How Optimally Selecting among Internal and External Opportunities for Waste Heat Valorization: a Case Study from the Steel Industry

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Abstract: Concerning waste heat recovery projects, especially in the energy-intensive industrial sectors, facility managers face indeed the challenge of making the optimal strategic choice within the different waste heat recovery options. In this context only the two energy recovery options based on a smart energy system approach, namely, power generation through an Organic Rankine Cycle (ORC) unit (both for self-consumption and grid selling) and the exploitation of the generated heat transfer fluid to feed an urban DH network. The economic objective represents the main driver, although environmental objectives are becoming increasingly important, also thanks to the rising value of green marketing. Indeed, when both the potential demand from external users and the opportunity to produce electricity represent attractive options, in order to allow the facility manager to select the most suitable waste heat recovery option and to decide which project to endorse, a deeper insight on the sustainability performances of each potential waste heat recovery solution is required. The developed DSS framework has then been applied adopting a facility manager's perspective, with the aim to investigate the economic, energetic and environmental performances of different options for waste heat recovery exploitation, thus allowing a strategic decision making for the endorsement of the related investments. The model application provided useful suggestions on the optimal configuration of the energy recovery system, i.e. the selection of the most suitable option for the exploitation of the recovered energy, also taking into account the possible combination of different technologies, their optimal sizing and the definition of the operational strategy.

Keywords: Waste heat recovery, Organic Rankine Cycle, District heating Network, Multi-objective optimization.

I. INTRODUCTION

Industry is responsible for 21% of greenhouse gas emissions (EPA, 2023). However, if emissions for electricity supply are also allocated to the industrial end-use sector, industrial activities account for a much larger share. There is extended literature on technological advancements with the aim to pursue the climate change mitigation goals. Many authors (Buonomano et al., 2013; Jouhara et al., 2017) focus on the use of several renewable energy sources, including waste heat recovery technology.

The latter represents one of the greatest opportunities, especially in energy intensive industries, to reduce their primary energy consumption thus increasing their competitiveness and sustainability (Brough and Jouhara, 2020).

There are relevant opportunities for the implementation of energy efficiency measures to be exploited not only inside the company itself, but also by overtaking its boundaries towards an external synergic integration between industrial and urban areas, based on the novel smart energy system concept, among these, waste heat recovery from the industrial process can be recognised (Villar et al., 2013). Steelmaking industry based on electric arc furnace (EAF) melting process has been identified as a suitable case study due to the relevance, among the most energy-intensive productive sectors, of both its energy requirements and energy efficiency opportunities, and because of its huge presence in both the European and the local territorial context (often at a useful distance from urban areas)(Manz et al., 2021).

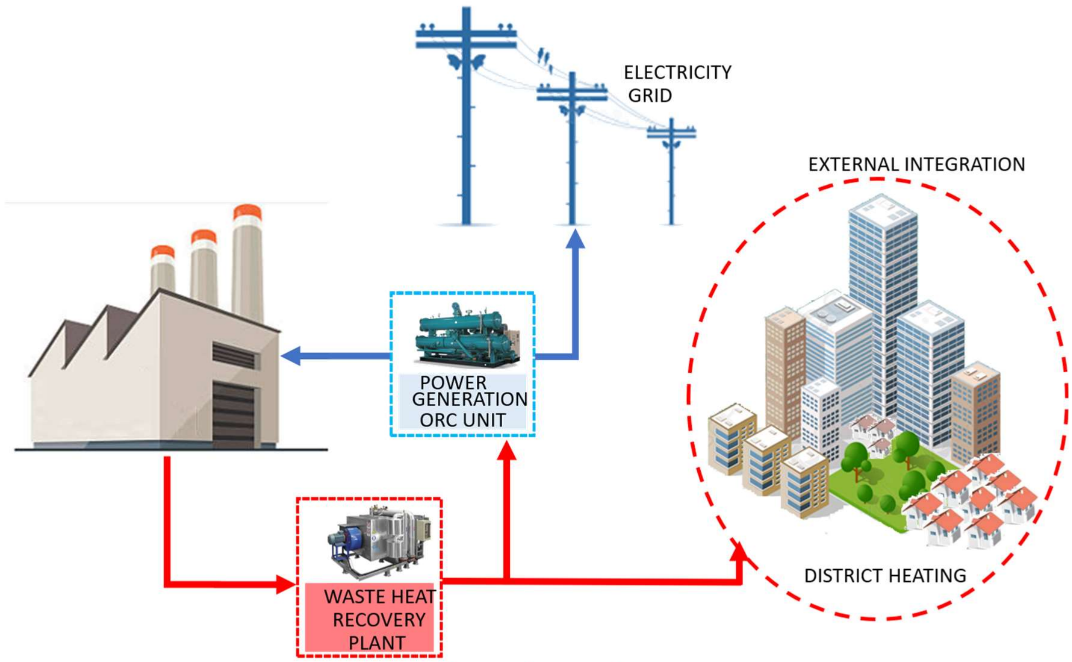

Figure 1: Layout of the considered waste heat recovery system

A comprehensive overview on the technical solutions for the recovery of waste heat from the EAF steelmaking process has been provided in (Nardin et al., 2018), ranging from the traditional approaches based on its internal use to the smart energy system concept based on the external integration of the resource. The research also proposed a conceptual framework for the preliminary identification of the suitable exploitation strategies for the recovered energy, to be then investigated in dept by means of suitable decision support models.

With the aim to foster the integration of industrial waste heat recovery into smart energy system, the decision-making challenge involved with the implementation of such an option, involving the industrial facility as the waste heat source and the urban neighbourhood as district heating network (DHN) end users, indeed, has been investigated in (Simeoni et al., 2019). However, the paper has been conceived to provide decision makers, namely policy makers, institutions responsible for territorial energy planning, investors, etc. with a tool that allows the optimisation of the DHN system by considering the different stakeholders involved, each driven by different and often conflicting objectives, highlighting the trade-off as well as possible win-win solutions to be exploited.

However, when both a potential heat demand from external users exists and also power production represents an attractive option (see Figure 1), facility managers face indeed the challenge of making the optimal strategic choice from the company's perspective (Ni et al., 2022). The different options could be both synergistic and conflicting, depending on the context, and the overcome of company's boundaries in favour of synergies might not necessarily represent the best option. The choice for the facility managers is even more difficult in these years because the economic objective is a main driver as well as the environmental ones due to the increasing value of green marketing (Papadas et al., 2019).

A tool for a deeper insight on the sustainability performances of each potential solution from a company perspective, in order to allow the facility manager to select the most suitable waste heat recovery option and to decide which project to endorse, is still lacking in the scientific literature.

Therefore, in this paper we analyse the case of a facility manager of a steel company who, should decide whether to exploit waste heat recovery internally or in the more systemic solution already described in (Simeoni et al., 2019). Among the several options identified in (Nardin et al., 2018), those belonging to the so-called Smart Energy System approach have been considered, i.e. electricity generation through an ORC unit (Loni et al., 2021) and the external integration of the recovered energy into an urban DHN. The decision-support model proposed for such a choice is based on evolutionary multi-objective optimisation.

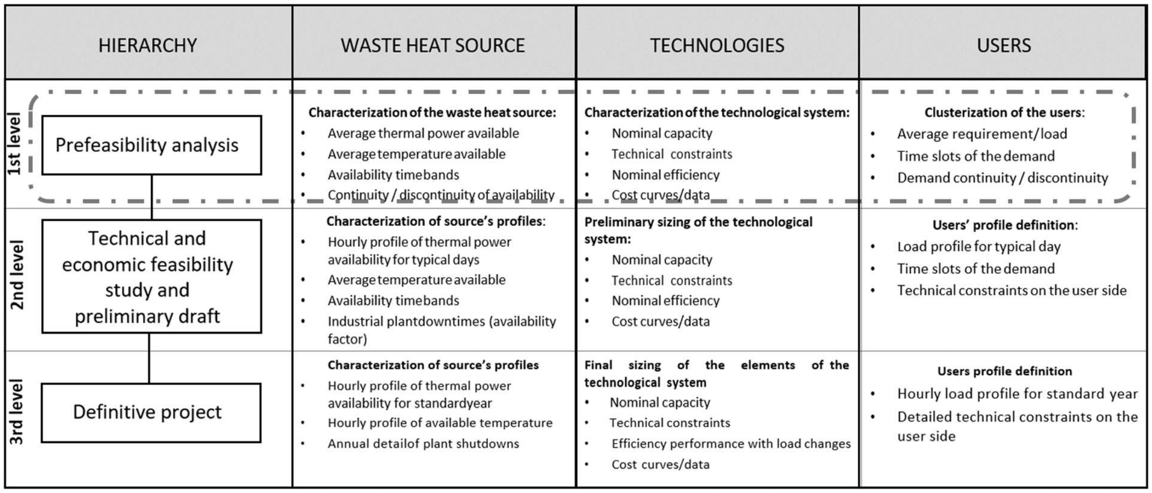

Figure 2: Hierarchy of the evaluation model

The preliminary test application of the developed model to an EAF steelmaking case study with a surrounding urban area has shown its ability to allow the facility manager to make informed decisions on the optimal configuration of the recovery system in terms of technology selection and their possible combination, as well as its optimal sizing and operational strategy definition.

The paper is structured as follows. In section II a framework for waste heat valorisation options selections is proposed and the related mathematical model is described. In section III the considered case study is introduced. Results are reported in section IV and conclusions are drawn in section V.

II. The Proposed Model

A. *Multi-objective optimization*

Since the goal is the identification of the most suitable solution for the industrial waste heat recovery exploitation strategy from the facility manager's perspective, the objective functions of the multi-objective optimization problem have been selected according to the company different conflicting objectives, as presented in Table 1.

Environmental objectives are increasing their importance for companies due to clients' pressure on sustainability goals.

Table 1: Goal of the multi-objective optimization problem

Stakeholder	Objective Function	Optimization
Industrial waste heat source facility manager	NPV	Maximization
	PES	Maximization
	GHG emissions	Minimization

Moreover, the rising value of both incentives provided to primary energy savings (e.g. white certificates TEE) and avoided CO2 emissions, such as. the carbon tax (CT) should be taken into account. Thus, beside the main goal represented by profit maximization (accounted with the conventional economic indicators as the NPV), the minimization of GHG emissions and the maximization of Primary Energy Saving (PES) have also been considered.

Primary Energy Saving indicator is considered as the energy recovered from the waste heat source and actually exploited in the whole reference calculation period. The GHG emissions reduction and PES deriving from the waste heat recovery project are calculated through the proper emission and conversion factors of the reference fuels/energy vectors.

When considering options for industrial waste heat recovery exploitation based on external integration of the waste heat by feeding a urban district heating network and on power generation through an ORC unit for self-consumption and grid selling (see Figure 1), there are basically two main variables influencing the absolute and relative performance of each solution: 1) the nominal capacity of the ORC plant; 2) the economic valorisation of the thermal energy sold to the external DHN.

The latter should be negotiated between the steel casting facility and the district heating network provider, thus representing a main decision variable of the optimization problem. The capacity of the external district heating network, which in turn determines the heat load of the network, does not represent a decision variable of the optimization problem from a facility manager perspective, but rather constitute an external condition of the specific case study. At the same time, in order to identify the optimal configuration of the energy recovery system that allows good economic and environmental performances the size of the electricity generation plant (ORC facility) is subject to optimization.

B. Assumptions

In the context of a preliminary assessment of waste heat recovery options, unlike preliminary drafts or definite projects, no detailed simulations of their behaviour are required, so the developed mathematical model is based on the following hypothesis. The waste heat is recovered from the off-gas of the EAF through a heat exchanger, whose investment cost has been neglected since it would have affected both recovery alternatives equally. The DHN has been considered has a black box since only the thermal load of the network influences the amount of recovered energy to be allocated through the DHN option. Both thermal availability and load variations have been neglected. In addition steady state condition of both the DHN and the ORC unit have been assumed (i.e. no dynamic effects are considered).

When adopting a facility manager perspective during evaluation of industrial waste heat recovery options deep investigation regarding the optimal matching between energy availability and demand and characterization of the potential heat sink are required, reaching the second or even third level of the hierarchy represented in Figure 2.

In the context of a preliminary framework development such level of detail is not required, thus the first level of the hierarchy can be adopted. With this assumption the hourly profiles of thermal power source from the industrial facility and of the DHN energy load can be obtained adopting the average values of power availability and requirements and their respective continuity/discontinuity rate.

C. Recovered energy allocation

When considering the prioritization problem of different waste heat exploitation options the main driver for the facility manager is represented by profit maximization. Thus for every considered scenario, the specific economic values of each alternative exploitation option (respectively the value of the thermal energy sold to the DHN, the value of electric energy produced through ORC for self-consumption and sold to the national grid) are evaluated based on the market values of energy vectors and sorted in descending order. This order represents the priority order for waste heat exploitation.

It's worth noting that the contribution of incentives provided to primary energy saving interventions (e.g. white certificates TEE) and the economic value of the avoided CO2 emissions, i.e. carbon tax (CT), have been accounted only in the case of power generation through the ORC unit, while concerning the district heating option the DHN service provider has been considered to take advantage of such economic grant.

The thermal power made available from the industrial waste heat recovery system is therefore assigned with priority to the option characterized by the highest potential economic value per unit of recovered energy, to foster profit maximization. Once the energy demand associated with this option is exhausted, in the event of residual availability of thermal power from the industrial waste heat recovery system, it would be allocated to the next option in terms of economic value and so on, thus iterating the cycle.

D. Cost characterization

Concerning investment costs related to the waste heat valorisation represented by electricity generation through an ORC plant, the cost has been evaluated by means of the following cost function (Lemmens, 2016):

$$c_{ORC} = 9907.5 \cdot P_{ORC,nom}^{-0.267}$$

where $P_{ORC,nom}$ represents the nominal capacity of the ORC plant expressed in kW.

As for the purpose of comparing the different valorisation options, the investment cost associated with the upstream waste heat recovery system does not affect the assessments since it must be incurred anyway, although it may actually be relevant. Thus the heat exchanger serving the DHN is assumed to be the only investment cost to be borne by the company. The heat exchanger cost has been calculated by means of the following function (Theissing,M. et al., 2010):

$$c_{HE} = 4076.2 \cdot H_{HE,nom}^{-0.71}$$

where $H_{HE,nom}$ represent the nominal capacity of the heat exchanger expressed in kW

As regards O&M, a cost of 2.4 € /MWh of generated electric energy has been considered (Herzog, U., 2015) for the ORC unit, while operation and maintenance of the district heating heat exchanger has been assumed to be charged to the DH service provider.

III. The Case Study

The considered industrial waste heat source is a steel casting company which operates scrap melting through an EAF in North-Eastern Italy. Assuming a EAF capacity of 140 t/h, the thermal power available from the waste heat recovery plant has been estimated up to around 13.5 MW (Baresi et al., 2014). To account for the productive cycle downtimes, an availability factor of 80% has been considered. For the downtime periods the available heat power has been assumed to be halved; 24 hours per day and 7 days per week operations of the steel plant has been considered. Plant downtimes due to maintenance have been neglected because they could influence unequally the two waste heat recovery options depending on the actual period of occurrence. The energy from recovery is available in the form of saturated steam, quite constant thanks to the remarkable buffering capacity features of the steam based EAF waste heat recovery system already discussed in (Nardin et al., 2018).

The typical hourly electric energy load profile for a steelmaking facility operating an EAF-based process has been considered to account for the internal load (Bause et al., 2015). It's worth noting that the energy generated from recovery through a potential ORC unit is likely to be quite entirely allocated to satisfy the company's internal demand due to the high power constantly required by a typical EAF in the "power on" phase of the melting cycle. Otherwise, to evaluate the performance achievable through an external integration of the recovered thermal energy, an urban district heating (DH) network of about 200 MW maximum installed power, fed by natural gas boilers has been considered as the heat sink.

Investment costs for the DH infrastructure, including the pipeline structure required to reach the industrial facility for the connection of the waste heat source to the DH network, are assumed to be carried out by the DH service provider. Only the main heat exchanger, providing the recovered energy to the DH, is assumed to be bought by the industrial facility, since it represents an integrated component of the waste heat recovery plant.

Concerning equipment efficiency, we considered a value of 98% for the DH heat exchanger and of 19% for the ORC unit, both constant with varying load. As regards the specific energy costs, for the sake of simplicity they have been considered constant throughout the whole simulated plant operation period, i.e., one typical year. Namely, a specific cost for the electric energy bought from the grid of 0.1 €/kWh has been considered for the industrial facility, and a valorisation of 0.04 €/kWh has been assumed for the selling of the eventual surplus of electric energy produced by the ORC unit. Moreover, fixed values of the financial incentives provided to the primary energy saving projects and of the CO2 emission savings have been considered (i.e., 250 €/TEE and 80 €/tCO2 for the Carbon Tax). Lastly, a specific cost for surplus heat dissipation (i.e. thermal energy available from recovery but exceeding end users' demand) of 4 €/MWh has been considered. DH's thermal load simulations were run accounting for the hourly average external temperatures for the whole heating period, i.e. from 15 October to 15 April, according to the Italian regulation. Out of that period, the DH load is assumed to be due to domestic hot water needs only. In Table 2 the variation ranges of the decision variables of the multi-objective optimization problem are reported.

Table 2: Variation ranges of the decision variables

Decision variable	Unit	Range of variation	Incremental step
v_{th}	€/MWh	1 ÷ 50	1
$P_{ORC,nom}$	kW	0 ÷ 10,000	500

The developed evolutionary multi-objective optimization method has been implemented by use of Matlab® as regards the simulation of the energy system through the mathematical model, while DOE algorithm, genetic algorithm and optimization have been performed by the ModeFrontier® software.

IV. Early results

The multi-objective optimisation problem for the considered case study has been solved by using a 16 GB RAM, i7 4770 3.40 GHz PC. A population of 100 individuals and 100 generations were adopted, resulting in 10,000 total evaluated designs, enough to obtain the convergence of the process. For the considered analysis the influence of the two decision variables on the trade-off between the economic and the environmental performance for the industrial company are represented in the diagrams of Figure 3. On the left side the current case, on the right the case before the energy crisis. Regarding the influence of the economic decision variable if the maximum value of the thermal energy were agreed, the economic goal of the steel casting facility could be easily achieved.

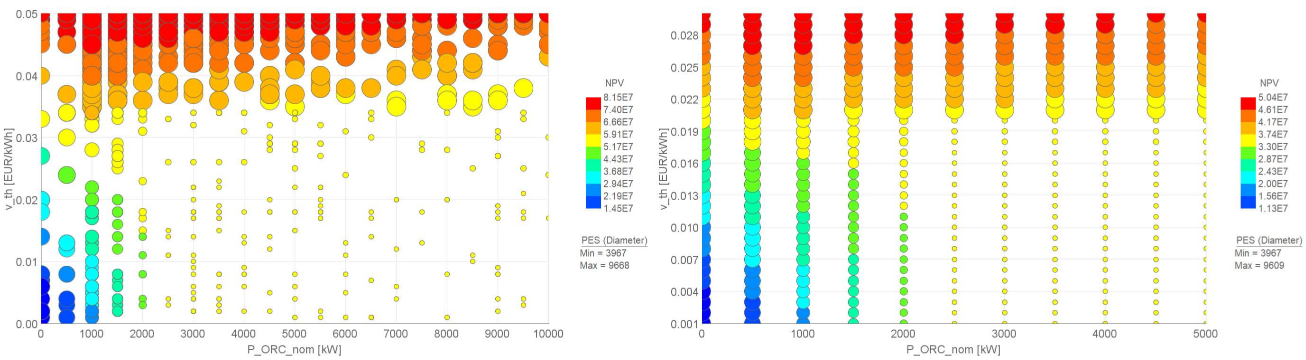

Figure 3: diagram representing the influence of optimization variables on economic and energy performances (on the left the current case, on the right the pre-energy crisis case)

Moreover there is a marked behaviour change at a thermal energy value of around 35 €/MWh, since above this value the external integration of the recovered energy into the urban DH network economically overcomes both electric energy valorisation.

At such value of the recovered energy, the size of the ORC unit seems to have a negligible impact on the economic performance indicator. Nonetheless, for growing ORC sizes a slight decrease in economical performances is present, since the increase of the investment and operation and maintenance costs of the ORC unit is not being balanced by electric energy valorization due to DH exploitation prioritization. However when considering ORC nominal capacities between the 1000 – 2500 kW range there are optimal solutions, for both the primary energy saving and the NPV indicators, thus leading to a win-win solution from a sustainability and competitiveness perspective for the industrial stakeholder.

When shifting to the field of ORC option priority, a different trend can be observed. The ORC represents in that case the priority destination of the thermal power available, and the DH option is considered only if the company’s electric load is exhausted, if the sale of electric energy is less economic efficient with respect to the DH option or when the ORC capacity is not enough to exploit the waste heat recovery potential related to a EAF capacity. Thus, as regards the plant design decision variable, the greater the ORC nominal capacity, the better the economic performance for a given value of the thermal energy sale. A higher ORC size would in fact allow to exploit as much waste energy availability as possible, while keeping still good economic indicators for the company, despite the greater initial investment and operation and maintenance costs of the ORC unit. Once the waste heat availability is saturated, a higher nominal capacity of the ORC would not be exploited, worsening the economic indicator due to the larger investment cost. For the considered EAF capacity, a nominal ORC capacity of around 2500 kW size would allow to achieve relevant environmental performances together with affordability.

From the environmental perspective, an opposite behaviour can be observed. The reason for that is found in the lower energy conversion efficiency of the ORC (19%) compared to the direct heat exploitation to feed the DHN (98% efficiency of heat exchanger). As a consequence increasing the ORC size leads to a decrease of the DH option contribution in energy recovery, thus causing a worsening of the PES indicator.

Instead, in the case of energy prices prior the energy crisis it can be noted how the change in these values doesn’t impact the behaviour of the objective function. Indeed the same effect of the variation of thermal energy value and ORC nominal capacity on the economical and energy performances as the previous case can be observed. However it is important to highlight a change in thermal energy value separating the DH exploitation option priority field from the one where the ORC option overcomes. In particular, as the grid electric energy price decreases, a lower thermal energy value is required for DH exploitation.

V. CONCLUSIONS

A framework development for energy, environmental and economic optimization of a steel casting facility waste heat recovery exploitation considering two different options has been presented in this study, focusing on the facility manager perspective. Heat direct utilization through a district heating network and electric energy production by means of a Organic Rankine Cycle options have been modelled. Value of thermal energy and nominal capacity of the ORC plant have been adopted as optimization variables. Two different scenarios have been implemented considering the current energy price situation, and the one before the energy crisis strike.

As the first results of its test application to a case study representative of the typical European climate context have underlined, the developed multi-objective optimization framework for decision support has showed to provide the facility manager precious suggestions regarding the selection of the most suitable option for the exploitation of the recovered energy and the best combination of different technologies, their optimal sizing and the definition of the operational strategy, based on the actual energy market situation. Moreover, the developed model can be used not only in the system design phase, but also as a support to the facility manager in the negotiation task, providing significant suggestions about the range of values of the thermal energy sale to an external DH service provider which could grant to satisfy the goals of the company that would make available the waste heat. Although the presented framework allows the selection of the most suitable waste heat recovery option a more detailed characterization of the waste heat source availability and users' demand can be developed, thus adopting an approach based on the second or third hierarchical level of the evaluation model.

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VII. References

Baresi, M., Filippini, L., Formenti, S., Setuain, E., Rosano, A., Campana, F., 2014. H-REII DEMO. Heat Recovery in Energy Intensive Industries. D5 - Performance Analysis.

Bause, T., Campana, F., Filippini, L., Foresti, A., Monti, N., Pelz, T., 2015. Cogeneration with ORC at Elbe-Stahlwerke Feralpi EAF shop. Iron Steel Technol. 12, 290–299.

Brough, D., Jouhara, H., 2020. The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. Int. J. Thermofluids 1–2, 100007. https://doi.org/10.1016/j.ijft.2019.100007

Buonomano, A., Calise, F., Dentice d'Accadia, M., Vanoli, L., 2013. A novel solar trigeneration system based on concentrating photovoltaic/thermal collectors. Part 1: Design and simulation model. Energy 61, 59–71. https://doi.org/10.1016/j.energy.2013.02.009

EPA, 2023. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430-R-23-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-andsinks-1990-2021.

Herzog, U., 2015. Technical and economical experiences with large ORC systems using industrial waste heat streams of cement plants.

Jouhara, H., Chauhan, A., Nannou, T., Almahmoud, S., Delpech, B., Wrobel, L.C., 2017. Heat pipe based systems - Advances and applications. Energy 128, 729–754. https://doi.org/10.1016/j.energy.2017.04.028

Lemmens, S., 2016. Cost Engineering Techniques and Their Applicability for Cost Estimation of Organic Rankine Cycle Systems. Energies 9, 485. https://doi.org/10.3390/en9070485

Loni, R., Najafi, G., Bellos, E., Rajaee, F., Said, Z., Mazlan, M., 2021. A review of industrial waste heat recovery system for power generation with Organic Rankine Cycle: Recent challenges and future outlook. J. Clean. Prod. 287, 125070. https://doi.org/10.1016/j.jclepro.2020.125070

Manz, P., Kermeli, K., Persson, U., Neuwirth, M., Fleiter, T., Crijns-Graus, W., 2021. Decarbonizing District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites? Sustainability 13, 1439. https://doi.org/10.3390/su13031439

Nardin, G., Ciotti, G., Dal Magro, F., Meneghetti, A., Simeoni, P., 2018. Waste heat recovery in the steel industry: Better internal use or external integration? Proc. Summer Sch. Francesco Turco 2018-September.

Ni, T., Si, J., Lu, F., Zhu, Y., Pan, M., 2022. Performance analysis and optimization of cascade waste heat recovery system based on transcritical CO2 cycle for waste heat recovery in waste-to-energy plant. J. Clean. Prod. 331, 129949. https://doi.org/10.1016/j.jclepro.2021.129949

Papadas, K.-K., Avlonitis, G.J., Carrigan, M., Piha, L., 2019. The interplay of strategic and internal green marketing orientation on competitive advantage. J. Bus. Res. 104, 632–643. https://doi.org/10.1016/j.jbusres.2018.07.009

Simeoni, P., Ciotti, G., Cottes, M., Meneghetti, A., 2019. Integrating industrial waste heat recovery into sustainable smart energy systems. Energy 175, 941–951. https://doi.org/10.1016/j.energy.2019.03.104

Theissing,M., Wanek, m., Alois, K., Theissing-brauhart, I., 2010. Instationarity as a limiting factor for the use of industrial waste heat in heating-networks.

Villar, A., Parrondo, J., Arribas, J.J., 2013. District heating from industrial surplus heat in avilés (spain). Environ. Prog. Sustain. Energy n/a-n/a. https://doi.org/10.1002/ep.11883