E3S Web of Conferences **197**, 02011 (2020) https://doi.org/10.1051/e3sconf/202019702011
75° National ATI Congress

sCO_2 Power Plant for Industrial Waste Heat Recovery: a Case Study

Ambra Giovannelli[*], *Matteo* Biondi, *Giuseppina* Di Lorenzo, *Coriolano* Salvini

Dept. of Engineering, University of Roma Tre, Via della Vasca Navale 79, 00146 Rome, Italy

Abstract. Industrial facilities release a large amount of heat as a by-product of their processes. To improve environmental performance and increase the process profitability, this waste heat can be recovered and employed to generate power. Supercritical carbon dioxide (sCO_2) systems have emerged as potential alternatives to the well-established technologies because of their high performance, reduced footprint and low water consumption. This paper aims to investigate the techno-economic feasibility of a sCO_2 closed loop for power generation coupled with heavy-industrial processes, which make flue gases available at high-temperatures (above 400 °C).

1 Introduction

It is widely accepted that climate change is one of the largest environmental threats of the 21st century. A key challenge is the need to massively reduce greenhouse gas emissions while keeping pace with the world's growing energy needs. This must be done without affecting sustainability, affordability, or service reliability [1]. Tackling this challenge would require a simultaneous reduction of greenhouse emissions across several sectors [2] beyond the power generation sector, which has thus far taken centre stage in any decarbonisation plans put forward. Various strategies are being explored, such as increasing efficiency in any industrial process, massive use of renewable energy sources, implementation of carbon capture and storage technologies.

Industrial waste heat is available over a wide range of temperatures, from 50 °C to over 1000 °C, depending on the industrial sector and process. Recent studies [3] show that in the U.S. industries, 20-30% of the energy consumption is lost as waste heat. Papapetrou et al. reported a complete survey of the industrial waste heat in EU countries from the year 2015. This study highlighted that one-third of the total potential waste heat (about 100 TWh/year) existed in the range of 100-200°C, almost 78 TWh/year were available at 200-500 °C, while the largest portion (124 TWh/year) belonged to waste heat available at temperatures over 500 °C. The latter referred mainly to three industrial sectors: glass, cement and steel manufacturing.

For an efficient WHR in such sectors, a sCO_2 closed-loop system can be a valid alternative to conventional options (Organic Rankine Cycles, Kalina cycles, steam power plants), especially for small-to-medium sized WHR plants. The sCO_2 cycles are highly

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[*] Corresponding author: ambra.giovannelli@uniroma3.it

efficient, they use an inert fluid and can be operated with compact equipment and turbomachinery. However, their primary disadvantage is the novelty of the technology, which means a current lack of experience and pilot power plants.

2 The Case Study

For the present study, a facility dedicated to cast iron cookware production was examined. In this production casting, sand preparation, melting, sandblasting/grinding and enamel coating are the most relevant processes. In particular, for the enamel coating, ovens usually work at high temperatures (up to 800 °C), and make available flue gases at 400-650 °C for a potential WHR system.

This facility operates 4,000 hr/year (16 hrs/day). The electricity consumption of the plant is estimated to be around 4000 MWh/year, and the gas consumption for the enamel kilns amounts to 10000 MWh/year. The enamelling section of the plant is composed of two gas-fired kilns, five enamel cabins and a dust collection system. An average temperature of 550 °C for the kilns' flue gases can be assumed, and the estimated heat waste potential is approximately 1.25 MWth.

Results of previous studies [4-6] have suggested that sCO_2 cycles could represent an appealing alternative to other candidates (steam and Organic Rankine Cycle plants), since steam plants are usually applied to recovery systems with greater heat potentials, while Organic Rankine Cycles can work only at medium-low temperatures and, consequently, the waste heat-to-power efficiency would be compromised.

Among the several cycles proposed in the literature for sCO_2 closed-loops, the Recuperated Brayton Cycle (RBC) seems to be one of the most promising, since it seems to be a good trade-off between plant performance and plant complexity [7]. Figure 1 depicts the reference plant scheme and thermodynamic cycle. The RBC layout facilitates broader exploitation of the waste heat potential than more complex cycles (e.g., the recompressed Brayton cycle), resulting in high waste heat recovery efficiency.

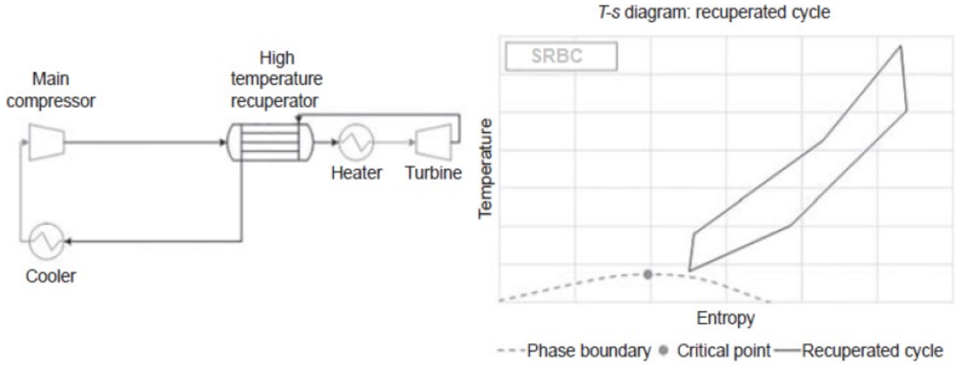

Fig. 1. sCO_2 Recuperated Brayton Cycle: main plant scheme and reference thermodynamic cycle.

3 Techno-economic Analysis

A specific tool written in Wolfram Mathematica was setup for a parametric techno-economic analysis of the sCO_2 RBC waste heat-to-power plant. The aim of this tool was to select the best techno-economic RBC arrangement for this case study.

The details of the in-house tool are reported in [8]. For a given waste heat potential, the tool can evaluate the thermodynamic states at the main stations and overall cycle performance, setting minimum and maximum pressures and temperatures, turbomachinery efficiencies, and heat exchangers pressure drops. For the present study, a parametric analysis was conducted, establishing minimum pressure (8.5 MPa) and temperature (37 °C), recuperator effectiveness (90%), heat exchangers pressure drops (2% of the inlet pressure), and varying the maximum pressure from 25 to 35 MPa, compressor efficiency from 75% to 85% and turbine efficiency from 80% to 90%. All of the fixed data and the parameters were in the typical ranges reported in the literature for the thermodynamic analysis of sCO_2 cycles [9].

From an economic point of view, the thermodynamic results were used in the tool as input for the evaluation of conventional economic performance indicators such as Net Present Value (NPV), Pay-Back Period (PBP), and Levelised Cost of Electricity (LCOE).

Since the industrial facility already existed, the capital costs did not include costs connected with the purchase of land or buildings. That is, only capital costs related to equipment and WHR plant construction were taken into consideration. Other costs were assumed to be proportional to the costs of the equipment (compressor, turbine, electric generator, and three heat exchangers). Moreover, the costs associated with the equipment were added together and increased by a factor that accounted for the costs of installation and auxiliaries. All of the applied correlations were taken from the literature and are summarized in Table 1.

Table 1. Equipment cost correlations

Component	Correlation	Reference	[#]
Compressor (c)	$C_c = C_c\,(m, \eta_c\,, \beta_c)$	[10]	(1)
Turbine (t)	$C_t = C_t\,(m, TIT, \eta_t\,, \beta_t)$	[10]	(2)
Electric Generator (eg)	$C_{eg} = C_{eg}\,(P_e)$	[11]	(3)
Heat Exchangers (HE)	$C_{HE} = C_{HE}\,(UA)$	[12]	(4)

Notes: m is the mass flow rate, β is the pressure ratio, η is the isentropic efficiency, TIT is the turbine inlet temperature, Pe is the output power, U is the exchanger overall heat transfer coefficient and A is the exchange surface area.

Moreover, operating costs and revenues were calculated to estimate the yearly cash flows. They were calculated using the relationship reported in [13]:

$$C_{OMk} = C_{OMk}(P_e, c_{OM}, er, \mathrm{k}) \tag{5}$$

where C_{OMk} is the yearly operating costs related to the k-year, c_{OM} are the operating costs per unit of installed electric power, and *er* is the escalation rate of these costs through the years, related to equipment degradation and increasing maintenance influence over the years.

Considering the small size of the WHR system (an output power of about 200 kW) and the relatively large size of the industrial facility (about 4 MWh of electricity consumption per year), the internal demand was large enough to absorb all of the generated power. The auto-consumption allowed avoiding tax expenses, as no net profit was associated with the operation of the WHR system.

The main economic parameters defining the plant cash flows were chosen accordingly to Table 2.

Table 2. Economic parameters assumed for the parametric economic analysis

Parameter	**Value**
Inflation rate [%]	5.00
Operating costs c_{OM} [\$/kW$_{\mathrm{e}}$]	30.00
Increase of capital costs C_{ia} [%]	30.00
er [%]	3.00
Degradation rate [%]	1.00
Cost of electricity c_e [c\$/kWh]	8.00
Plant life [years]	20
Operating hours per year	4000
capital costs uncertainty [%]	+ 50% / -30%
operating costs uncertainty [%]	+ 10% / -10%

4 Results and Discussion

The three best-performing cycles were selected on the following criteria: highest NPV, lowest capital costs, and shortest PBP. These were identified by varying the abovementioned key design parameters in the dedicated in-house tool. Further details on the three best cycles are summarized in Table 3, where Case 1, Case 2 and Case 3 represent the cycles achieving the highest NPV, the lowest capital costs and the shortest PBP. Furthermore, a sensitivity analysis was conducted to assess the economic performance of the three best-performing configurations, varying yearly operating hours, duration of WHR plant life, and cost of electricity. The variation range of these three input parameters is reported in Table 4. The influence of every parameter was individually evaluated, maintaining the others at the value declared in Table 2.

Finally, the total yearly operating hours was the most relevant parameter affecting economic indexes. NPV increased linearly with the number of operating hours. The revenue increase allowed for shortening the PBP and improving the cash position at the end of the life of the plant. The LCOE significantly dropped, increasing the operating hours, since the capital costs were spread over a larger amount of kWh generated in the lifespan of the plant.

The life of the plant determined the number of cash flows associated with the investment and the final cash position of the investment. Therefore, the NPV increased alongside the life of the plant. PBP and the slope of the cumulative cash flow curve did not change as the life of the plant changed. The cost of electricity determined the amount of savings, and it therefore had a significant impact on the revenue. NPV increased linearly with the cost of electricity, while the PBP decreased because the slope of the CCF curve rose. The LCOE was not influenced because the market price of electricity is not related to the LCOE in any way.

To illustrate, the main results for the first best case are reported in Figures 2 and 3, varying the yearly operational hours of the WHR plant, whereas Figures 4 and 5 show the results for the first case varying the lifetime of the plant and the cost of electricity respectively.

Table 3. Main results for the three best configurations

Case	**β**	**m [kg/s]**	**η [%]**	**WHR eff [%]**	**P [kW]**	**NPV [k$]**	**PBP [yr]**	**LCOE [c$/kWh]**
1	4.1	2.2	30.4	53.4	201.7	241.4 – 462.3	3.0-6.9	1.62 – 3.03
2	2.9	2.3	26.0	49.1	159.0	194.9 – 366.5	3.0-6.8	1.60 – 2.99
3	3.5	2.3	27.1	51.0	171.0	218.0 – 398.0	2.9-6.6	1.57 – 2.92

Table 4. Economic parameters for the sensitivity analysis

Parameter	**Range of Variation**
Operating hours [h]	4000 - 8000
Lifetime of the plant [years]	20 - 28
Cost of electricity [c$/kWh]	6 - 10

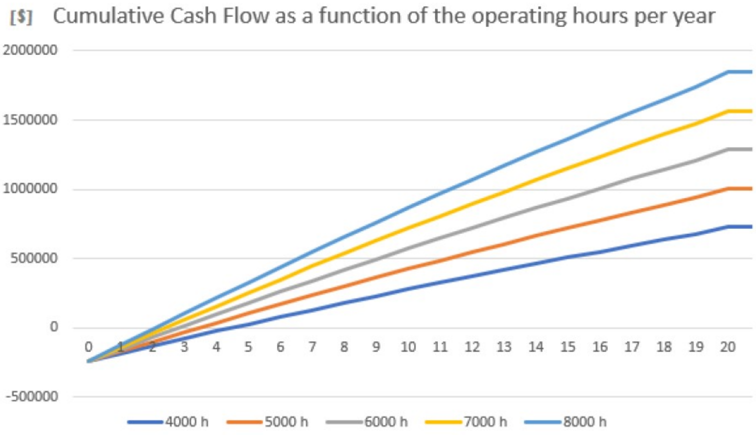

Figure 2. Case 1: cumulative cash flow b) PBP and LCOE varying yearly operational hours

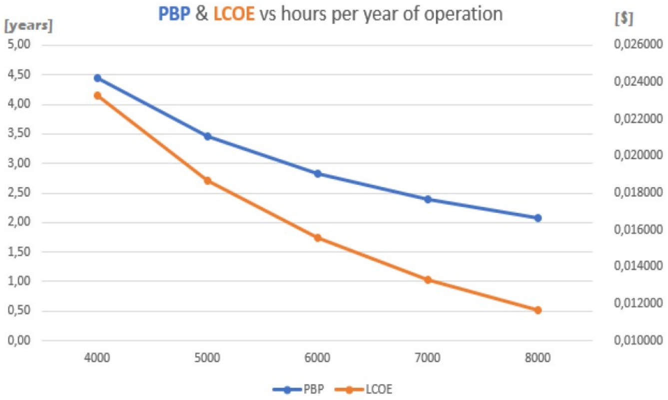

Figure 3. Case 1: PBP and LCOE varying yearly operational hours

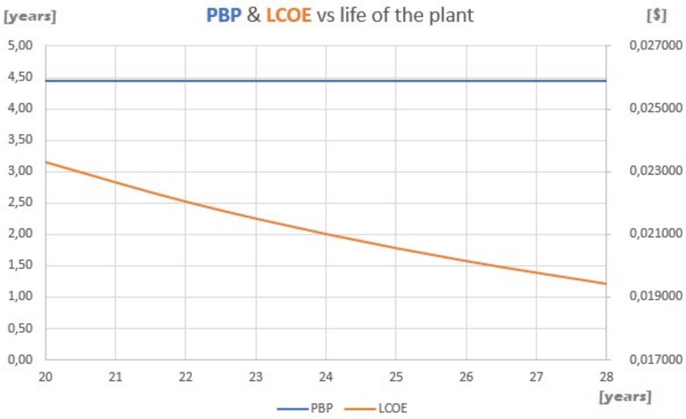

Figure 4. Case 1: PBP and LCOE as function of the life of the plant

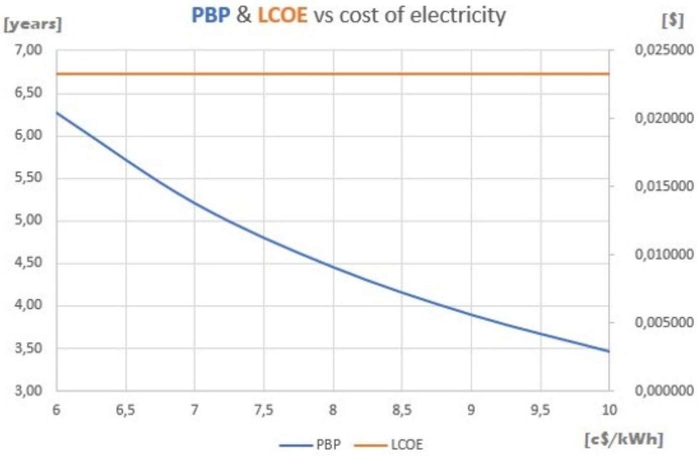

Figure 5. Case 1: PBP and LCOE as function of the cost of electricity

5 Conclusions

The assessment of a waste heat-to-power system based on a sCO_2 RBC for a cast iron cookware facility was carried out on the basis of a parametric techno-economic analysis. Several RBC arrangements were taken into consideration, varying the most relevant cycle parameters, and, in the end three of these configurations were selected using the criteria of the highest NPV, the lowest capital costs, and the shortest PBP. The following economic performances were achieved: NPV between 235 and 376 k$, PBP between 4.2 and 7.6 years, and LCOE between 2.26 and 3.35 $cent/kWh.

Furthermore, a sensitivity analysis was conducted to evaluate the economic performance of the plant, varying yearly operating hours, plant life-time and cost of electricity. The resulting NPV was up to 1 100 k$, a PBP of at least 2 years, and a LCOE of at least 1.11 $cent/kWh.

Therefore, this technology is expected to be profitable. The final cash position and the NPV of the investment are respectively near 3 and 1.5 times the starting expenditures, respectively. The LCOE was rather low, especially if compared to current LCOEs for large-scale power generation (operational costs for fuel consumption were not to factored into the present case study). Finally, the estimated PBPs were short enough to attract potential investors to make their productions more profitable and environment-friendly.

Acknowledgments

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

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