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Techno-Economic Analysis of Waste Heat Recovery with ORC from Fluctuating Industrial Sources

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Abstract

A significant portion of the consumed energy by the industrial sector is rejected as waste heat in the medium temperature range. Organic Rankine Cycles (ORC) are a valuable technology to recover the available waste heat at medium temperatures, and produce electricity or combined heat and power (CHP). A trade-off has to be found between the reduced environmental impact of an industrial site and investment costs for waste heat recovery (WHR). Very challenging for the WHR are the large fluctuations in temperature and/or mass flow rate. In the present work, the economic feasibility of industrial WHR with ORC is analyzed for different applications, with and without heat storage: hot air from clinker cooling (fluctuating heat source temperature), exhaust gas from rolling mill reheating furnace (fluctuating heat source mass flow rate) and a case of exhaust gas from electric arc furnace (both fluctuating heat source temperature and mass flow rate). The different configurations are developed and simulated by combining MATLAB® and EBSILON®*Professional*. A latent heat buffer with $LiNO_3$ appeared to be the best option for WHR from cement clinker cooling. In case of rolling mill reheating furnace, a design for the minimum mass flow rate and bypass of any exceeding fluctuation appeared the most economical solution, whereas the best environmental performance was achieved for lower bypass of the heat source. In case of electric arc furnace, the best economic solution appeared to be without storage, even though the latent buffer could guarantee the highest CO_2-savings. The described design and analysis method should help investors, designers and decision makers take better choices to increase the efficiency and improve the economy of industrial sites with ORC technology.

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Keywords: Waste heat recovery; industry; ORC; fluctuations

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1. Introduction

The industrial sector contributed for around one fourth of the energy consumption in the European Union in 2013 and around one fifth of the greenhouse emissions came from manufacturing processes in 2014 [1, 2]. To limit the environmental impact and fossil fuel consumption of the industry, the recovery of industrial waste heat to produce additional electricity, heat or combined heat and power (CHP) is of primary importance. The recovered energy can be either reused directly in the same industrial site where it is produced, or it can be fed in a distribution network. To which extent waste heat can be recovered depends on several technical and economic factors, e.g. heat source temperature, amount of available waste heat, dust content in the heat source, chemical composition, intermittency/availability of the source. Organic Rankine Cycles (ORC) can be applied to recover waste heat in the medium and low temperature range, to produce electricity or CHP. As shown in several publications [3–6], the waste heat is very often affected by fluctuations in temperature and flow rate. Since the waste heat recovery (WHR) is subordinated to the main process and should affect it as less as possible, the ORC has to be developed taking care of the heat source fluctuations. Therefore, it is important to include the off-design performance on the design and economic analysis of ORCs as highlighted in [7, 8]. Typical heat source profiles are shown in Fig. 1 and discussed in the following. In the cement production, waste air that cools down the produced clinker is usually found in the range 150-350°C [9]. As shown in Fig. 1a, the temperature of the clinker cooling air can fluctuate, leading to large fluctuations in heat rate available [3]. The mass flow rate can instead be considered approximately constant [4]. In Fig. 1b, the Cumulative Distribution Function (CDF) of the temperature profile is shown. The temperatures at 25%, 50%, 75% and 100% CDF are highlighted by red lines. In the steel production, steel stocks (billets, slabs, blooms) are forwarded through rolling mills of different size under high temperature, so that the desired shape of the steel product is achieved by means of plastic deformation. A flue gas recuperator at the rolling mill furnace can ensure a (approximately) constant waste heat temperature, whereas the mass flow rate undergoes large fluctuations. Fig. 1c shows the measured profile at a hot reheating furnace (HRF) over one day. Fig. 1d shows the CDF as a function of the mass flow rate and the mass flow rate at 25%, 50%, 75% and 100% CDF is highlighted. Both high intermittency in temperature and volume flow rate is instead typically shown by hot gases leaving Electric Arc Furnaces (EAF) [10]. A representative profile for hot gases from an EAF in Germany is shown in Fig. 1e (adapted from [10]). The CDF of the mass flow rate and temperature is shown in Fig. 1f. Given the high variability of the heat source, heat storage can help smooth out variations in time, but its economic feasibility has to be analyzed and compared with the case of single ORC. In this paper, different ORC configurations, with and without storage, are discussed for the three heat source profiles in Fig. 1. This work provides a method for analysis of waste heat recovery with ORC from industrial processes, and evaluates its economic feasibility, considering also the integration of heat storage. Given the results of the analysis, the best configurations can be chosen, comparing the economic performance of the ORC and the electricity/CO_2-savings from the waste heat recovery.

Nomenclature

C	Costs	WHR	Waste Heat Recovery
E	Electricity Produced	EAF	Electric Arc Furnace
k	Year Index	CO_2	Carbon Dioxide
n	Number of Years	CEPCI	Chemical Engineering Plant Cost Index
i	Interest Rate	CHP	Combined Heat and Power
ORC	Organic Rankine Cycle	LCOE	Levelized Cost of Electricity

2. Waste heat recovery with ORC: different configurations and cost computation

An Organic Rankine Cycle power system typically consists of four main components (see Fig. 2a): a preheater/evaporator (1-3), where the working fluid is vaporized; an expansion machine (3-4), where the thermal energy of the fluid is converted into mechanical power; a condenser (5-7), where the working fluid is converted back

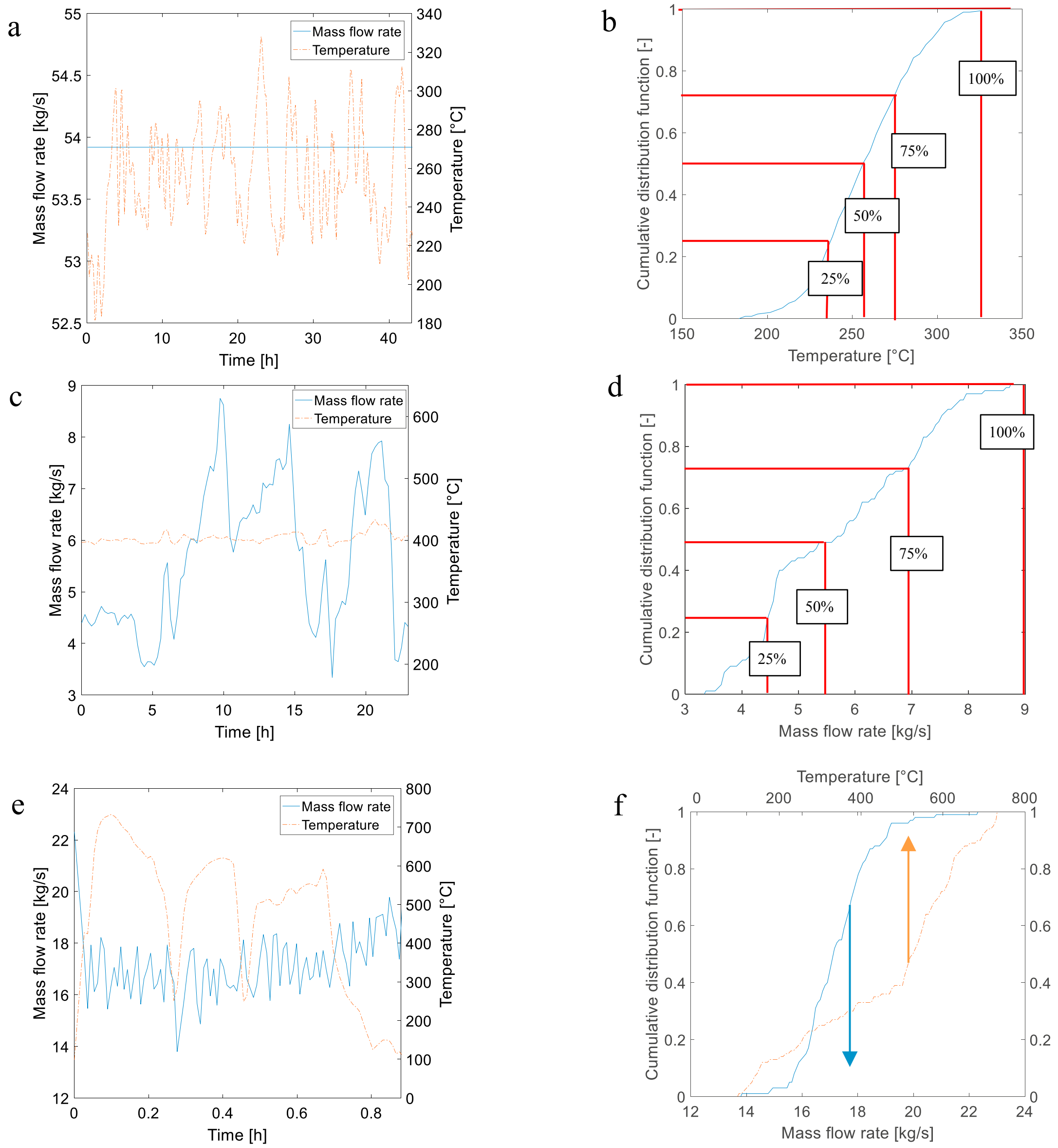

Fig. 1. Temperature profile/mass flow profile and CDF for (a)-(b) clinker cooling air [3] ; (c-d) flue gas from HRF; (e-f) flue gas from EAF.

into the liquid state; a pump (7-0), which forwards the condensed fluid from the low condensing pressure to the higher evaporation pressure. Especially for dry organic fluids, a recuperator is beneficial in terms of thermal efficiency. The recuperator preheats the working fluid exiting the pump, by cooling down the vapor from the turbine. Since it increases the average temperature of heat addition and reduces the average temperature of heat removal, the thermal efficiency increases. Additional configurations are analyzed in this study and shown in Fig. 2b-f. An intermediate oil loop can convert fluctuations in temperature into fluctuations in mass flow rate by keeping the oil temperature constant and controlling the oil mass flow rate (Fig. 2b). The oil loop can also ensure that the working fluid temperature does not exceed its thermal stability range, thus limiting fluid degradation. Alternatively, injection of cold air could be considered (Fig. 2c). The higher temperature is in this case converted into a higher mass flow rate, with the disadvantage of reduced exergy content in the heat source, because of the reduced temperature.

A heat storage might be used between the heat source and the ORC to smoothen out the fluctuations. The integration

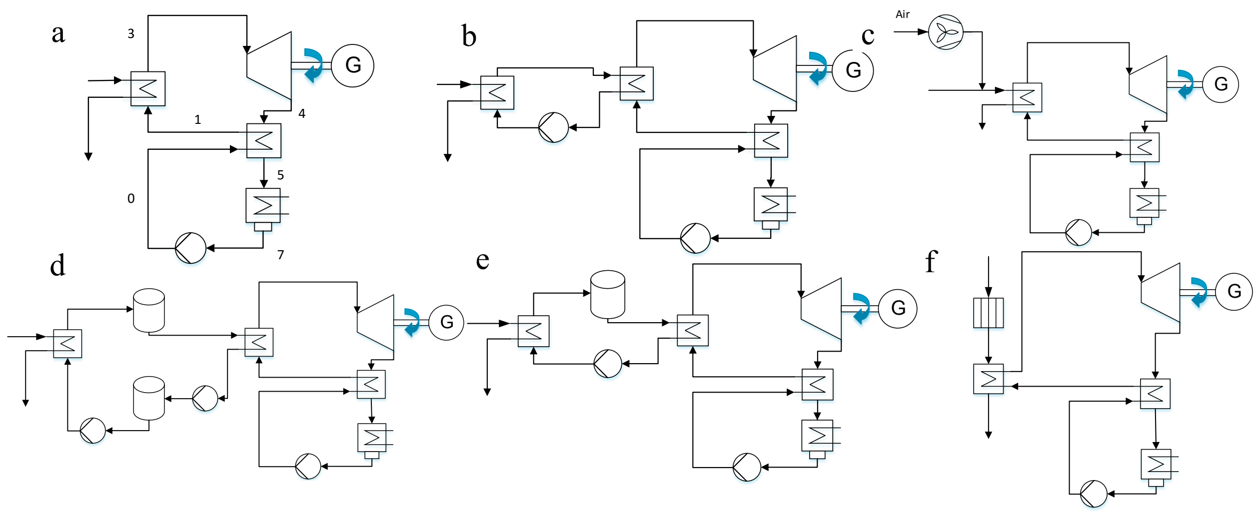

Fig. 2. Process flow diagram for (a) recuperated ORC; (b) Intermediate oil loop; (c) Fresh air injection; (d) Two tank sensible storage; (e) Single tank sensible storage; (f) Latent heat buffer.

of a heat storage has the advantage of reducing peaks in heat input to the ORC, limiting the investment costs of the ORC and its operation in off-design. The heat storage might however increase the overall plant investment and maintenance costs, because of the larger number of components. This works considers two-tank and single tank sensible storage (Fig. 2d-e) and a latent heat buffer (Fig. 2f). The first two require an integrated intermediate loop, whereas the latent buffer smooths out the heat source fluctuations directly at the heat source pathway before the ORC evaporator.

Given different design points in terms of heat source temperature, mass flow rate and chemical composition, the ORC cycle can be thermodynamically optimized. The working fluids considered are water, toluene, pentane and MM. For water, the recuperator effectiveness is set to zero. The fluid that achieves the maximum net power output (electrical generator power output minus pump motor power input) in each configuration was chosen for the analysis.

An economic model to compute the investment costs is developed, based on [11]. The model was already used for ORCs in several works [12–14]. A number of factors, depending on the equipment type, the material used and the operating pressure, determines the direct and indirect purchase costs of equipment (so-called "bare module costs" in [11]). This value is multiplied by the factor 1.18 to account for contingency and fees. The exchange rate USD/€ is set at 1.25 and a CEPCI of 578.4 is used as a reference (November 2014). For the heat exchangers, the following heat transfer coefficients, which agree with the ranges given in [15], are used: 80 W/m^{2}K for hot source/oil heat exchanger, heat source/ORC evaporator and air-cooled ORC condenser; 200 W/m^{2}K for the ORC recuperator and 600 W/m^{2}K for the oil/ORC evaporator. The coefficients are assumed the same for any working fluid for simplicity. For the air injection system, the costs of the air ventilation are considered, given the rated air flow rate and a pressure drop of 10 mbar through the waste heat exchanger. In the case of latent heat storage, the purchase costs are determined considering the storage material (price in Table 2) and the steel pipes used for the storage (92.22 €/m updating the costs in [16]). The heat transfer coefficient between hot gas and storage material is in this case computed by using a heat transfer correlation from [17], where the thermal conductivity of steel was set to 17 W/m K. For the latent heat, storage properties are taken from [18] and [19]. To evaluate the economic performance of the waste heat recovery independently from the current electricity price, the Levelized Cost of Electricity (LCOE) is used:

Table 2. Price of sensible and latent storage material. Currency exchange rate USD/€ = 1.25.

Material	Type	Unit	Cost	Source	Quantity	Type	Unit	Cost	Source
Therminol VP-1	Sensible	(€/kg)	1.60	[20]	$LiNO_3$	Latent	(€/kg)	8.00	[21]
HITEC® Heat Transfer Salt	Sensible	(€/kg)	0.74	[22]	50wt-NaCl / 50-wt $MgCl_2$	Latent	(€/kg)	0.14	[21]*

*Approximated from 48wt-NaCl / 52wt MgCl

$$LCOE = \frac{\sum_{k=1}^{n} \frac{C_k}{(1+i)^k} + C_0}{\sum_{k=1}^{n} \frac{E_k}{(1+i)^k}} \tag{1}$$

where i is the interest rate, n the number of years, C_k are the yearly maintenance costs, C_0 are the investment costs, E_k is the yearly electricity production. In all cases, the yearly maintenance costs C_k are equal to 2% C_0. For the LCOE, a period n of 10 years is considered, and the interest rate amounts $i = 4\%$.

3. Simulation model

The thermodynamic optimization and cost computation of the ORC and heat storage are performed with an in-house code written in MATLAB®. The simulation of the plant under varying heat source conditions is carried out in Ebsilon®Professional. Dynamic transients in the ORC are neglected and simulated by means of a quasi-steady state approach. For the heat storage, the charging level is computed by integrating with trapezoidal rule over constant time steps. Before the off-design is considered, the thermodynamic optimization is carried out at different design points. The objective function is the net power output, which has to be maximized. Table 3 summarizes assumptions, constraints and degrees of freedom. Only subcritical systems are considered, with a maximum evaporation pressure equal to 80% the fluid critical pressure. Excluding water, for every other fluid a maximum turbine inlet temperature of 350°C was set. Given the large fluctuations of the heat source, it is important to represent properly the off-design of the ORC and heat storage. Ebsilon®Professional offers correction curves for heat exchangers, which correct the heat exchanger thermal capacity UA according to the fluid mass flow rate (see Fig. 3a). This dependency seems reasonable, since the heat transfer is in the considered case predominantly convective, and therefore mainly dependent on the fluid velocity and mass flow. All heat exchangers are assumed to operate in counter-flow. Since the focus of this work is to assess economically the waste heat recovery rather than achieving a detailed simulation of the single ORC components, and given the low accuracy (e.g. ±50% as mentioned in [23]) of available heat transfer correlations, the correcting factor shown in Fig. 3a is considered sufficient for the scope of this work. For the turbine and pump, the correlations proposed by [24] are used. These correlations are function of the fluid mass flow rate. As an example, the off-design performance is compared with the typical off-design performance shown by Turboden Srl in Fig. 3b [25]. The mass flow rate is controlled to achieve the minimum heat source outlet temperature, without reducing excessively the evaporator pinch-point temperature difference. The pressure is adjusted according to the Stodola equation. The ORC is supposed to have a minimum load of 20% of the design value, and the turbine can accept up to 120% the design inlet pressure and mass flow rate. Given the off-design performance of the ORC, the electricity produced for a given heat source profile can be computed. The reduced environmental impact thanks to the ORC can be computed multiplying the average electrical power produced over the source profile by a factor of 535 tCO_2/GWh [26] and 8000 h/y of operation [27]. Given the higher dust content in WHR from EAF [10], in this case the operational hours are set to 7000 h/y. The model assumption for the heat storage configurations are summarized in Table 4.

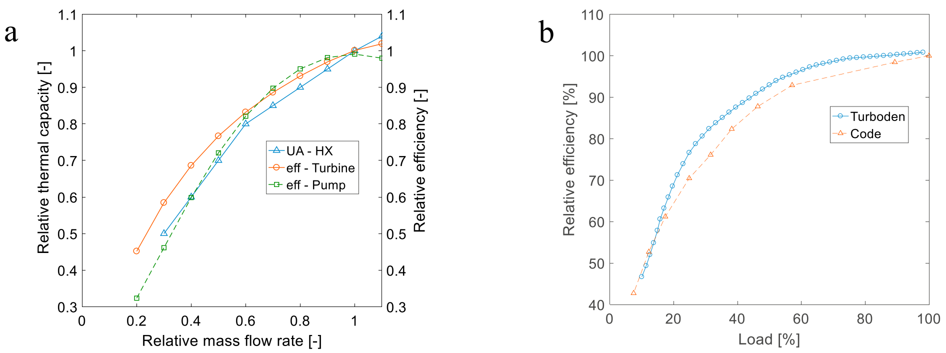

Fig. 3. (a) Off-design correlations for heat exchangers, turbine and pumps; (b) Off-design perfomance of ORC.

Table 3. Model assumptions for thermodynamic optimization code at design point. (*When used - for water, set to zero)

Quantity	Unit	Value	Quantity	Unit	Value	Optimization variable	Unit
Min. heat source temperature	(°C)	150	Turbine efficiency	(%)	75	Evaporator pressure	(bar)
Pinch-point	(K)	10	Generator efficiency	(%)	97		
Pump efficiency	(%)	70	Recuperator effectiveness*	(%)	80	Turbine inlet temperature	(°C)
Pump motor efficiency	(%)	85	Condensation temperature	(°C)	30		

4. Results

In this section, the main results of the analysis for the three applications are discussed. The analysis scheme is shown in Fig. 4a. The configurations are compared in terms of LCOE and CO_2-savings. For clinker cooling (profile in Fig. 1a), direct evaporation uses Pentane for the 25% case, and MM for the remaining. As shown in Fig. 4b, the solution with lowest LCOE is the latent buffer (8.9 ct/kWh), followed by the two tank storage (9.2 ct/kWh). The latent heat buffer also allows the largest CO_2-savings (5296 tCO_2/y). For WHR from HRF (Fig. 1c), the heat source fluctuates only in mass flow rate, whereas the heat source temperature is approximated to be constant at 403.53°C. Toluene is used as working fluid in every configuration. If the ORC mass flow rate overcomes 120% of the design value, the surplus flue gas is bypassed. The latent heat storage is in this case not considered, because of the additional complexity required with respect to Fig. 1e. The air injection has no significant advantage, since it would convert the fluctuations in mass flow rate into fluctuations in temperature, largely degrading the ORC efficiency. The best economic performance is achieved by direct evaporation with design at the minimum mass flow rate (6.7 ct/kWh, see Fig. 4c). This has the advantage of low investment costs because of the low size of the ORC. The high bypass ratio results in low CO_2-savings. The largest CO_2-savings are reached by the design for 75% CDF in mass flow rate (1780 tCO_2/y). In this case, the ORC does not cover the maximum peak in mass flow and at the same time does not by-pass most of the fluctuations. In WHR from EAF, both mass flow rate and temperature undergo significant fluctuations. Given the high maximum temperature of the flue gas, an intermediate oil loop is considered, at 360/220°C (Therminol VP-1). Given the high temperature of the source, Toluene is applied as working fluid for every configuration. The simulation results are shown in Fig 4d. The best configuration without storage reaches the lowest LCOE (5.46 ct/kWh), strictly followed by the two tank and latent heat buffer (5.51 and 5.63 ct/kWh). For the best configuration with no storage, the design is carried out for the 50% CDF temperature and 100% CDF mass flow rate. The latent heat buffer recovers also the largest amount of energy, leading to the highest CO_2-savings (5806 tCO_2/y).

5. Conclusions

This work presents a design methodology and analysis of WHR with ORC. The economic performance is evaluated by means of the LCOE, and the environmental benefit from the WHR in terms of CO_2-savings. Heat storage seems to be economically beneficial when the heat source is affected by large fluctuations in temperature. Smoothing out temperature fluctuations allows to reduce the investment costs and operate the ORC closer to the design point. When

Table 4. Model assumptions for heat storage (*temperature given as A/B: A: high temperature tank/B: low temperature tank)

Storage	Heat source	Medium	Temperatures (°C)	Quantity (t)	ORC working fluid	Notes
Two-tank	Clinker cooling air	Therminol VP-1	220/92.5*	159.07	Pentane	If source temp. < 230°C, source bypass
	Flue gas HRF	Therminol VP-1	370/92.5*	17.87	Toluene	
	Flue gas EAF	HITEC®	400/225*	10.80	Toluene	If source temp. < 410°C, source bypass
Single tank	Clinker cooling air	Therminol VP-1	variable	1000	Pentane	
Latent heat buffer	Clinker cooling air	$LiNO_3$	254	70.44	MM	Properties from [19]
	Flue gas EAF	50wt-NaCl/50-wt $MgCl_2$	450	9.96	Toluene	Properties from [18]

the mass flow rate oscillates, a by-pass of the peaks in mass flow rate could be useful. In the result evaluation, it must be considered that the purchase costs correlations used to estimate the investment costs are affected by an error between -25% to +40% [11]. A LCOE lower than 5.5 ct/kWh can be achieved recovering heat from EAF, thanks to the high temperature of the flue gas (> 700°C), whereas in case of recovery from hot reheating furnace (around 400°C), 6.7 ct/kWh are achievable. For clinker cooling (180°C<T<330°C), the LCOE could not go below 8.9 ct/kWh. The LCOE shows the complexity of recovering the waste heat at low (fluctuating) temperature level, and the benefit from high temperature heat source. The results of the present work can lay the foundation for a design procedure for ORC subjected to fluctuating heat sources, suggesting the best plant configuration. Source profile and economic boundary conditions might have an influence on the applicability of the results for other industrial sectors, but the theoretical procedure described in the paper remains valid. As part of future work, dynamic models of the ORC and heat storage will be developed to account for and assess the impact of dynamic effects neglected in the present work.

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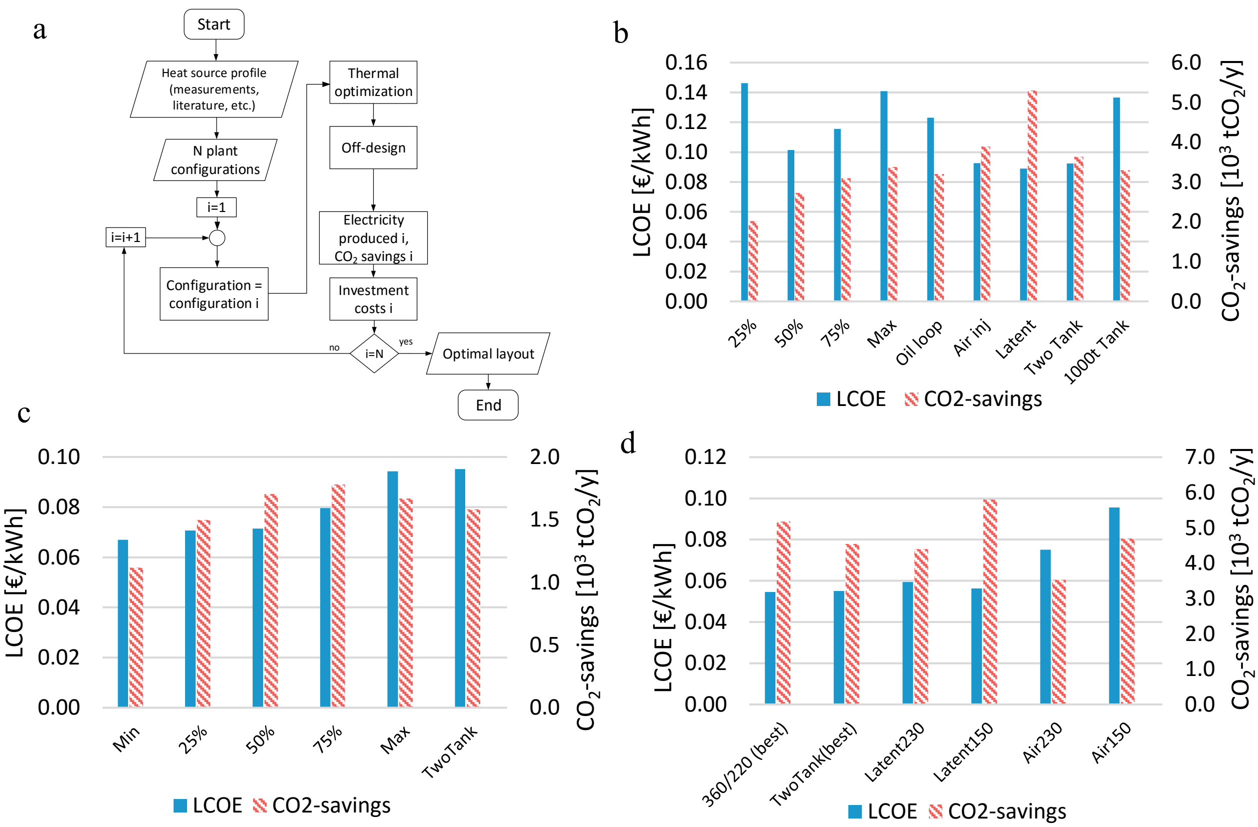

Fig. 4. (a) Design and analysis diagram; (b) LCOE and CO_2-savings for heat recovery from clinker cooling; (c) LCOE and CO_2-savings for heat recovery from hot reheating rolling mill; (d) LCOE and CO_2-savings for electric arc furnace. '150' and '230' refer to flue gas outlet temperature.

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