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Energy Reports 6 (2020) 298–304

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7th International Conference on Energy and Environment Research, ICEER 2020, 14–18 September, ISEP, Porto, Portugal

Techno-economic analysis of a sCO_2 power plant for waste heat recovery in steel industry

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Received 1 November 2020; accepted 15 November 2020

Abstract

Industrial facilities release a large amount of heat as a by-product of their processes. To improve environmental performance and increase process profitability, a portion of the waste heat can be recovered and employed for power generation by recovery systems. Supercritical carbon dioxide (sCO_2) plants are emerging as potential alternatives to the well-established technologies for waste heat recovery (WHR) power generation in heavy industry. This paper offers a preliminary techno-economic analysis of a waste heat-to-power system based on a sCO_2 closed-loop for a heavy-industrial process.

By conducting a parametric investigation on the WHR sCO_2 system's key design parameters, a number of preferable configurations from a thermodynamic perspective were initially identified; they were subsequently analyzed from the economic point of view in terms of net present value (NPV) and pay-back period (PBP). The privileged WHR system configuration achieved an overall efficiency of 30.4% and a power output of 21.6 kWe, providing an NPV of almost US k$ 376 with a PBP of approximately 4.5 years.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

Keywords: Supercritical carbon dioxide; Waste heat recovery; Techno-economic analysis; Power production; Heat-to-power

1. Introduction

Harnessing industrial process waste heat, which would otherwise remain unexploited, could lead to significant energy savings for the industrial sector, a considerable reduction of fossil fuel use and, consequently, a deep cut in environmental pollutant emissions [1,2]. For instance, it was assessed that before the pandemic, in Europe almost 26% of primary energy was wasted in industrial processes as rejected heat, i.e. approximately a theoretical potential of 920 TWh, and a Carnot potential of 279 TWh [3]. Similar scenarios, however, were highlighted in most of the developed countries worldwide [2]. In Europe, approximately 124 TWh/year was made available at temperatures over 500 °C [4], and it was suggested to boost recovery systems for waste-to-power applications.

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https://doi.org/10.1016/j.egyr.2020.11.147

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

Currently, conventional technologies applied to waste heat-to power systems are Organic Rankine Cycles (ORC) and Steam power plants. ORCs match well with energy sources at low/medium temperatures (generally lower than 400 °C), while steam plants are usually fit for energy sources at medium/high temperature and medium/large waste heat potentials. Therefore steam plants do not usually suit with small/medium applications.

In the last years, supercritical carbon dioxide (sCO_2) closed-loop systems have been taken into consideration as a valid alternative to conventional options, mainly for small-medium industrial WHR plants [5]. sCO_2 cycles have high efficiency. They use an inert fluid and can be operated with compact equipment and turbomachinery.

Results of previous studies regarding the applicability of sCO_2 technologies in the WHR field [6–9] suggest that sCO_2 cycles can represent an appealing alternative to conventional options especially when a small waste heat potential is available at temperatures over 400 °C.

The main attraction of this technology derives from the chemical and physical properties of the working fluid. Compared to organic compounds, sCO_2 is not flammable and is more stable from a chemical perspective. Moreover, these systems are characterized by high performance (i.e., a significant increase in the power output and the cycle's thermal efficiency resulting from a substantial reduction in compression work), reduced carbon footprint and water consumption. However some significant challenges to the full development, commercialization and deployment of this technology still exist [6].

This work investigates the techno-economic feasibility of a simple-recuperated sCO_2 Brayton cycle system (RBC) integrated with a waste heat source from a real industrial steelmaking site. The work highlights some relevant aspects, and it provides insight into the potential role of sCO_2 cycles as a profitable option for heat-to-power conversion. The results offer valuable information regarding how key design inputs impact heat-to-power technical potential and economic performance, which will guide the design process as sCO_2 cycle technology increasingly progresses to commercial scales.

2. Case study

The reference industrial plant is a cast-iron cookware facility in operation for 4000 hr/year (16 hours/day) where several processes are carried out (e.g., metal casting, molding, sand preparation and surface treatments, enameling). The WHR focuses on the enamel coating process, which typically provides flues at 450–650 °C. Electricity consumption for the induction furnace was estimated to be approximately 4 TWh/year, and the enamel kilns' gas consumption was almost 10 TWh/year.

Based on the literature results [10,11], the sCO_2 recuperated Brayton cycle (RBC) was selected as a prospective WHR unit for the considered industrial facility. The RBC has a simple plant layout and allows broader exploitation of the waste heat potential (WHP) than more complex cycles (e.g., recompressed Brayton cycle). A schematic diagram of the plant is shown in Fig. 1. The system consists of five basic components: main compressor, recuperator, primary heater, turbine and cooler. The cycle process is as follows: the working fluid is first compressed to high pressure and is subsequently preheated (by recovering a considerable portion of the heat available at the turbine exit) in the recuperator; in the primary heater, the fluid receives heat from flue gases, and it enters the turbine at high temperature and high pressure to generate power; the low-pressure fluid at the turbine exit is then delivered into the recuperator to release heat and is finally cooled to begin a new cycle.

3. Techno-economic analysis

Thermodynamic and economic models of the key sCO_2 system units were developed and implemented in an in-house tool. For a given waste heat potential, the tool can evaluate the thermodynamic states at the main stations and the overall cycle performance, setting minimum and maximum pressures and temperatures, turbomachinery efficiencies, and heat exchangers pressure drops. The evaluation of the heat transfer in the heat exchangers was based on the log mean temperature difference (LMTD) method. Moreover, the tool can evaluate costs (capital and operating costs) associated with the specific configuration.

From the thermodynamic point of view, the expected power output of the recovery plant can be expressed as follows:

$$P = Q_{WHP}\eta_{WR}\eta_{th} \quad (1)$$

where Q_{WHP} is the kilns' waste heat potential made available at the primary heater, η_{WHR} the WHR efficiency, and η_{th} the cycle thermodynamic efficiency, respectively. η_{WHR} is a fundamental parameter for the evaluation of the

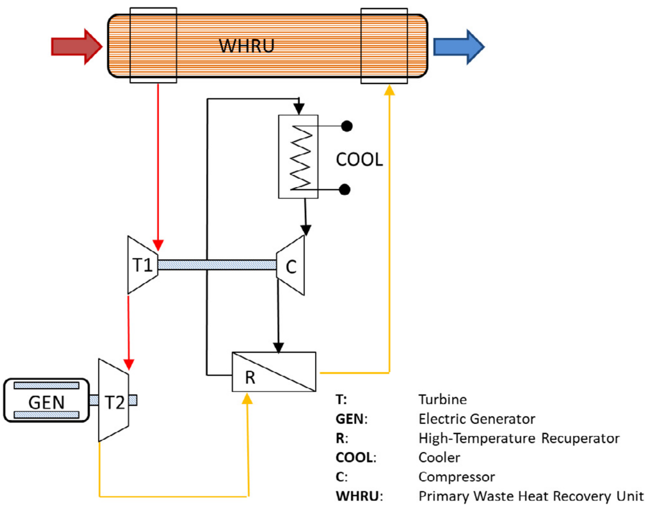

Fig. 1. Simplified schematic of the sCO_2 RBC.

waste heat-to-power system because it is directly linked to the cycle's power output, and it is defined as the ratio between the heat extracted from the flue gases and the waste heat potential (Eq. (2)):

$$\eta_{WHR} = \frac{Q_{extracted}}{Q_{WHP}} \tag{2}$$

For a given WHP, the best performing layout is, in general, the one that maximizes the product between $\boldsymbol{\eta}_{WHR}$ and η_{th}, and a simple RBC fits well with such a characteristic without increasing the complexity of the WHR system as well.

The capital cost evaluation of the power plant was performed using a bottom-up approach. The cost of the key components (indicated in the following as C) was estimated according to the following equations retrieved from the literature [12–14]:

$$C_{comp} = \frac{71.1\dot{m}}{0.9 - \eta_{compr}} \beta_{compr} \ln \beta_{compr} \qquad \text{compressor} \tag{3}$$

$$C_{turb} = \frac{479.34\dot{m}}{0.92 - \eta_{turb}} \beta_{turb} \left(1 + e^{(0.036 T_{IT} - 54.4)}\right) \qquad \text{turbine} \tag{4}$$

$$C_{gen} = 60\, P_e^{0.95} \qquad \text{generator} \tag{5}$$

$$C_{HE} = \gamma \ (UA) \qquad \text{heat exchangers} \tag{6}$$

where $\dot{m}$, η, β and TIT are the mass flow rate, turbomachine isentropic efficiency, turbomachine pressure ratio and turbine inlet temperature, respectively. Pe, U and A stand for electrical power output, overall heat transfer coefficient and heat transfer area, respectively. γ is the cost of the heat exchanger per unit of the product UA. Its value depends on the type of heat exchanger taken into consideration.

The resulting overall capital cost, given by the sum of the single abovementioned component costs, was increased by a factor (Cia) to account for installation and auxiliary equipment costs.

The yearly operating and maintenance costs were estimated according to the relationship proposed by previous studies [11]:

$$C_{OMk} = P_e \left[c_{OM} \left(1 + er\right)^k\right] \tag{7}$$

where c_{OM} are the operating costs per unit of installed electric power, and 'er' is the escalation rate of these costs due to equipment degradation and maintenance over time.

Considering the system small size (approximately 200 kWe of net output power) and the relatively large industrial facility size (4 x 10^6 kWh of electricity consumption per year), the electricity produced is assumed to be used by the industrial facility itself and not sold to the grid. This assumption allows one to omit taxes in the cash flow calculation because no net profit is associated with the WHR system operation.

The plant's economic viability was primarily analyzed in terms of net present value (NPV) and pay-back period (PBP), two criteria widely used in assessing the economic competitiveness of novel and conventional energy conversion systems [15–17]. Whereas NPV quantifies a project's potential profit, PBP indicates the duration for which cash invested in the project is exposed to risk.

In light of the aforementioned assumption (i.e., the electricity generated by the sCO_2 WHR system exploited by the industrial facility), it is quite evident that the NPV is not a measure of a new revenue stream for the steelmaking facility but rather of the expected cost savings following a reduction in electricity purchase from the grid over the entire operative lifespan of the plant.

4. Results and discussion

The reference industrial plant makes available at the enamel kilns flue gases at an average temperature of 550 °C. The estimated WHP is approximately 1.25 MWth.

The thermodynamic performance of the sCO_2 power cycle was preliminarily evaluated using the input data reported in Table 1. To explore the design space and achieve some information about the effect of cycle pressure ratio and mass flow rate on the WHR system power output, a parametric analysis of the RBC was carried out. The influence of the two abovementioned parameters was compared mainly in terms of net electrical output Pe, WHR efficiency η_{WHR} and thermal efficiency η_{th}. At this stage of the analysis, the isentropic efficiency of turbomachinery and pressure drops of heat exchangers were assumed constant, as reported in Table 1.

Table 1. Key technical input data for the parametric analysis.

Input parameter	Value
Minimum cycle pressure	8.5 MPa
Turbine isentropic efficiency	90%
Compressor isentropic efficiency	85%
Heat Exchangers pressure drop	2%
Minimum Cycle Temperature	37 °C
ΔTu[a]	20 °C
WHR inlet temperature (sCO_2)	270 °C

[a]Difference between the temperature of flue gases and sCO_2 temperature at WHR inlet section.

Results are reported in Fig. 2, arranged in three groups, one for each maximum pressure of the cycle taken into consideration (25, 30 and 35 MPa). For each group, the reference sCO_2 mass flow rate was taken as the second parameter, and it was increased from left to right (from 2 to 2.33 kg/s). Consequently, the maximum temperature of the cycle decreases (from 500 °C to 475 °C approximately), since the WHR potential is assumed.

It is relevant to highlight that, for each maximum pressure, the higher the mass flow rate, the higher Pe. Although Pe raises with the maximum pressure of the cycle, it is possible to conclude that the selection of high maximum pressures is not recommended. For this specific case study, an increase of 10 MPa (from 25 to 35 MPa) brings about an increment of Pe of almost 18%. However, it would involve to severe technical challenges for the appropriate design of some plant components.

From the results of the first part of the parametric analysis, the best performing cycles in terms of power output for each maximum pressure were selected for further analysis (namely cycles D, H and N for 25, 30 and 35 MPa, respectively). To explore the impact of machinery performance on the economic indexes, a parametric analysis was carried out varying the compressor isentropic efficiency from 75 to 85% and the turbine isentropic efficiency from 80% to 90%, as reported in Table 2. For the sake of simplicity, Fig. 3 reports the results only in terms of economic performance (NPV and PBP for each case). The values of the main economic parameters applied to the evaluation of the WHR system cash flows and costs uncertainties of the models are summarized in Table 3.

The achieved economic results highlight that NPV and PBP evaluated through economic correlations reported in literature are remarkably affected by machines' efficiency, while the cycle maximum pressure is not relevant as the

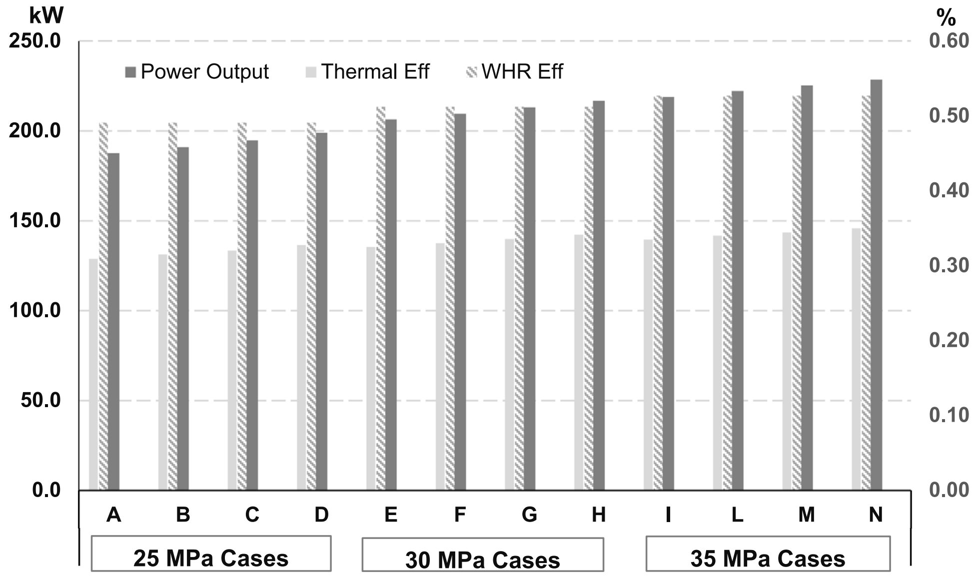

Fig. 2. Main results of the thermodynamic parametric analysis varying maximum pressure and cycle mass flow rate.

Table 2. Machinery performance for each group of RBCs.

Case	Compressor isentropic efficiency [%]	Turbine isentropic efficiency [%]
1	85	90
2	82.5	87.5
3	80	85
4	77.5	82.5
5	75	80

Table 3. Key economic assumptions.

Input parameter	Value
Inflation rate	5%
Operating costs (c_{OM})	30 $/kWe
Increase of capital costs (Cia)	30%
Escalation rate	3%
Degradation rate	1%
Cost of electricity (ce)	8 c$/kWh
Plant life	20 years
Operating hours	4000 hours/year
Ratio between salvage revenue and total capital costs	5%
Capital costs uncertainties	+50%/−30%
Operating costs uncertainties	+10%/−10/

variation of NPV and PBP is negligible in comparison with the model uncertainties on costs estimations. Therefore, solutions at lower pressures (i.e. 25 MPa instead of 30 or 35 MPa), and lower machinery efficiency seem those to be privileged. However, a more accurate investigation of the reliability of capital costs correlations for sCO_2 plants reported in the literature is suggested. In fact, it is beyond doubt that information coming from the realization of new prototypes for the plant key components will help the setup of more specific models, improving the reliability of economic investigations for sCO_2 systems.

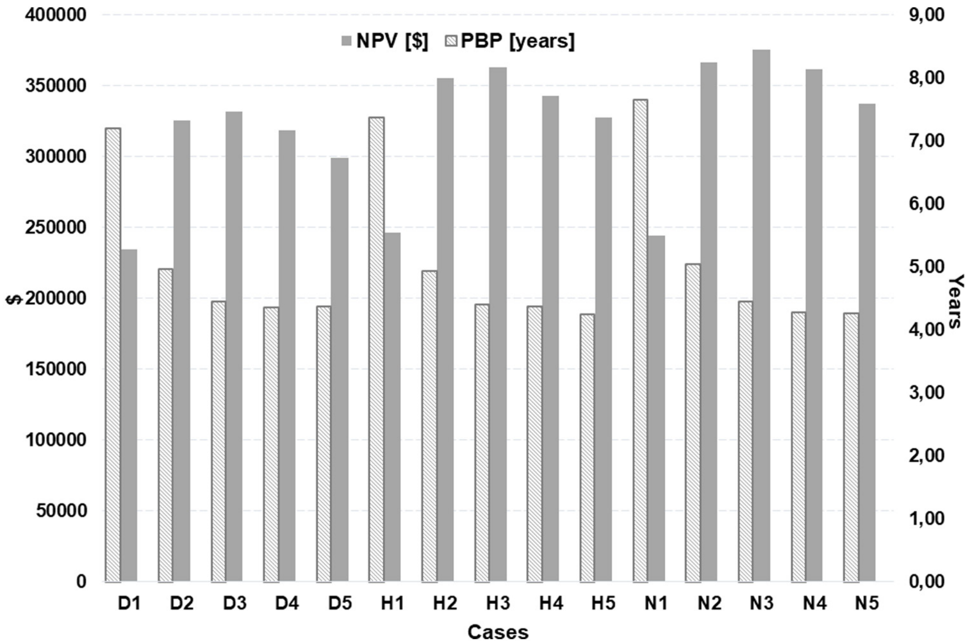

Fig. 3. Main results of the economic parametric analysis varying machines' efficiencies.

5. Conclusion

This paper offered a WHR solution to an industrial steelmaking industry sector site, taking into consideration the technology's performance and prevailing operating site conditions. The integration of the sCO_2 plant with the industrial facility was assessed by a parametric investigation to determine the most commercially attractive WHR system configuration. The effect of the cycle maximum pressure and machinery performance were considered. In the range of investigation, a NPV from 234 to 375 US k$ was found. The technology is expected to be appealing for potential investors because PBPs were estimated from 4.2 to 7.6 years based on 4000 plant operating hours per year.

However, the estimation of capital costs for sCO_2 plants should be investigated more accurately, mainly updating them through data coming from the on-going activities on new prototypes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors want to acknowledge the European Turbine Network (ETN) association and the University of Roma Tre, Italy for their kind support.

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