Industrial Waste Heat Recovery Strategies in Urban Contexts: a Performance Comparison

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***Abstract*—In increasingly populated urban areas, the optimization of energy resources is of vital importance not only for economic and ethical reasons, but also to reduce greenhouse gas emissions. Industrial plants and factories usually located around cities often require (and in some case also dissipate) large amounts of energy. As known, the waste heat generated by high-temperature industrial processes can be partially recovered for a variety of applications. Unfortunately, cost and efficiency issues limit the feasibility of some of these solutions. In this paper two possible waste heat recovery strategies are described and compared, i.e. electrical generation based on Organic Rankine Cycle (ORC) and District Heating (DH). The proposed analysis focuses on the recovery of the waste heat produced by foundries and it relies on the experimental data collected in a real case study. Several simulation results, based on such experimental data sets, enable a reasonably fair comparison between these two heat recovery strategies, thus paving the way to the deployment of a demonstrator at SCM Foundries, Rimini, Italy.**

***Keywords*—Energy efficiency, data acquisition, smart energy systems, district heating (DH), Organic Rankine Cycle (ORC).**

I. Introduction

According to UN statistics, 54% of the current world's population lives in urban areas, with an expected increment in the coming years [1]. This phenomenon is even more evident in Europe, where this percentage is already about 73%. In this context, keeping under control and improving the use of city resources through management, technological or regulatory strategies is of vital importance, e.g. for road lighting reduction [2], public transport enhancement [3] or optimal charging and discharging of electrical vehicles [4]. In the energy sector (which currently has a high priority in the political agenda due to serious environmental concerns) utilities (e.g., electrical and thermal), public institutions and final users (both industrial and residential) are required to cooperate to reach the targets established by the European Energy Efficiency Directive (EED) 2012/27/EU, i.e., 20% reduction in fossil fuel consumption, 20% increase in energy efficiency and 20% increment of renewable energy sources by 2020.

The industrial sector currently dissipates about 37% of the world's total delivered energy, i.e. more than any other end-use sector [5]. Usually, about one third of the energy absorbed by factories is transformed into heat and it is often dumped in the environment. The use of Energy Management Systems (EnMS), as described in the ISO Standard 50001:2011, enables "an organization to follow a systematic approach in achieving continual improvement of energy performance, including energy efficiency, energy use and consumption" [6]. In this respect, recovering part of this large amount of *waste heat* could be used to implement a variety services for citizens.

An important example of energy reuse is electricity generation. Of course, the efficiency of the conversion process depends on heat temperature. An excellent solution to exploit sources at a relatively moderate temperature is the Organic Rankine Cycle (ORC). Several industrial processes are suitable for this purpose [7]–[9]. Alternatively, industrial waste heat can be used to supply a district heating (DH) network. This solution is profitable when a factory is located at a reasonable distance from end users [10]. DH is usually regarded as a very sustainable technique, especially in cities. Also, the joint use of combined heat and power (CHP) generation and DH (exploiting the waste heat resulting from electricity generation) is currently considered as one of the cheapest methods for reducing carbon emissions [11], [12]. In this context, the purpose of this work is to analyse the energetic and economic benefits of ORC-based and DH-based heat recovery strategies in foundries [13]. Indeed, for this type of industries the possibility of waste heat internal reuse is usually limited, thus making it more attractive for external applications. Among them, ORC and DH (considering the temperature levels usually available) appear as natural candidates for electrical and thermal energy generation, respectively.

The rest of the paper is structured as follows. First, in Section II, potentialities and technology-related issues of waste heat recovery in foundries are shortly described from a qualitative point of view. In Section III, the basic models to perform the steady-state energetic analysis of ORC and DH heat recovery solutions are explained. Section IV presents the experimental data collected at the SCM Foundries, Rimini, Italy, and points out possible problems of both heat recovery strategies. Finally, Section V reports some simulation results based on the available experimental data in order to compare their performances. Conclusions and future work are described in Section VI.

II. Waste heat recovery in foundries

Generally, industrial waste heat recovery is particularly profitable when high-temperature processes are involved. Foundries, for instance, inherently demand and generate large amounts of thermal energy. The main source of waste heat in a foundry is the melting furnace. In this paper, the specific

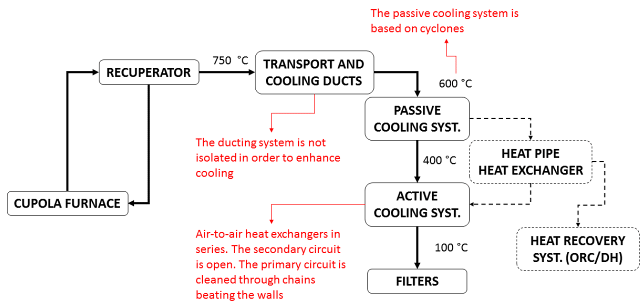

Fig. 1. Block diagram of the aspiration system of the exhaust gases generated by a cupola furnace.

case of an iron foundry using a hot blast cupola furnace is considered. This is a furnace burning coke and exploiting a recuperator to pre-heat the combustion air from flue gases. A block diagram of the flue gases aspiration system is shown in Fig. 1, where it can be seen that, after the recuperator, the gases generated by the melting process have a temperature of about 750 °C. Such flue gases are first transferred to a passive cooling system based on *cyclones*, i.e. devices removing heavy particulate through centrifugal separation. Then, the output cleaner gases (at a residual temperature of about 400 °C) are further cooled down to about 100 °C by a series of air-to-air active heat exchangers (i.e. fans). Finally, a bank of fabric filters (whose reliable operation requires temperatures not higher than 100 °C) further removes the residual particulate.
In order to recover heat from the flue gases generated by a furnace the Heat Pipe Heat Exchangers (HPHE) are probably the best solution [14]. Heat pipes exploit the transformation of the phase latent heat of a fluid. In heat pipes, an internal fluid vaporizes because of the heat of flue gases. The vapor rises in the pipe till reaching the other side of the exchanger. This is immersed in a fluid which is in contact with a secondary system at a lower temperature. In this way, when the system absorbs the heat, the pipe's internal fluid recondenses ready to be vaporized again [15]. HPHEs rely on standard technologies up to about 500 °C. Above this temperature, special steel types and internal fluids are needed. These HPHEs can be considerably more expensive. Of course, the amount of usable thermal energy depends on the position of the exchanger along the exhaust duct, as flue gases temperature progressively decreases due to thermal losses. A major problem affecting heat recovery from flue gases in foundries is the presence of particulate, especially before the cyclones. If the HPHE is installed upstream of the cyclones, a larger amount of thermal energy can be recovered. However, more expensive heat exchangers are needed. Moreover, the accumulation of particulate greatly reduces heat exchanger efficiency [16]. To avoid this problem, HPHEs should be cleaned frequently, thus making maintenance costs considerably higher. On the contrary, if the HPHE is installed downstream of the cyclones, equipment and maintenance costs are lower, but the amount of recovered heat is roughly halved. While the best approach strongly depends on the features of the specific foundry considered, the latter solution, although conservative, is generally preferable, because standard HPHEs are much cheaper and the effect of fouling due to particulate is hard to predict a priori. For these reasons, the waste recovery strategies considered in the rest of this paper will rely on the assumption that the HPHE is installed downstream of the cyclones.

III. Energy Analysis Models

As introduced in Section I, two heat recovery strategies are compared in this paper, i.e. ORC and DH, as they tend to exploit in the best way the available thermal energy at temperatures in the order of a few hundred °C.
When the *ORC-based strategy* is used, the heat absorbed through the HPHE is transferred to an intermediate hydraulic circuit (e.g., filled in with diathermic oil) connected to the hot side of the ORC. The thermal energy not converted into electricity is then transferred to an additional circuit (e.g., running water) and dissipated through a cooling system (e.g., a cooling tower). The residual heat in the flue gases is finally dissipated by cooling fans.
In the case of the *DH-based strategy*, the heat absorbed through the HPHE is transferred to an intermediate circuit connected to another heat exchanger (e.g., a flat plate heat exchanger), which delivers heat to the DH network. Again, the residual heat of flue gases is dissipated by the existing cooling fans.
It can be recognized that, as shown in the block diagrams of Fig. 2 (a)-(b), both schemes rely only on three basic components, i.e., heat exchangers (HEXs), the ORC machine, and cooling systems (CS).

- The HEX can be used in two positions: either to deliver the heat absorbed from flue gases to an intermediate circuit, or to deliver the heat absorbed from an intermediate circuit to the DH network. The specific heat exchanger type is expected to be different in the two cases, but these technological details are not relevant for the intended analysis. Hence, in both cases the same HEX model, based on the arithmetic mean temperature difference (AMTD) approximation, will be used (see below).
- The ORC block is used to transform the recovered thermal energy into electricity, with a given efficiency.
- The CS blocks can be used either to cool the flue gases down to a temperature suitable for the filtering system or to dissipate the low-temperature heat generated by the ORC. Again, the CS implementation in the two cases can be different, but this it not important for the proposed analysis.

In order to compare the performances of the two heat recovery strategies, the following simplifying assumptions will be made in the rest of this paper, i.e.

1) The physical parameters (e.g., the specific heat) used in the model equations are assumed to be constant, as their dependence on temperature is not significant in the considered range of operating conditions.
2) At each time step, the system is supposed to be in stationary conditions. This implies that the dynamic effects due to thermal capacity are neglected.
3) Linearized heat exchange models are used. This is related to the use of the AMTD model, which is expected to be reasonably accurate for the temperature differences considered.

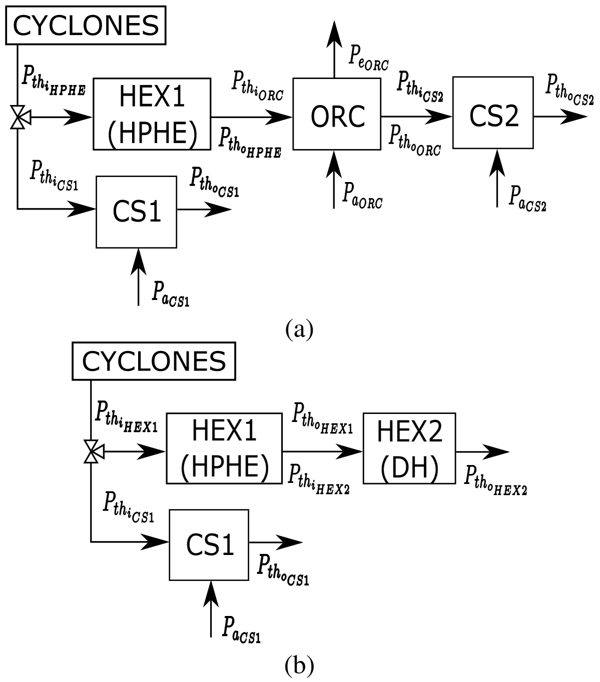

Fig. 2. Block diagrams of the waste heat recovery strategies based on (a) ORC and (b) DH, respectively.

4) For both ORC-based and DH-based strategies, the HPHE is supposed to be located downstream of the cyclones, as explained in Section II. Moreover, the HPHE is assumed to be cleaned regularly and the effect of fouling due to particulate is neglected.

The above assumptions introduce some approximations, the one about fouling being probably the most important. A more detailed model could consider a heat exchange coefficient reduction with operating time. However, the installation of a self-cleaning HPHE could strongly reduce the effect of fouling.

Based on assumptions 1)-4), the thermodynamic behavior of each block in Fig. 2(a)-(b) can be described by the same system of equations, i.e.

$$P_{th_{i_k}} = Q_{i_k} C_{i_k} \left(T_{H_{i_k}} - T_{C_{i_k}} \right) \quad (1)$$

$$\begin{aligned} P_{th_{o_k}} &= \eta_k P_{th_{i_k}} = Q_{o_k} C_{o_k} \left(T_{H_{o_k}} - T_{C_{o_k}} \right) \\ &= \frac{U_k}{2} \left[(T_{H_{i_k}} + T_{C_{i_k}}) - (T_{H_{o_k}} + T_{C_{o_k}}) \right] \end{aligned} \quad (2)$$

$$P_{a_k} = \begin{cases} \alpha_k P_{th_{i_k}} & \text{if block } k \text{ includes active components} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where:

- index $k \in \{\mathrm{HEX1}, \mathrm{HEX2}, \mathrm{ORC}, \mathrm{CS1}, \mathrm{CS2}\}$ refers to the name of the block;
- $P_{th_{i_k}}$ and $P_{th_{o_k}}$ are the thermal powers extracted from the input or transferred to the output of the $k-$th block, respectively;
- Q_{i_k} and Q_{o_k} are the mass flow rates of the fluids at the input and at the output of the $k-$th block;
- C_{i_k} and C_{o_k} are the corresponding fluid specific heat coefficients;
- $T_{H_{i_k}}$ and $T_{C_{i_k}}$ are the hot and cold temperatures of the fluid at the input of the $k-$th block, i.e. before and after releasing heat;
- $T_{H_{o_k}}$ and $T_{C_{o_k}}$ are the hot and cold temperatures of the fluid at the output of the $k-$th block;
- η_k denotes the efficiency of the heat exchange process occurring inside the $k-$th block;
- U_k is the heat exchange coefficient of the $k-$th block;
- finally, P_{a_k} denotes the electrical power drawn by the $k-$th block to operate properly. In practice, P_{a_k} is larger than zero only when the $k-$th block includes some active component (e.g. ORC pumps or CS fans). In steady-state conditions, P_{a_k} is approximately equal to a given fraction α_k of the thermal power $P_{th_{i_k}}$ available at the input of each block.

Of course, in order to evaluate and to compare the profitability of different heat recovery strategies, P_{a_k} should be properly taken into account in the overall energetic balance.

A. Heat recovery based on ORC

The ORC is a closed-loop thermodynamic cycle converting heat into mechanical work. A working fluid pumped into a high-temperature exchanger evaporates because of the input heat and then it passes through an expansion device (e.g. a turbine or a similar expander) where the fluid energy is transformed into mechanical work to generate electricity. The colder fluid at the output of the turbine then recondenses ready to be vaporized again. Unlike the classic Rankine cycle (which relies on plain water as a working fluid), the ORC derives its name from the fact that the working fluid is an organic compound (e.g. hydrofluorocarbon, hydrocarbon, fluorocarbon or silicon oil) characterized by an almost isentropic saturation vapor curve, a low-freezing point, a high temperature stability and above all, a lower boiling point than water at a given pressure. Because of these properties, an ORC-based generator can exploit relatively "cold" heat sources, while yielding higher energy conversion efficiency than a standard Rankine cycle [7]. In general, an ORC is a complex system, which is difficult to model in detail. However, since the focus of this paper is just on heat recovery efficiency, the ORC can be simply regarded as a "black box" and, particularly, as a special example of an active heat exchanger. In the case considered, the ORC block exploits the thermal power recovered by the HPHE to generate electrical power with some residual heat. Therefore, using the same notation as in (1)–(3), the power flows at the output of the ORC block are:

$$\begin{aligned} &P_{e_{ORC}} = \eta_e P_{th_{i_{ORC}}} = \eta_e Q_{i_{ORC}} C_{i_{ORC}} \Big(T_{H_{i_{ORC}}} - T_{C_{i_{ORC}}} \Big) \\ &P_{u_{ORC}} = P_{e_{ORC}} - P_{a_{ORC}} = (\eta_e - \alpha_{ORC}) P_{th_{i_{ORC}}} \\ &P_{th_{o_{ORC}}} = \eta_{ORC} \, (1 - \eta_e) \, P_{th_{i_{ORC}}} \end{aligned} \quad (4)$$

where $P_{e_{ORC}}$ is the (gross) electrical power generated by the ORC, $P_{u_{ORC}}$ is the corresponding useful output (electrical) power (calculated as the difference between the generated power and the self-consumption $P_{a_{ORC}}$). Finally,

$$\eta_e = \beta_{ORC} \left(1 - \frac{T_{C_{o_{ORC}}} + T_{H_{o_{ORC}}}}{T_{C_{i_{ORC}}} + T_{H_{i_{ORC}}}} \right) \quad (5)$$

is the efficiency of the thermal-to-electrical energy conversion process (not to be confused with the efficiency η_{ORC} of the heat transfer occurring inside the ORC block). Observe that η_e depends on the mean temperature at the input and the output of the ORC block, and can be modeled as a given fraction ($\beta_{ORC} \approx 0.5$) of an ideal Carnot cycle. Finally, $P_{th_{o_{ORC}}}$ is the residual output thermal power due to the limited efficiency of the electrical generation process. This can be either dissipated by CS2, as shown in Fig. 2(a), or used for some other purpose. However, the latter possibility is out of the scope of this paper.

B. Heat recovery through DH

The purpose of DH is to replace a multitude of boilers located in residential or commercial buildings with a single, large and centralized heating facility distributing hot water to multiple users, typically in densely populated urban districts. In the case considered in this paper, the DH strategy includes two heat exchangers in series (HEX1 and HEX2), as shown in Fig. 2(b). Under the assumption of stationary conditions, these heat exchangers can be modeled as a single one. Thus, using the same notation as in (1)–(3), the output useful (thermal) power is simply given by

$$P_{u_{DH}} = P_{th_{o_{DH}}} = Q_{o_{DH}} C_{o_{DH}} \left(T_{H_{o_{DH}}} - T_{C_{o_{DH}}} \right). \quad (6)$$

Observe that, if the heat transfer efficiency tends to 1, almost all the thermal power recovered by the HPHE is transferred to the DH network.

IV. A CASE STUDY

The theoretical models described in Section III have been used to analyze and to compare the performances of the ORC-based and DH-based heat recovery strategies at SCM Foundries, Rimini, Italy. The whole iron casting process is monitored and controlled through a Supervisory Control And Data Acquisition (SCADA) system based on a network of Allen Bradley Programmable Logic Controllers (SLC 500 or PLC-5) equipped with various data acquisition modules. Such modules collect and digitize signals from different kinds of analog sensors. For the purposes of this paper, only the temperature and the mass flow rate sensors located in the flue gases aspiration system are considered. The temperature sensors are Type-K (chromel - alumel) analog thermocouples (compliant with the Standard ANSI MC96.1 Class 1) operating in the range 0-800 °C with an output current between 4-20 mA and a sensitivity coefficient of 41 μV/°C. The total relative uncertainty of the whole data acquisition chain (including sensor signal conditioning circuitry and analog-to-digital conversion), evaluated in compliance with [17], is generally within $\pm 2\%$, i.e. small enough not to perturb the energy analysis significantly.

The mass flow rate of flue gases is measured by a Tecsas averaging Pitot tube coupled with a differential pressure sensor Invensys IDP10-T. Similarly to a standard Pitot tube, an averaging Pitot tube relies on the Bernoulli theorem to produce a difference of pressure proportional to the flow rate between two points along the tube. In addition, an averaging tube has more than one hole in the radial direction (with respect to the pipe section). As a result, the gas stream pressure can be measured at different points. The IDP10-T device is used to

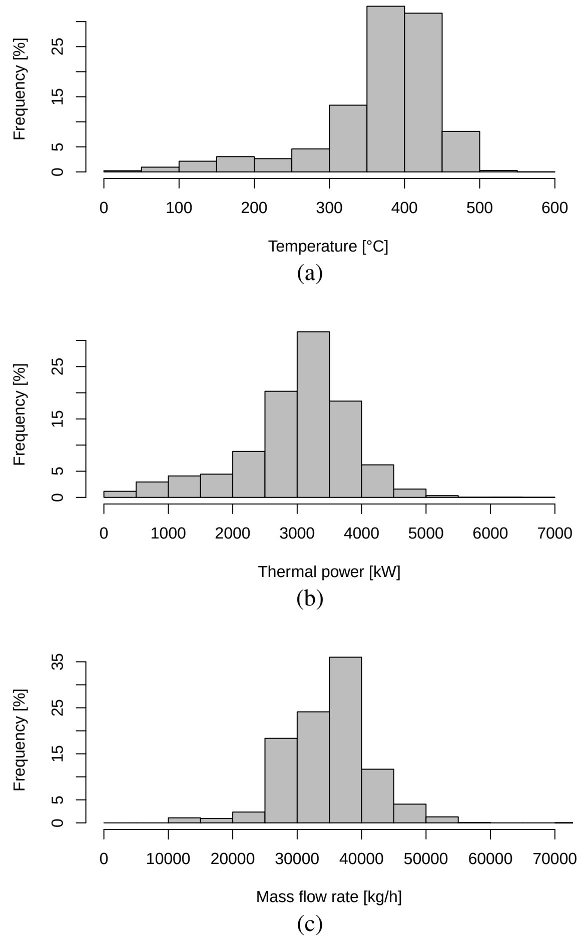

Fig. 3. Histograms of the temperature $T_{H_{i_{HPHE}}}$ downstream of the cyclones (a), the available input thermal power $P_{th_{i_{HPHE}}}$ (b), and the mass flow rates $Q_{i_{HPHE}}$ (c) at the input of the HPHE that could be installed for waste heat recovery. The histograms are based on the experimental data collected at SCM in 2014 considering only the working hours of the foundry.

measure the average differential pressure and to transfer these values to one of the SCADA data acquisition modules. The sensor relative uncertainty is within $\pm 1.6\%$. Therefore, also the flow rate measurements are accurate enough not to perturb the energy analysis and the comparison between the two heat recovery strategies considered in this paper.

The collected data are stored into the SCM database every minute. Most of Programmable Logic Controllers are connected to a Data Highway Plus network, which ensures half-duplex communication at 57.6 kilobaud over a single link. An Ethernet-based Local Area Network (LAN) is used to connect the gateways of the PLC network to the servers of the factory, where the measurement data are finally stored and processed. In this paper, in order to reduce processing requirements, the original data sets are decimated by a factor 15. In addition, hourly averages of all quantities are computed.

Fig. 3 shows the histograms of the temperature $T_{H_{i_{HPHE}}}$ (a), the available input thermal power $P_{th_{i_{HPHE}}}$ (b) and the mass flow rates $Q_{i_{HPHE}}$ (c) downstream of the cyclones, i.e. at the input of the HPHE to be installed for waste heat recovery. The relative frequencies reported in the histograms of Fig. 3 refer to the data collected by the SCADA only during the working time of the factory in 2014 (usually from Tuesday through Friday between 4:00 and 20:00). Observe that all monitored quantities exhibit a considerable variance and mean values equal to about 369 °C, 3.25 MW and 37500 kg/h, respectively. The total working time is about 2300 h/year out of 8760 h/year, i.e. approximately 1/3 of the available time. Therefore, the total amount of thermal energy that can be recovered from the foundry is inherently limited by its actual duty cycle. This problem is further stressed by the large variance of temperature and thermal power distributions. In fact, some heat recovery strategies are not usable or profitable when the input temperature drops below a given threshold. For instance, the generation of electricity based on ORC requires start-up times between a few minutes and about half an hour. Also, ORC is generally quite inefficient when the input thermal flow is not continuous. For instance, an ORC module designed for a mean input temperature of about 300 °C has a minimum activation temperature of about 250 °C due to the physical properties of the internal fluid. In the SCM case, an ORC module of this kind could be used for about 85% of the total foundry working time.

The DH heat recovery strategy is characterized by a higher efficiency, as thermal energy is easier to recover. Nonetheless, DH is inherently affected by seasonality issues, since the demand of heat in spring and summer is much lower than in autumn and winter. This roughly halves the average recovery efficiency over one year. Hence, to evaluate and to compare the performances of different heat recovery strategies, not only the efficiency of power conversion, but also the long-term usability of the recovered energy should be taken into account. These aspects will be further discussed in the next Section.

V. Simulations and techno-economic analysis

The energy models described in Section III have been implemented and simulated in Matlab/Simulink. In the following, the main simulation parameters, the control policies required by both heat recovery strategies as well as the respective most important results (expressed in terms of yearly energy yield, payback time, and net present value after 25 years) are summarized. In all cases, the net present value (NPV) is calculated assuming a 3% loan rate for the initial investment and a 2% discount rate. An overview of the investment costs for both heat recovery strategies is summarized in Table I.

TABLE I. Costs of ORC and DH heat recovery strategies.

Elements	**Cost (k€)** ORC	DH
Flue gas heat exchanger (2 MW)	240	71
ORC	750	0
Ducting	100	50
Cooling	50	0
Auxiliary equipment (20% of main equip.)	228	24
Installation (5 % of main equip.)	57	6
Total investment costs	1,425	151

A. Heat recovery based on ORC

The simulations in the ORC case strongly rely on the experimental data reported in Section IV. A simulation time step of 15 minutes ensures fast processing, while preserving a reasonably accurate tracking of the temperature variations between consecutive melting cycles. The main model parameters used to simulate the ORC-based recovery strategy are listed in Table II. In addition, all thermal efficiencies η_k for $k \in \{\text{HEX1}, \text{HEX2}, \text{ORC}, \text{CS1}, \text{CS2}\}$ are set equal to 1 (i.e. thermal losses are assumed to be negligible, which is realistic in the case considered).

TABLE II. ORC model parameter values based on the features of a commercial ORC module.

Parameter	Symbol	Unit	Value
Oil supply temperature	$T_{H_{i_{ORC}}}$	°C	315
Oil return temperature	$T_{C_{i_{ORC}}}$	°C	145
Nominal power	$P_{th_{i_{ORC}}}$	kW	2000
Flue gases nominal inlet temperature	$T_{H_{i_{HEX1}}}$	°C	400
Flue gases temperature before the filters	$T_{H_{o_{CS1}}}$	°C	90
Flue gases nominal total mass flow rate	$Q_{i_{HEX1}}$	kg/h	32,000
Heat Pipe Heat Exchange nominal coefficient	U_{HEX1}	W/K	32,000
Nominal ORC electric efficiency	η_e	%	19.2
ORC self-consumption coefficient	α_{ORC}	%	1.4
CS1 coefficient	α_{CS1}	%	0.8
CS2 coefficient	α_{CS2}	%	1.5

The simulated ORC module controller is designed to maintain the input temperature as constant as possible around the optimal working value. This is achieved by modulating the mass flow rate in the intermediate circuit between the HPHE and the ORC module itself. When the flue gases temperature is too low to keep this condition, temperature modulation is allowed down to 250 °C. It is during this modulation phase that the dependence of ORC efficiency on temperature comes into play. Below 250 °C no electricity is generated, so heat recovery efficiency drops to zero. Ultimately, the main results of simulations and the techno-economic analysis can be summarized as follows, i.e.

- The thermal energy recovered in one year is about 4,200 MWh. This can be used to produce about 700 MWh of electricity in accordance with (4);
- The payback time for this heat recovery strategy is about 20 years;
- The NPV after 25 years is in the order of 350 k€, assuming that the cost of electricity is 160 €/MWh.

From these results it is evident that this solution is not very profitable without some incentive. On the other hand, it is important to emphasize that these numbers strongly depend on the actual amount of working hours per year. So, for foundries with a more intensive schedule than SCM this strategy would be more viable [7]. For example, if the total working time were about 5000 h/year (which is feasible for foundries specialized in large series production), yearly electricity generation would be more than double with respect to the SCM case.

B. Heat recovery through DH

The performance analysis of the DH heat recovery strategy relies not only on the experimental data reported in Section IV, but also on the actual hourly power demand provided by a DH network manager located near SCM. The main model parameters are listed in Table III. Again $\eta_k = 1$ for $k \in \{\text{HEX1}, \text{HEX2}, \text{ORC}, \text{CS1}, \text{CS2}\}$. The DH system has been designed to maximize its duty cycle (although with a lower efficiency) assuming that the minimum thermal power demand (in summer) is about 400 kW. As a result, the seasonality effects are mitigated.

TABLE III. DH MODEL PARAMETER VALUES.

Parameter	Symbol	Unit	Value
DH supply temperature	$T_{H_{oHEX2}}$	°C	90
DH return temperature	$T_{C_{oHEX2}}$	°C	60
DH minimum demand	$P_{th_{oHEX2}}$	kW	400
Flue gases nominal inlet temperature	$T_{H_{iHEX1}}$	°C	369
Flue gases nominal total mass flow rate	$Q_{i_{HEX1}}$	kg/h	35,000
CS1 coefficient	α_{CS1}	%	0.8

The role of the simulated DH heat recovery controller is mainly to provide the correct amount of power to the DH network, by modulating the flue gases flow into the HPHE. When this is not possible, the DH system stops, heat recovery efficiency drops to zero and CS1 [see Fig. 2(b)] keeps on working. The results of the simulations and the techno-economic analysis can be summarized as follows, i.e.

- The yearly thermal energy yield is of about 1,000 MWh.
- The payback time for this heat recovery strategy is in the order of 5 years.
- The NPV after 25 years is about 600 k€, assuming that the thermal energy cost is about 30 €/MWh.

Therefore, this solution is economically more promising than the other, even without incentives. Moreover, the foundry operation schedule is less critical than in the ORC case, and a proper optimization of the heat recovery system could further reduce the payback time.

VI. CONCLUSIONS

This paper presents a techno-economic analysis and a comparison between two alternative strategies (i.e. electrical generation based on Organic Rankine Cycle vs. District Heating) to recover the waste heat produced by iron foundries, thus improving energy usage and efficiency in urban contexts. The proposed comparison relies on general energy models which, although based on simplifying assumptions and on stationary conditions, can be used to perform a time-dependent analysis based on real input data. In the case of the SCM Foundries located in the town of Rimini, Italy, it turns out that a DH system is significantly more profitable than an ORC one. Indeed, the ORC system exhibits very long payback times, due to the high investment costs and the limited duty cycle of the furnace over one year. While this result does not rule out the possibility to generate electricity in general (the ORC system could in principle be substituted by customized turbine generators, possibly with better efficiency/cost ratios), it also shows that this kind of solutions are difficult to apply whenever furnace operation is discontinuous. On the other hand, while DH exhibits a reasonable payback time, its seasonality (due to the limited power demand in summer) prevents a full exploitation of the available thermal energy. These qualitative conclusions are expected to hold also in other contexts and in other EU countries, as the existing differences (e.g., in terms of energy prices) are not large enough to alter the overall picture. In the future, other strategies (e.g. based on the joint use of ORC and DH) could be investigated in order to find a better compromise between the amount of recovered energy and the related economic aspects.

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REFERENCES

[1] United Nations, Department of Economic and Social Affairs, Population Division (2015), *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*. New York: United Nations, 2014.

[2] A. Sittoni, D. Brunelli, D. Macii, P. Tosato, and D. Petri, "Street lighting in smart cities: A simulation tool for the design of systems based on narrowband PLC," in *Proc. IEEE First International Smart Cities Conference (ISC2)*, Guadalajara, Mexico, Oct. 2015, pp. 1–6.

[3] K. Farkas, G. Feher, A. Benczur, and C. Sidlo, "Crowdsending based public transport information service in smart cities," *IEEE Communications Magazine*, vol. 53, no. 8, pp. 158–165, Aug. 2015.

[4] H. N. T. Nguyen, C. Zhang, and M. A. Mahmud, "Optimal coordination of g2v and v2g to support power grids with high penetration of renewable energy," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 2, pp. 188–195, Aug. 2015.

[5] E. Abdelaziz, R. Saidur, and S. Mekhilef, "A review on energy saving strategies in industrial sector," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 150 – 168, Jan. 2011.

[6] ISO 50001:2011, *Energy management systems – Requirements with guidance for use*, Geneve, Switzerland, 2011.

[7] D. Forni, N. Rossetti, V. Vaccari, M. Baresi, and D. D. Santo, "Heat recovery for electricity generation in industry," in *ECEEE 2012 Summer Study on Energy Efficiency in Industry*, Arnhem, Netherlands, Sep. 2012, pp. 523–534.

[8] J. Larjola, "Electricity from industrial waste heat using high-speed organic rankine cycle (ORC)," *International Journal of Production Economics*, vol. 41, no. 1-3, pp. 227 – 235, Oct. 1995.

[9] A. Amiri and M. R. Vaseghi, "Waste heat recovery power generation systems for cement production process," *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 13–19, Jan. 2015.

[10] A. Kaizawa, H. Kamano, A. Kawai, T. Jozuka, T. Senda, N. Maruoka, N. Okinaka, and T. Akiyama, "Technical feasibility study of waste heat transportation system using phase change material from industry to city," *ISIJ International*, vol. 48, no. 4, pp. 540–548, Apr. 2008.

[11] H. Lund, B. Möller, B. V. Mathiesen, and A. Dyrelund, "The role of district heating in future renewable energy systems," *Energy*, vol. 35, no. 3, pp. 1381–1390, Mar. 2010.

[12] D. Connolly, H. Lund, B. V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard, and S. Nielsen, "Heat roadmap europe: Combining district heating with heat savings to decarbonise the eu energy system," *Energy Policy*, vol. 65, pp. 475–489, Feb. 2014.

[13] Foundrybench Project, *Improving the energy efficiency of foundries in Europe*, 2012.

[14] W. Srimuang and P. Amatachaya, "A review of the applications of heat pipe heat exchangers for heat recovery," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 4303–4315, Aug. 2012.

[15] D. Reay, R. McGlen, and P. Kew, *Heat Pipes: Theory, Desing and Applications*. Waltham, MA, USA: BH, Elsevier, 2014.

[16] K. Thulukkanam, *Heat Exchanger Design Handbook*. Boca Raton, FL, USA: CRC Press, 2013.

[17] *ISO/IEC Guide 98-3:2008: Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement*, Geneva, Switzerland, 2008.