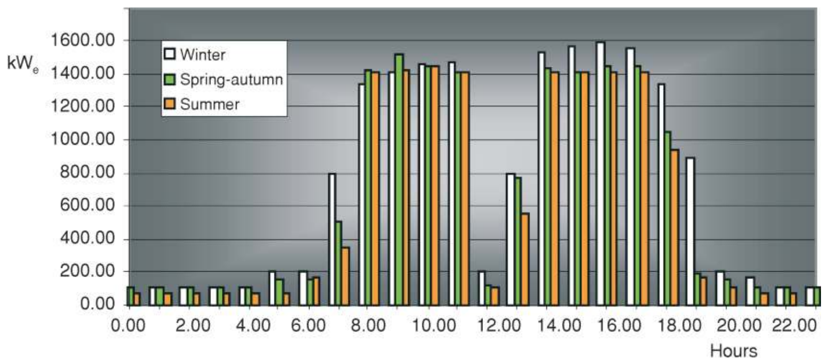

Figure 4. Electrical power – load curve

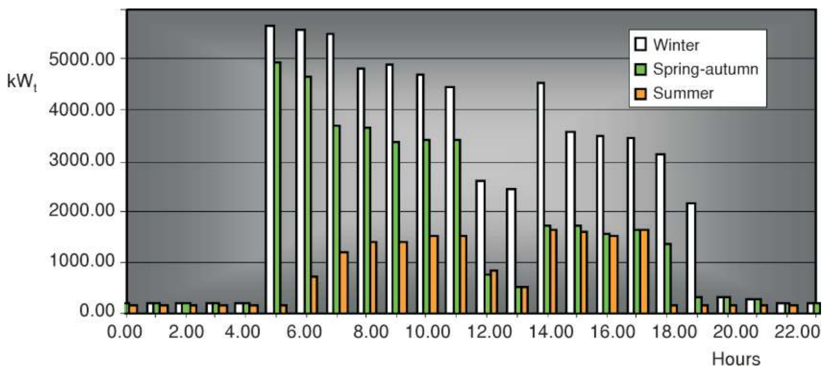

Figure 5. Thermal power – load curve

on the basis of the simplified year model. Nevertheless the suggested methodology would not change if a grater number of typical days had to be introduced, accordingly with energy users' characteristics.

The ORC technology

The ORC technology is well known in the field of geothermal energy conversion [7, 8]. In recent years, some small size CHP units came to the market [9-11] and nowadays various applications can be found, mainly in biomass to energy co-generation plants [12-15]. A plant of this kind is shown in fig. 6. Diathermic oil at a temperature of about 300 °C is produced by the biomass furnace and sent to the saturated vapour generator (evaporator), inside the ORC unit.

As in conventional steam Rankine cycles, the evaporated working fluid expands in the turbine, producing useful work and than electrical energy through an asynchronous generator. At turbine exit the working fluid is still in a state of super heated vapour, so that it can be cooled inside a heat exchanger (the recuperator) and than condensed. The condenser cooling circuit supplies the thermal users with the co-generated heat.

A possible cycle pattern in the *T-s* plane is shown in fig. 7. Organic fluids (pure, or in a mixture) are used instead of steam in this kind of cycle and dry fluids (*i. e.* fluids with a positive slope of the vapour saturation curve in the *T-s* diagram) are preferred, because they results much more well suited for low temperature heat sources exploitation. Note that a fully dry expansion is possible from saturated vapor condition also (point 4) and that a strong internal regeneration effect is obtained, like it happens in recuperated gas turbine.

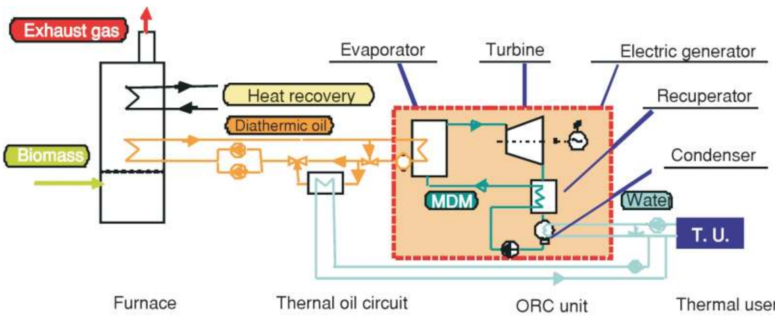

Figure 6. Schematic of a ORC biomass to energy co-generation plant

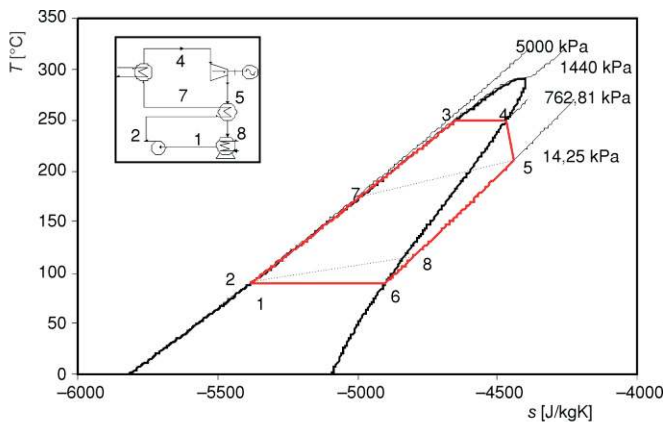

Figure 7. Saturation curves and a possible Rankine cycle using MDM (short name for octamethyl-trisiloxane, formula $S_8H_{24}Si_3O_2$) as working fluid

The unit's control system is supposed to operate the extraction pump at different speeds, in order to modify the working fluid mass flow rate accordingly with the mass flow rate of hot thermal oil entering the unit. The main technical features of ORC units can be summarized as [14]:

– fairly good efficiency and high total efficiency in CHP operation, at part load too,
– high turbine isentropic efficiency (up to 85%),
– low mechanical stress in the turbine, because of the low peripheral speed,
– electric generator directly driven by the turbine, without the need of a gear box,
– negligible blade erosion, as a consequence of completely dry expansion,
– working fluids not damaging pipes, valves and blades, allowing a long life of the unit, and
– water treatment system not required.

The simplicity of start-stop and load modulation procedures, the low noise operation, and the reduced maintenance needs have to be regarded as further advantages of this kind of units.

An alternative biomass to energy technology could be found in biomass gasification and syngas utilisation in an internal combustion engine. This option seams to be promising in view of obtaining a higher electrical efficiency, but problems in the syngas cleaning process are still not completely overcome, affecting long run operations and maintenance costs.

ORC units now available on the market are the result of a strong standardization and cost reduction process; they have an electrical nominal power in the range 500-1500 kW_e and a nominal thermal power in the corresponding range 2300-7000 kW_t [16]. Plants of these sizes are expected to operate in a remote controlled mode, without the need of a supervisor always present beside the plant.

Taking into account the furniture manufacturing district previously introduced, 30 factories were found matching with thermal and electrical output of market available ORC units, but the suggested technology could be applied to smaller factories too, by grouping them in consortium.

The suggested solution

The easier option for introducing an ORC unit inside the selected factory is converting the pressurized water boilers into thermal oil ones and putting the ORC unit between boilers and collectors (fig. 8). The ORC unit can be regarded as a heat exchanger block, receiving the hot thermal oil from the boilers and the water coming back from thermal users.

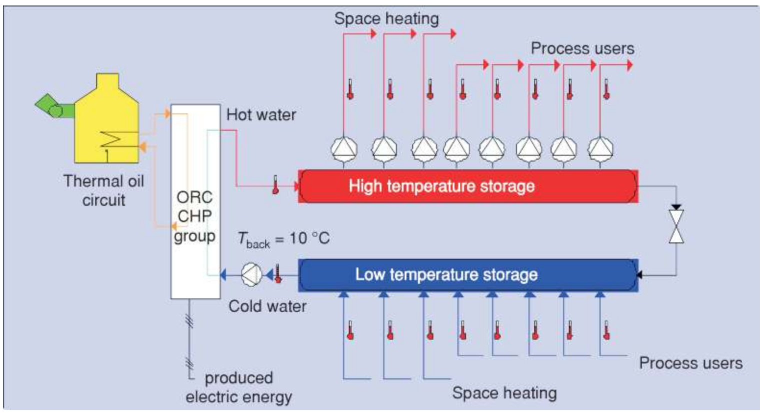

Figure 8. Modified schematic of the thermal plant of the selected factory

The energetic, economic, and environmental advantages of introducing the CHP unit inside the selected factory have been evaluated for each typical day by means of a simulation code, based on Aspen Plus® modular simulation software. In fact Aspen Plus® contains a wide library of working fluids thermo-chemical properties and it allows customized modules to be easily defined, where subroutine *ad hoc* can be eventually introduced, to take part load performance into account. In view of the objects of the work, the model focus on nominal and part load thermodynamic cycle performance, neglecting a detailed analysis of component geometry [6]. The model simulates an ORC unit having the following design parameters: vaporization temperature 250 °C (vaporization pressure 762.81 kPa), condensation temperature 90 °C (condensation pressure 14.25 kPa), electrical output 1000 kW_e, and thermal output 5600 kW_t.

The simulations takes into account the actual operating conditions monitored on the plant for high and low thermal collectors, so that the electrical efficiency of the unit is necessarily affected by the high temperature of the water coming back from thermal users, that is the cooling fluid of the Rankine cycle condenser. Thus, the ORC group has always to work in off design conditions in the case study. Due to the high temperature of the water coming back from thermal users (about 100 °C), the condensation temperature can not be lowered under 110 °C, corresponding to a condensation pressure equal to 35 kPa. Further constant parameters are used in the simulations. Their proper values, suggested by ORC unit manufacturers, are shown in the following:

- thermal oil inlet temperature: 300 °C,
- water pressure: 3 bar,
- feed pump isentropic efficiency: 0.75,
- feed pump mechanical efficiency: 0.95,
- feed pump motor efficiency: 0.95,
- turbine mechanical efficiency: 0.95, and
- electric generator efficiency: 0.97.

Taking all these hypothesis into account, the simulation model degrees of freedom are reduced to two only, so that each performance figure can be fully described by means of a parametric curves family in a two-dimension diagram.

Working fluid thermophysical properties directly affect ORC pattern and unit's efficiency, as it can be easily inferred. In the simulation model octamethyltrisiloxane (short name MDM, formula $C_8H_{24}Si_3O_2$) has been used as working fluid, accordingly with literature [17, 18] and manufacturers' suggestions [16], because of its low toxicity and flammability and because of its high thermo-chemical stability in the required temperature range.

Taking the electrical and thermal demand courses into account, a heuristic operation strategy of the ORC unit has bee adopted. In details, the thermal demand is followed if it is higher than the minimum thermal load of the unit; otherwise minimum possible heat dissipation is permitted only if industrial presses are in operation. If they are not the CHP unit is turned off and the small remaining thermal demand is met with an integration boiler. In this way the CHP unit operates much more time with respect to the simple strategy of always following thermal demand, obtaining a higher electrical production along the year; at the same time, thermal dissipation is not so big as it could be if following electrical demand strategy were adopted.

ORC unit energetic performance

In fig. 9 thermal and electric power obtained from the ORC unit in different operating conditions are shown. Condensation pressure values result higher than nominal one in consequence of higher temperature of input water in the condenser. The minimum thermal output re-

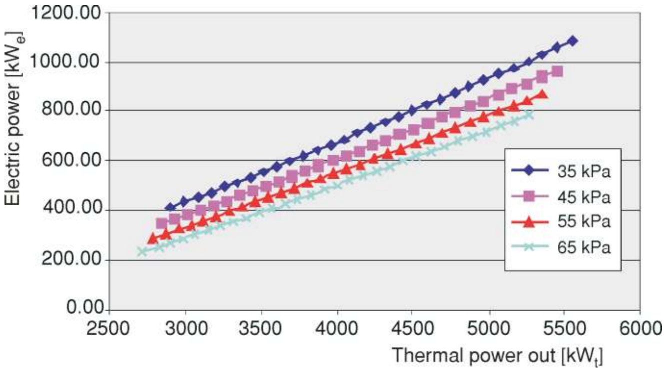

Figure 9. Electric power *vs.* thermal power from ORC plant and condensation pressure

sults to be about 2730 kW$_t$, at the higher condensation pressure (65 kPa), whereas electrical power is about 230 kW$_e$. By comparing these values with thermal demand in fig. 5, the need for thermal dissipation in the afternoon of the middle-season day and for almost all the summer day long, can be easily inferred. In figs. 10 and 11 the electric to thermal power ratio and the electric efficiency are shown, respectively, as a function of input thermal power from the boiler, having condensation pressure as a parameter. It can be easily inferred from these figs. that operating the ORC unit at the minimum condensation pressure (35 kPa), implies the advantage of a higher electrical production, whatever the load is, with the acceptable disadvantage of a slight increase in the minimum thermal load and consequently in the dissipated heat too.

At least from the economic point of view, benefits are expected to overcome, taking account of high waste wood availability (greater than 5500 t per year) and its low market price

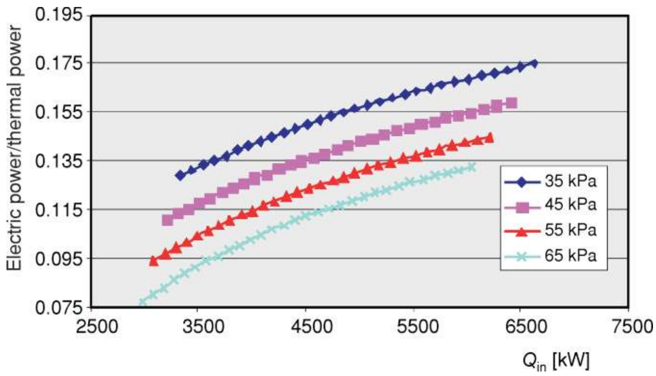

Figure 10. Electric to thermal power ratio *vs.* input thermal power (Q_{in}) and condensation pressure

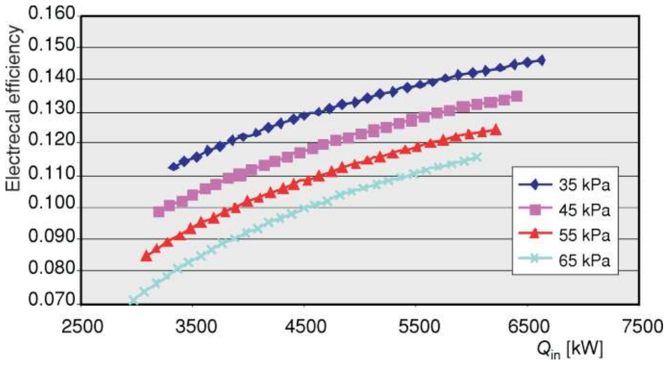

Figure 11. Electrical efficiency *vs.* input thermal power (Q_{in}) and condensation pressure

(0.1 €/t). Thus, minimum condensation pressure operation has been introduced in the simulation model.

Figures 12 and 13 show water mass flow rate and delivery temperature as a function of input thermal power, having condensation pressure as a parameter. Keeping the hypothesis of operating at minimum pressure, water mass flow rate results to be sufficient for maximum thermal users' requirements (180 kg/s). In these conditions, the ORC unit can produce up to 5700 kW_t, that are very close to the maximum thermal demand (see fig. 5). Furthermore, the delivery water temperature results to be always suitable for the industrial thermal request, which is in the range 114-116 °C.

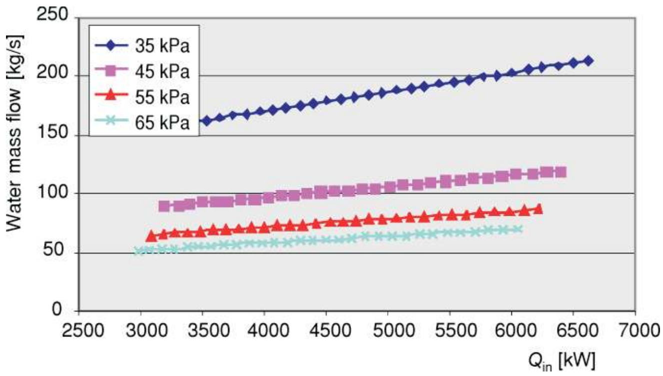

Figure 12. Water mass flow *vs.* input thermal power (Q_{in}), varying the condensation pressure

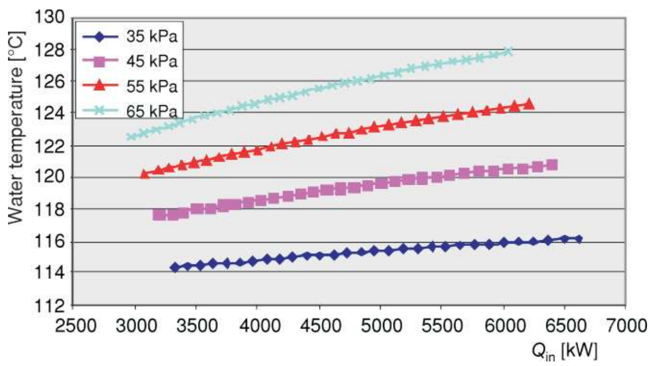

Figure 13. Water temperature vs. input thermal power (Q_{in}), varying the condensation pressure

Energetic economic and environmental advantages

Taking previous hypothesis into account, the simulation model has been used to evaluate the electrical production of ORC unit in each typical day. The results are compared with the electrical demand in figs. 14, 15, and 16, showing that the CHP unit allows a significant electrical energy saving and also a surplus which is sold to the grid. In the summer day the low thermal demand implies a small electrical production too (less than 450 kW_e), in spite of thermal dissipation. The simulation model allows thermal production, dissipated heat and CO_2 emissions to be obtained as well, so that the total year amounts can be easily calculated. The results are shown in tabs. 1, 2, and 3. The adopted operation strategy allows the CHP unit to comply with thermal demand in winter and spring-autumn days and to be in operating several ours long in the summer day too, so that co-generated heat satisfies more than 98% of year thermal demand and thermal dissipation is only 16.6% of co-generated heat.

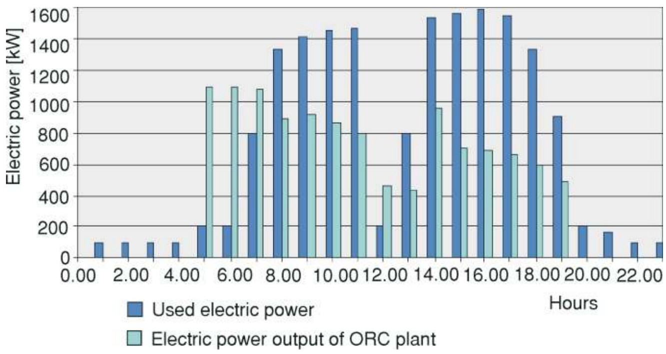

Figure 14. Comparison between electric demand and ORC unit power output in a winter day

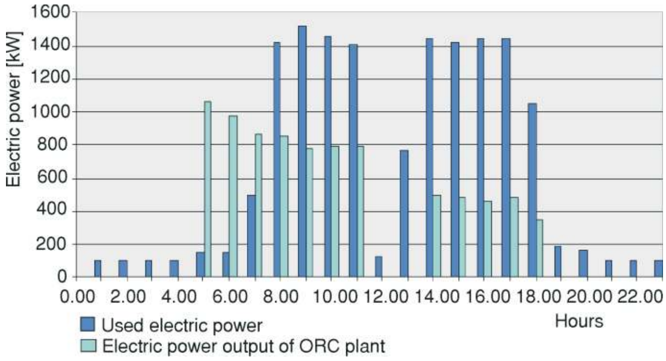

Figure 15. Comparison between electric demand and ORC power output in spring /autumn day

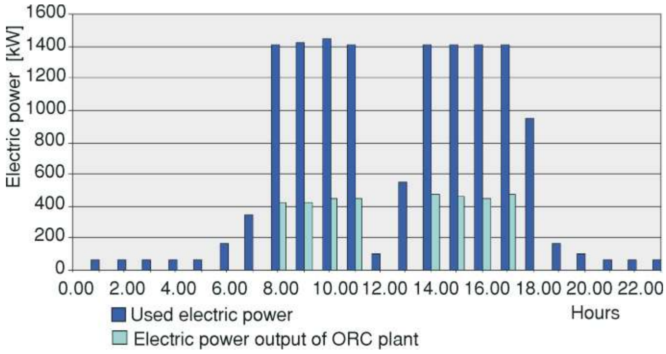

Figure 16. Comparison between electric demand and ORC unit power output in a summer day

Realizing the waste wood to energy CHP system allows self production to satisfy about 41% of electrical energy demand and to obtain more than 4000 t per year of CO_2 avoided emissions.

The economic feasibility of the suggested solution can now be evaluated on the basis of previously obtained energy flows, taking actual market price of gas electricity [19] and waste wood into account (and their courses intra day and all year long), as well as additional maintenance costs of the ORC unit. Further main economic parameters introduced in the analysis are the capital cost of the investment (1300000 €), the discount rate (5%), and the plant residual value (zero). An additional income, equal to 0.0824 €/kWh has been introduced as a public economic support to renewable electrical energy production, named in Italy "Certificati verdi" (Green cards) [20].

Table 1. Annual energy flows – thermal energy

	Winter	Spring-autumn	Summer	Year
Thermal energy co-generated [MWh]	7278.72	2797.84	3638.05	13714.61
Thermal energy dissipated [MWh]	468.00	607.50	1200.00	2275.50
Boiler integration [MWh]	0.00	0.00	193.24	193.24
Total thermal energy demand [MWh]	**6810.72**	**2190.34**	**2631.29**	**11632.35**
Wasted heat/co-generated heat [%]	6.43	21.71	32.98	16.59
Co-generated heat/thermal demand [%]	100.00	100.00	92.66	98.34

Table 2. Annual energy flows – electric energy

	Winter	Spring-autumn	Summer	Year
Electric energy co-generated [MWh]	1218.41	376.65	359.96	1955.02
Electric energy sold [MWh]	242.12	94.64	0.00	336.76
Electric energy saved [MWh]	976.29	282.01	359.96	1618.26
Electric energy bought [MWh]	835.27	412.61	1068.47	2316.35
Electric energy demand [MWh]	**1811.56**	**694.62**	**1428.43**	**3934.61**
Electric energy sold/co-generated [%]	19.87	25.13	0.00	17.23
Electric energy saved/demand [%]	53.89	40.60	25.20	41.13

Table 3. CO_2 avoided emissions and primary energy consumption saved

	CO_2 [t per year]	toe per year
Electrical production	1564	420
Thermal production	2517	1093
Total	4081	1513

A constant value of the reverse metering factor (*i. e.* the selling to purchase ratio of electrical energy) equal to 0.60 has been considered in the economic evaluation. Extending the following considerations to different countries, all these parameters would have to be updated, accordingly with the actual context. Figure 17 shows the net present value (NPV) of the investment in a time interval equal to the assumed life time (20 years). Note that positive cash flows are generated also after the 8th year, when the public economic support is supposed to be cut off. The pay back time is less than 5 year, much less than the plant fife time. The internal rate of return results grater than 22% and the NPV for 20 years of operation is evaluated as 1800000 €.

A more precise economic evaluation could be realized, taking account of detailed capital cost for ORC unit integration inside the thermal plant, and of actual energy purchase agreements and country regulations. On the other hand, also an extremely detailed economic analysis

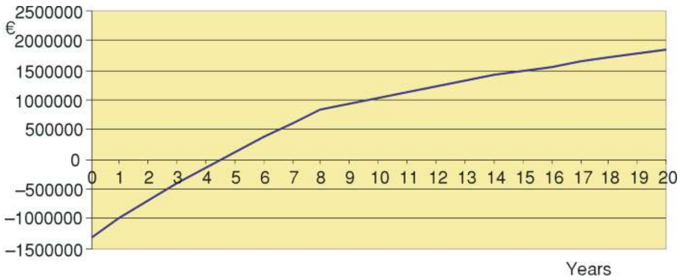

Figure 17. Net present value of the investment (discount rate 5%)

would be affected by intrinsic approximations, related with atmospheric conditions all year long, or with the long time courses of electricity and natural gas.

Conclusions

The adoption of the ORC unit in a typical factory of the furniture manufacturing district results to be of certain interest, in particular if it is compared with other RES conversion technology. This is in spite of its electrical efficiency, which is not very high because of technical choices (in particular the use of thermal oil, limiting the maximum cycle temperature) and of specific operating conditions (in particular the required output water temperature, higher than in the nominal design condition). The expected energetic, economic, and environmental advantages of introducing the ORC unit inside the chosen furniture manufacturing factory are: (1) the co-generated heat satisfies more than 98% of thermal demand and self produced electrical energy satisfies about 41% of electrical demand, (2) more than 4000 t per year of CO_2 emissions are avoided and more than 1500 toe per year of fossil fuels are saved, and (3) the capital investment pay back time is less than 5 year, taking account of public economic support to renewable electrical energy production, justifying a further economic analysis of this and of other analogous possible applications of ORC units.

If 11% only of present thermal production from waste wood in the Italian furniture manufacturing industry were obtained through this CHP technology, previous figures would have to be multiplied by 100. The expectation is that even better performance would be obtained if the ORC units were located in areas with larger winter thermal needs.

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