Business case for sCO_2 Waste Heat Recovery System

ETN report

Acknowledgements

The "Business case for sCO_2 Waste Heat Recovery System" was issued by European Turbine Network (ETN), as part of the activities within ETN's Supercritical CO_2 (sCO_2) Working Group.

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The organisations listed below are part of the ETN sCO_2 Working Group:

Introduction

The “Business case for sCO2 Waste Heat Recovery System” report was issued by European Turbine Network (ETN), as part of the activities within ETN’s Supercritical CO_2 (sCO_2) Working Group.
The sCO_2 Working Group aims to bring together manufacturers, end users, suppliers, and academia to assess the development and the current state of the art of sCO_2 technology.

The objective of this business case is to investigate the techno-economic feasibility of a sCO_2 closed loop waste heat recovery system coupled with heavy-industrial processes (e.g. cast-iron, cement production, aluminium production, etc.), which have available flue gases at high temperature (above 400°C) in reference to a specific business case.

Industrial facilities release a large amount of heat in the atmosphere as a by-product of their processes. To improve environmental performance and increase the process profitability, a portion of the waste heat can be recovered and employed for power generation by recovery systems.
Supercritical CO_2 systems are emerging as potential alternatives to the well-established technologies for Waste Heat Recovery (WHR) power generation in heavy industry. Such systems are characterised by high performances, reduced footprint, reduced water consumption and they are suitable for a wide range of heat sources.

Currently, technologies like Organic Rankine Cycles can be applied only to low-medium temperature heat sources, while steam plants cannot be downscaled to be applied in many WHR cases. In this respect, sCO_2 plants could be an interesting alternative to conventional technologies, or a solution for a market share currently underserved.

The business case started with the assessment of the available waste heat in a specific industrial site. Consequently, a thermodynamic analysis has been carried out to define the most suitable cycle. Some preliminary plant layouts have been designed where the main plant components such as turbomachinery and heat exchangers have been taken into consideration.

Finally, plant economic performance indicators, such as NPV, PBP, LCOE, IRR etc., have been evaluated and discussed as results of the analysis.

Contents

Acronyms

List of abbreviations or acronyms.

CSP	Concentrated Solar Power
IRR	Internal Rate of Return
LCOE	Levelised Cost of Electricity
NPV	Net Present Value
PBP	Pay Back Period
sCO_2	Supercritical Carbon Dioxide
WHR	Waste Heat Recovery

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1 sCO_2 FOR ENERGY EFFICIENT INDUSTRIES

The purpose of a thermodynamic cycle intended for power generation is to convert thermal power from a heat source in electric power. Process industries that have a large availability of waste heat are the ideal candidate for the deployment of technologies using thermodynamic cycles to increase the energy efficiency.

The Brayton and the Rankine cycles are the most common cycles deployed for power generation on large scale. The first one normally adopts air as working fluid, while the latter is usually operated with water that undergoes the liquid-vapor transition. The Brayton cycle is usually used by gas turbine plants for electric power generation, having the advantage of operating at high Carnot efficiencies, given the high temperatures (sometimes higher than 1500°C).

The Rankine and the Brayton cycles have complementary features: in the first one, the turbine inlet temperature is much lower (up to more than 600°C, for ultra-supercritical plants), but it requires less work for the compression of the fluid. Hence the efficiency of the plants operating with these two fluids is comparable.

Despite the large variety of available working fluids, air and water are the most common choice for the power-generation plant realisations, because of their beneficial properties. They are highly available, cheap, not flammable, chemically stable, not highly corrosive, and generally compatible with plant components. The choice of a different fluid must therefore be justified by consistent benefits. The reason why the use of supercritical CO_2 is being currently under investigation lies in two main factors:

- A proper exploitation of the fluid properties near the critical point could guarantee high cycle efficiencies (even 5% higher, if compared to Rankine cycle efficiency);
- The low critical temperature of the sCO_2 (around 31°C) grants the adoption of a wide range of heat sources and allows heat rejection to a near-ambient temperature sink.

For these and other consistent reasons the energy conversion technologies that utilise sCO_2 are currently a subject of interest among the industrial world and the scientific community.

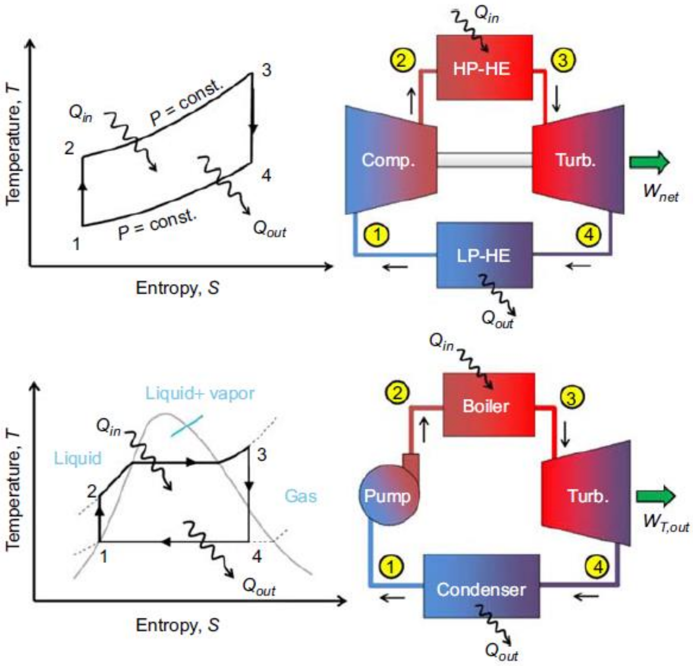


Figure 1 - Brayton and Rankine cycles (up and down respectively in the illustration) and relative plant components

1.1 ADVANTAGES OF sCO_2 CYCLES

A Brayton cycle operating with sCO_2 as a working fluid would allow to combine the previously mentioned advantages of both Brayton-air and Rankine cycles [1].

One of the main advantages of the sCO_2 technology would be the extreme compactness of the turbomachinery, deriving from the elevated fluid density throughout the entire loop of the process.

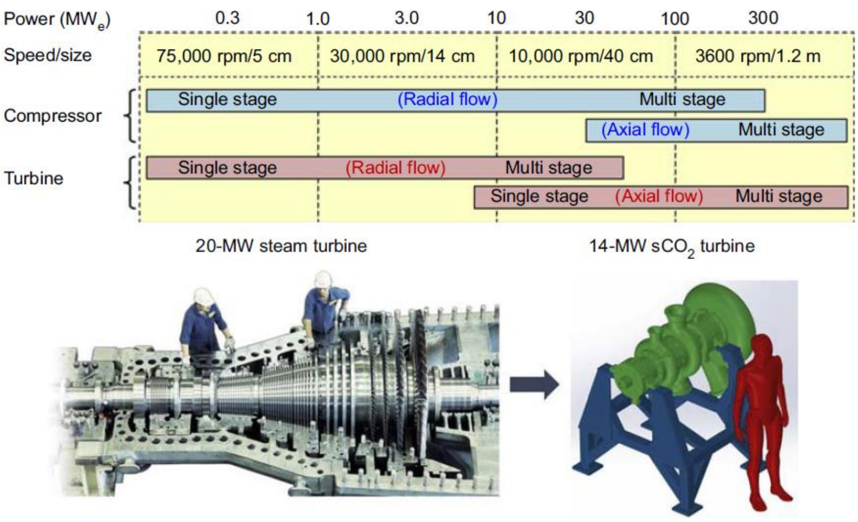


Figure 2 - Size of the sCO2 turbomachinery as a function of power and speed [2].

Supercritical CO_2 plants are gaining more and more interest because they offer consistent advantages and solutions over a wide range of applications and heat sources. Some of these solutions include:

- a substantial increase of the energy conversion process efficiency
- the effective economic feasibility of the implementation of such technology in Concentrated Solar Power (CSP) plants, geothermal plants and emission free fossil fuel plants
- the possibility to create new markets due to the compact turbomachinery, high efficiency and innovative nature of the technology, in fields related to naval propulsion and bulk energy storage
- the possibility of serving a market niche which is still underserved by the current technologies (Waste Heat Recovery (WHR) for small and medium-sized fossil fuel plants, biofuels and bulk energy storage).

The peculiar sCO_2 properties and the features of the related technology (like elevated power density, elevated pressure, low viscosity and the large variation of those properties near the critical region) imply design foresight and arrangements that normally are not contemplated in the standard design procedures for machines and exchangers. Such complications are:

- thermal dilation during transient operation and the resulting mechanical interference
- Temperature limits for seals, gaskets and bearings
- problems due to the condensation of CO_2 near the seals
- corrosion and erosion related to the high power density

1.2 sCO_2 Technology

The sCO_2 power cycles' components are strictly related to the thermodynamic cycle adopted. However, the main components are compressors (or pumps), turbines and heat exchangers.

Turbomachinery

The high density in sCO_2 power cycles results in extreme compactness of the turbomachinery. The extremely low volumetric flow rate allows a 1 MWe power cycle to have a single stage compressor with an impeller diameter of nearly 10 cm. However, CO_2 compressors and pumps have already been commercialised and widely available from several vendors.
Since the compression usually takes place near the critical region, the design of the compressor is simplified by the low temperature of the compression, while the same thing cannot be said for the turbine.
Turbine design is the most delicate phase in the entire plant design. Most of the risk comes from the lack of experience as only few vendors have actually designed, tested and built sCO_2 turbines. However, there are also technical difficulties not directly related to the lack of experience: the ultra-high power density (comparable, as often said, to that in a rocket engine), the high temperatures and pressures all contribute to make the turbine design one of the hardest challenges for the current turbomachinery state of art. This is of particular interest since every two points of efficiency increase in the turbine results approximately in a one-point increase in cycle efficiency, while the impact of compressor efficiency is half that [2].
Axial machines generally perform better at lower head and higher volume flow rates than radial machinery. Hence, axial turbomachines are more adequate to operate high power cycles, even though maintaining high efficiencies over a wide off-design flow range tends to favour radial compressors over axial compressors.

Heat Exchangers

Heat exchangers are among the most crucial components in a sCO_2 power cycle plant, because of their size and cost. Heat exchangers can be divided into three groups:

- primary heat exchangers - defined as the exchangers that provide heat to the working fluid from the primary source.
- recuperators - defined as internal heat exchangers (CO_2-CO_2) whose purpose is to heat up the working fluid with some of the residual heat of the working fluid after the expansion.
- chillers or precoolers - whose purpose is to reject heat from the working fluid to the environment to complete the cycle and bring the fluid to its initial state.

Usually the heat exchangers account for a large portion of the capital costs of the plant.
Therefore, the size and cost of the heat exchangers is a key factor when evaluating the economic feasibility of a sCO_2 power cycle. The high cost associated to the heat exchangers is mainly related to the high thermal duty and the challenging working conditions (that require high temperatures, high pressures, or both). The design of the exchangers aims to find the optimal trade-off between performances and costs.

1.3 sCO_2 APPLICATIONS

The sCO_2 technology can be implemented in a wide range of applications such as industrial WHR, CSP plants, fossil fuel plants, nuclear and geothermal plants.

Waste Heat Recovery

The market for the systems that are capable of recovering the heat from industrial waste gas is extremely large and includes all the biggest process industries such as the iron and steel, the glass industry, the chemical & pharmaceutical industry, the petrochemical industry, the aluminium and nonferrous metals industry, the textile industry, the cement industry, the food and beverage industry and the paper industry.
A worldwide waste heat potential of 14.6 GWth has been estimated [3], half of which is available above the temperature of 232°C. The current amount of waste recuperated is only a small fraction (766 MW) compared to the whole potential market.

Concentrated Solar Power

Concentrated Solar Power systems are energy conversion systems based on the use of lens and reflective surfaces in order to concentrate sunlight on the surface of a small sized receiver. In this case, a double advantage is achieved: firstly, in terms of efficiency because the convective and radiative losses are proportional to the receiver surface and secondly because the plant cost is also proportional to the receiver surface. It must be noted, however, that the main portion of the expenditure would then be represented by the reflective equipment.
Studies have shown [4] the need for energy conversion systems that would guarantee efficiencies greater than 50% in order for the plant to generate electric power at a LCOE (levelized cost of electricity) of 0.06$/kWhe. This requirement makes the sCO_2 technology a perfectly eligible candidate since similar efficiencies could be achieved with the use of the Brayton recompressed cycle.

Natural gas power plants

A first implementation of the sCO_2 technology with fossil fuels can be represented by medium-sized plants (150MWe) that would operate at efficiencies close to 50% with turbine inlet temperatures of about 700-750°C [5].
Another interesting application for the sCO_2 technology with fossil fuel combustion is the oxy-combustion. The process consists in the adoption of pure oxygen as oxidising gas, which is then compressed with the fuel at 30 MPa and the resulting

mixture is ignited. The oxygen separation allows to avoid the presence of nitrogen in the oxidising gas, that otherwise would be air, thus preventing any NOx formation in oxy-combustion processes, whose primary products are just CO_2 and H_2O.
In the direct version of the oxy-combustion the combustion products are directly injected into the working fluid in order to raise its temperature. The ratio between the mass flow rates of combustion gases and sCO_2 is around 1:20. This allows to heat the working fluid mixture (which is 97.5% CO_2 and 2.5% H_2O) up to 1100-1200°C without the use of a heat exchanger. It is therefore possible, with this kind of process, to obtain efficiencies greater than 60%. The indirect version of the oxy-combustion process features lower combustion temperatures (800-1000°C) and pressures (10-12 MPa). Combustion gases are not directly injected in the plant loop as it was for the direct process, but they are conveyed into a heat exchanger.

Nuclear Plants

One of the main reasons that justify the constantly rising interest towards sCO_2 technology is its particular fitness for nuclear applications. The MIT investigated the implementation of the technology in the new IV Generation reactors [6].

Bulk Energy Storage and Geothermal

Bulk quantities of thermal energy can be stored as hot water and ice, to produce dispatchable electric power with the use of sCO_2 technology. These plants can produce between 50 and 100 MWe for as long as 6 hours. sCO_2 heat pump cycles can be used for charging and Rankine cycles for discharging [7]. It is thought that for the previously mentioned plant size, efficiencies of about 55-60% can be achieved.

Despite the lower efficiency, if compared to hydroelectric or battery storage (about 70%), the sCO_2 system would not suffer from lack of eligible locations as hydroelectric does or not even from considerable costs or from a limit number of discharges as battery do. sCO_2 can also serve dry geothermal sites. In order to absorb the heat from a dry geo-thermal heat plume, cold sCO_2 must be injected into a specific several kilometres long well. The injected sCO_2 gets heated up at the bottom of the well, its density decreases and therefore natural circulation drives the upward flow to the surface. Once the sCO_2 is extracted from the well, it can be expanded through a turbine until it reaches 7.5-8 MPa.

2 The Business Case

In this chapter the business case will be introduced, and different cycles and plant layouts will be compared in order to proceed with the economic analysis.

The ultimate goal of the business case is to investigate the possibility to build a sCO_2 closed-loop waste heat recovery system and its economic and technical feasibility. The candidate for the specific business case is a company whose production is dedicated to cast iron cookware; their facilities carry out processes such as casting, sand preparation, melting, sandblasting/grinding and enamel coating. The opportunity to recover waste heat lies in the enamel coating process, which generates several different flues. The dedicated ovens work at a temperature of about 800°C, therefore the temperature of the off-gases leaving the process is between 400 and 650°C.

Despite the continuous operation of the kilns, the flue temperatures are subjected to large fluctuations: the average temperature is at about 550°C with a 80°C standard deviation among the different measurements.

The enamel process

Industrial porcelain enamel is the use of vitreous enamel for industrial applications. The enamel consists of a thin layer of ceramic or glass applied to a substrate of metal (cast iron, for the specific business case) in order to protect surfaces from chemical attack and physical damage and improve the appearance of the cookware.

The facility taken into consideration operates 4000 hours per year, 16 hours per day. The electricity consumption for the induction furnace is estimated to be around 4 000 000 kWh per year and the gas consumption for the enamel kilns amounts for the equivalent of 10 000 000 kWh per year.

The waste heat potential

An average temperature of 550°C relative to the flue gases generated from the two kilns was assumed based on the provided measurements within 2 hours of operation. The following flow rates have been provided for the two kilns:

$$Q_1 = 6443\, m^3/h \approx 1.79 m^3/s$$
$$Q_2 = 6002\, m^3/h \approx 1.66 m^3/s$$

As the temperature and pressure at the tip of the flue were known, it was possible to estimate the density of the fluid:

$$\rho_1(230°C; 950\, hPa; 5.30\% hum.) \approx 0.6347 kg/m^3$$

$$\rho_2(234°C; 950\, hPa; 5.50\% hum.) \approx 0.6263 kg/m^3$$

At this point it was possible to calculate the respective mass flow rates:

$$\dot{m}_1 = \rho_1 Q_1 \approx 1.136 kg/s$$

$$\dot{m}_2 = \rho_2 Q_2 \approx 1.040 kg/s$$

The specific heat was roughly assumed as the average between its values at 550°C and ambient temperature:

$$\overline{cp_1} = \overline{cp_2} \approx 1.0545\ kJ/kg\ K$$

Thus, it was possible to estimate the waste heat potential from the two sources:

$$P_1 = \dot{m}_1 \overline{cp_1}\,(T_{550℃} - T_{amb}) \approx 629kW$$

$$P_2 = \dot{m}_2 \overline{cp_2}\,(T_{550℃} - T_{amb}) \approx 611kW$$

Therefore, the total waste heat potential of the two kilns amounts to slightly less than 1.25MW$_{th}$.

Cycle arrangement

Initially both simple recuperated Brayton cycle and recompressed Brayton cycle layouts and their relative performances have been evaluated, but eventually only the simple recuperated configurations have been taken in consideration due to the following reasons. A study found in literature [8] suggests that the simple recuperated Brayton cycle grants the shortest payback period and the lowest capital costs. Furthermore, the simplicity of the layout and the presence of a single compressor makes control and regulation of the system, therefore avoiding problems of stability associated to the interactions of more compressors as reported in literature [9]. And lastly, simple recuperated Brayton cycles, with constant maximum temperature and pressure, allows a broader exploitation of the waste heat as the inlet temperature of the working fluid in the primary heater is lower if compared to the recompressed cycle. Hence cooling down the waste gas to a lower temperature allows to extract more heat from the hot flues. The amount of extracted heat is quantified by the waste heat recovery efficiency:

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

Where $Q_{extracted}$ stands for the effective amount of heat recovered and Q_{WHP} stands for the waste heat potential of the site. In fact, the power output can be expressed as:

$$P = Q_{WHP}\eta_{WHR}\,\eta_{th}$$

where η_{th} stands for the thermodynamic efficiency of the cycle. It must be noted that for a given waste heat potential the best performing layout is the one that maximizes the product between η_{th} and η_{WHR}, which is not necessarily the layout that features the highest thermodynamic efficiency η_{th}. This is due to the fact that the cycle is powered from heat that otherwise would be wasted if not recovered, hence the most important parameter for the plant performance is the power output (related to the product between η_{th} and η_{WHR}) and not the quality of the energy conversion process (expresses as η_{th}). Considering the small size of the plant, the newness of the technology and the mentioned reasons, the simplest thermodynamic cycle with the internal heat recuperation was chosen. Despite its simplicity, the simple recuperated Brayton cycle is one of the most investigated cycles for WHR applications in literature as the low capital costs associated allow it to be economically competitive towards more sophisticated plant layouts [10].

2.1 Profitability Assessment

Fifteen different cycles have been investigated, each different for maximum pressure, mass flow rate and turbomachinery isentropic efficiencies.

The profitability of each cycle has been assessed through the evaluation of economic performance indicators such as NPV, IRR, PBP and LCOE.

A sensitivity analysis has been carried on the three best performing cycles, chosen according to the following criteria: highest NPV configuration, lowest capital cost configuration and shortest PBP configuration.

The overall capital costs have been computed with the following relation:

$$C_{OC} = \left(C_{comp} + C_{turb} + C_{gen} + \sum_{i=1}^{3} C_{HE_i} \right)(1 + C_{ia})$$

Where the costs associated to every piece of equipment (compressor, turbine, generator, and heat exchangers respectively) are added together and increased by a Cis factor accounting for the installation and the auxiliary equipment costs. The mentioned costs have been investigated with relations found in literature.

The cost of the compressor can be expressed as:

$$C_{comp} = \frac{71.1\dot{m}}{0.9 - \eta_{cis}} \beta_c \ln \beta_c \ [\$]$$

where $\dot{m}$, η_{tis}, β_c are the mass flow rate, the isentropic efficiency, and the pressure ratio, respectively. In the same fashion, the cost of the turbine can be estimated with the following relation:

$$C_{turb} = \frac{479.34\dot{m}}{0.92 - \eta_{tis}} \beta_e (1 + e^{(0.036T_{IT} - 54.4)}) [\$]$$

where $\dot{m}$, η_{tis}, β_e and T_{IT} are the mass flow rate, the isentropic efficiency, the pressure ratio and the turbine inlet temperature (expressed in Celsius degree) respectively. The capital cost for the electric generator can be expresses [11] as a function of its electrical power output Pe (expressed in kW):

$$C_{gen} = 60P_e^{0.95}$$

For the estimation of the capital cost associated to the exchangers, a method that was used did not require the detailed design of the exchangers (and relative computation of the overall heat transfer coefficient U) but only the overall product between U and the exchange surface area A. For every type of exchanger, it was assumed a different cost coefficient γ, defined in the following way:

$$\gamma = \frac{C_{HE}}{UA} \text{ where } UA = \frac{Q}{\Delta T_{LM}}$$

where C_{HE} is the cost of the exchanger and γ is the cost of the exchanger per unit of the product UA (expressed in $/(kW/°C)). The values of γ for every heat exchanger have been quantified accordingly to literature [10]. In order to estimate the cash flow associated to the operation of the plant yearly operating costs and revenues had to be estimated. Previous studies found in literature have already quantified operating costs with the following relation [8]:

$$C_{OM_K} = P_e[c_{OM}(1 + er)^k] \ [\$]$$

Where C_{OM_K} are the yearly operating costs relative to the year k expressed as a function of the installed electric power P_e . C_{OM} are the operating costs for unit of electric power installed (expressed in $/kWe) and er is the escalation rate of these costs through the years, due to the degradation of the equipment and the increasing influence of the maintenance over the years.

Considering the small size of the system (~200kW of net power output) and the relative large size of the industrial facility (4x10^6 kWh of electricity consumption per year, only considering the EAF) it is more appropriated because the internal demand is large enough to absorb all the power generated and the auto-consumption allows to avoid tax expenses as no net profit is associated with the operation of the WHR system. The exclusion of taxes allows a general improvement of the economic performance of the system and its profitability.

Positive cash flows relative to the revenue of the year k can be quantified in the following way [8]:

$$R_k = P_e[t_h c_e 91 - dr)^k] \ \ [\$]$$

where t_h are the yearly hours of steady operation of the system, c_e the cost of the electricity expressed as $/kWh and dr the degradation rate of the plant.

Hence, assuming a 20 year lifespan, the cash flow of the investment of the business case related to the year k can be expressed as:

$$CF_0 = -C_{oc} for\ k = 0$$

$$CF_k = R_k - C_{OM_k} for\ 1 \leq k \leq 19$$

$$CF_{20} = R_{20} - C_{OM_{20}} + SR\ for\ k = 20$$

Where SR is the salvage revenue of the plant after 20 years.

The value of the main economic parameters that define the cash flow of the plant have been chosen accordingly to the following table (1):

Parameter	Value
i [%]	5.00
c_{OM}[$/kWe]	30.00
C_{ia}[%]	30.00
er[%]	3.00
dr[%]	1.00
c_e[c$/kWh]	8.00
$\tau_h[years]$	20
$t_h[hours/year]$	4000
SR/C_{OC}[%]	96.00
i_r[%]	5.00
i_r[%]	2.00
Capital costs uncertainty [%]	+50%/-30%
Operating costs uncertainty [%]	+10%/-10%

Table 1 - Economic parameters considered and their relative assumed values

Where i is the discount rate, τ is the lifespan of the plant, n_g is the efficiency of the generator and i_r is the inflation rate used for the computation of the LCOE. The other parameters have already been presented.

Results

The results of the analysis are presented in the following table (2):

Plant	NPV [$]	IRR [%]	PBP [years]	LCOE [c$/kWh]
D1	234706	11.96	7.20	3.2070
D2	325352	18.73	4.97	2.4996
D3	331862	21.12	4.46	2.3350
D4	318687	21.69	4.36	2.3003
D5	299349	21.59	4.38	2.3066
H1	246696	11.59	7.37	3.2613
H2	355676	18.90	4.93	2.4873
H3	362999	21.47	4.40	2.3139
H4	343231	21.57	4.38	2.3073
H5	327514	22.29	4.25	2.2651
N1	244394	11.01	7.66	3.3498
N2	366538	18.44	5.04	2.5218
N3	375910	21.19	4.45	2.3310
N4	361547	22.12	4.28	2.2754
N5	337629	22.13	4.27	2.2748

Table 2 - Results of the economic analysis of the 15 definitive plant configurations

The NPV of the investigated configurations over the span of 20 years is quite different and ranges from 234 706 $ (configuration D1) to 375 910 $ (configurations N3). Between the three groups investigated and sorted by maximum pressure (D, H and N with 25, 30 and 35 MPa respectively) the configuration with the highest NPV is always the third (D3, H3 and N3 respectively). The third configuration usually represents an acceptable trade-off between capital costs and cycle performance. As previously explained, the first cycles (D1, H1 and N1) are the ones that imply larger capital costs and thus better performances, while the fifth cycles (D5, H5 and N5) feature the lowest capital costs and lower performances. From the obtained results, it is legitimate to assume that lower capital costs are to be preferred over higher performances to a certain degree, as fifth cycles guarantee higher profitability than first cycles. However, it must be noted that the gap between the different configurations in terms of capital costs is due to the cost of the purchase of turbomachinery, as the cost of the exchangers does not vary significantly.

The IRR of the investment is strictly related to the NPV by definition: all the considerations made for the results of the NPS can be extended to the results of the IRR of the investment. However, their trends do not overlap as the IRR seem to raise as the capital costs decrease: the relative curve does not have a well-defined maximum point as the one related to the NPV. Therefore, it appears that the main factor influencing the IRR of the investment is the starting expenditure, while the efficiency of the plant is not as relevant as it could be for the NPV.

Payback Period and Levelised Cost of Electricity are strictly related to each other and share the same trend. How the capital costs are spread and absorbed over the entire lifespan of the plant is the main factor determining both PBP and LCOE.

The LCOE ranges from 2.2748 (N5) to 3.2070 c$/kWh (D1), and the general trend is defined: the LCOE tends to decrease as the maximum pressure of the cycle increases and as the capital costs decrease. The estimated PBPs span from 7.66 (N1) to 4.25 years (H5) with the same trend as the LCOE.

When evaluating the profitability of a WHR system, it is important to keep in mind that the power generation is perceived more as an opportunity to offset some of the operating costs than as a profit opportunity, since power generation does not represent the core business of the company. Companies are usually prone to invest larger sums in their core business rather than in other kind of investments. In light of this, one of the most considered factors is the risk associated to the investment, together with the following factors:

- PBP – or, in other terms, how quick is the investment to generate a positive cash position
- Capital Costs – or, in other terms, the initial amount that the investor is willing to risk on the project

Therefore, all the projects with long PBPs (longer than 5 years) should be avoided as they are not likely to convince investors to risk their capital in investments that cannot guarantee returns on the short run. Studies found in literature [8] with similar analysis methods found a PBP of approximately 2 years for a similar plant: the gap between the PBP found in this analysis (~4 years) and the one just mentioned is due to the fact that for the latter it was assumed a yearly activity of 7450 hours, instead of 4000 hours. Doubling the operating hours per year allows to double the cash flows and therefore to halve the PBP. Therefore, despite producing a different outcome, the analysis of the business case leads to results in accordance with the current literature.

The three best-performing cycles are selected on the following criteria:

- Highest NPV – N3 is the configuration that generated the highest value over the lifespan of the plant
- Lowest capital costs – D5 is the configuration that resulted in the lowest starting expenditure
- Shortest PBP – H5 is the quickest configuration to generate a positive return

The mentioned three plant configurations and their economic performance are illustrated in figures 1, 10, 18.

A sensitivity analysis has been conducted to assess the economic performance of the three best-performing configurations as the following parameters change:

- Operating hours per year (t_h) – higher utilization of the plant allows to recover the capital costs in a shorter time and to generate higher profits over the lifespan of the plant
- Life of the plant (τ) – a longer life of the plant leads to a better absorption of the capital costs and to higher profitability
- Cost of electricity (c_e) - the higher the cost of electricity purchased by the industrial facility, the higher are the savings generated from the internal power generation. As a reference, the cost of electricity in Turkey for industry [6} ranges from 51.3217 to 57.7638 TRYcent/kWh (respectively for medium and low voltage) or from 0.084 to 0.094 $ as of February 2020

- Uncertainty of the estimated costs – the newness of the technology implies large uncertainty when estimating capital and operating costs, especially for the purchase of the turbine, the heater and the recuperator. The sensitivity analysis shows how the profitability of the investment changes as costs change under a certain degree of uncertainty

The influence of every parameter is evaluated individually, with the other parameters being equal to the value declared in table 1.
The results of the sensitivity analysis are illustrated on pages 8, 10 and 12. A brief summary of the influence of the mentioned parameters is provided.

The operating hours per year heavily influence the slope of the cumulative cash flow curve: the higher the number of working hours per year, the steeper is the curve. NPV and IRR increase linearly with the number of operating hours. The revenue increase allows to shorten the PBP and improves the cash position at the end of the life of the plant. The LCOE drops significantly as the operating hours increase because the capital costs are spread over a larger amount of kWh generated in the lifespan of the plant.

The life of the plant determines the amount of savings implied to the construction of the WHR system and therefore has a significant impact on the revenue. NPV and IRR increase linearly with the cost of electricity, while the PBP decreases because the slope of the CCF curve rise. The LCOE is not influenced because the market price of the electricity is not related to the LCOE by any means.

Lastly, uncertainties on capital and operating costs are considered to show how the economic performance indicators are affected by them. The following uncertainties are assumed:

- For the capital costs the assumed uncertainty is +50%/-30%
- For the operating costs the assumed uncertainty is +15%/-15%

And in relation to those three main cases defined:

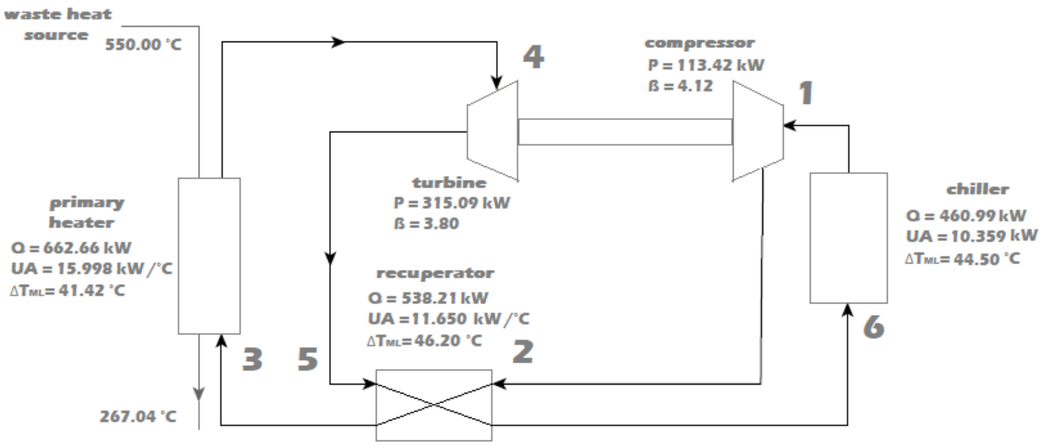
- The best case, defined as the case with the lowest capital costs and operating costs

- The expected case; defined as the case with the expected capital costs and operating costs

- The worst case, defined as the case with the highest capital costs and operating costs

The results of the uncertainty analysis are exposed in figures 1, 10 and 18.

2.1.1 Simple Recuperated Brayton Cycle – N3 Layout



N3	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
1	37,000	8,5000	504,09	334,79	1,4344	18,061
2	101,24	35,000	710,77	386,34	1,4621	1,9284
3	247,04	34,300	372,82	630,96	2,0221	1,4251
4	475,56	33,614	224,97	932,14	2,5075	1,2737
5	333,26	8,8504	78,514	788,93	2,5500	1,1480
6	122,27	8,6730	139,16	544,31	2,0563	1,2775

Plant parameters

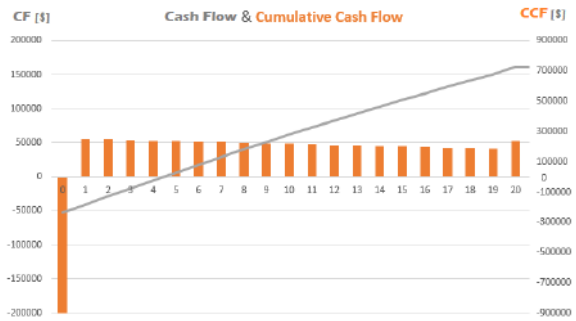
Pmin/Pmax = 8.5/35 MPa

m = 2.2002 kg/s

η = 30.43% ηt = 85.00% ηc = 80.00%

P = 201.67 kW

WHReff = 53.44%



Capital costs

Turbomachinery: 66 731 $

Heat exchangers: 109 487 $

Generator: 8 927 $

BOP: 55 436 $

Total: 240 222 $

Assumptions:

discount rate = 5%

life of the plant = 20 years

cost of electricity = 8.00 c$/kWh

yearly activity = 4000 hours/year

Economic performance indicators
(expected case, best case, worst case)

Indicator	Expected case	Best case	Worst case
NPV	375 910 $	462 303 $	241 473 $
IRR	21.19 %	31.95%	12.49%
PBP	4.45 years	3.03 years	6.93 years
LCOE	2.3310 c$/kWh	1.6249 c$/kWh	3.0272 c$/kWh
cash position	727 881 $	824 060 $	583 657 $

Figure 3 - Simple Recuperated Brayton Cycle N3 Layout

Sensitivity analysis for configuration N3

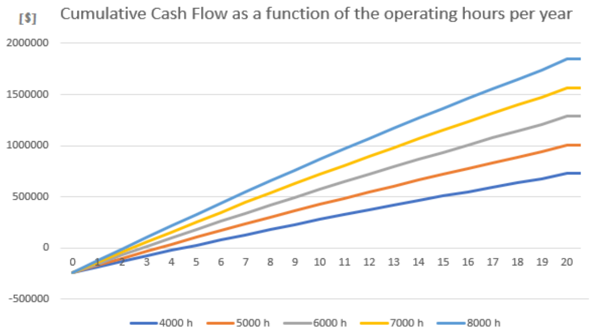


Figure 4 - Cumulative cash flow as function of the operating hours per year

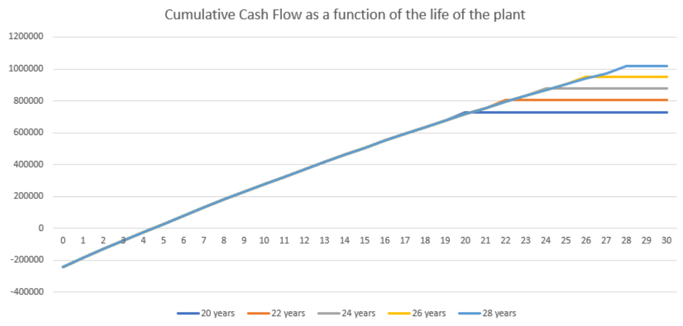


Figure 5 - Cumulative cash flow as a function of the life of the plant

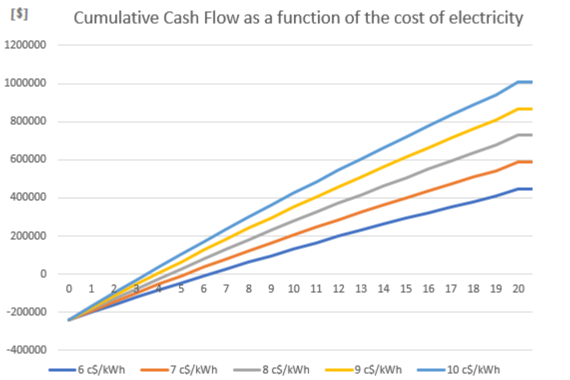


Figure 6 - Cumulative cash flow as a function of the cost of electricity

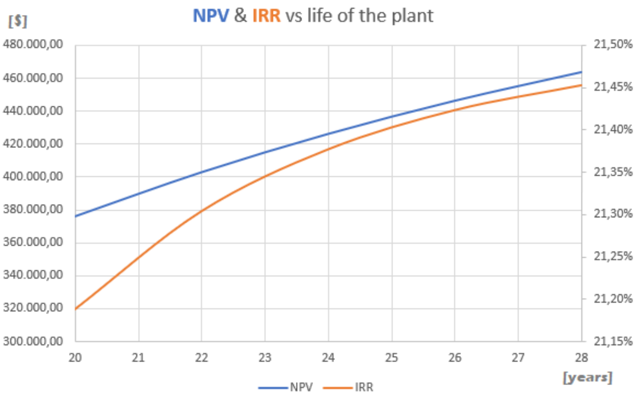


Figure 7 - NPV & IRR vs life of the plant

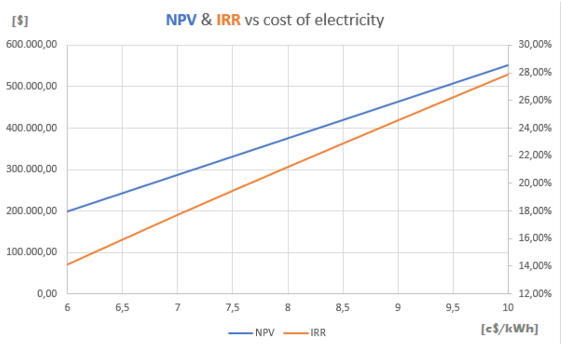


Figure 8 - NPV & IRR vs cost of electricity

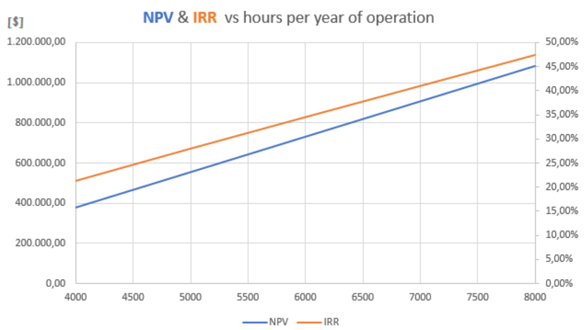


Figure 9 - NPV & IRR vs hours per year of operation

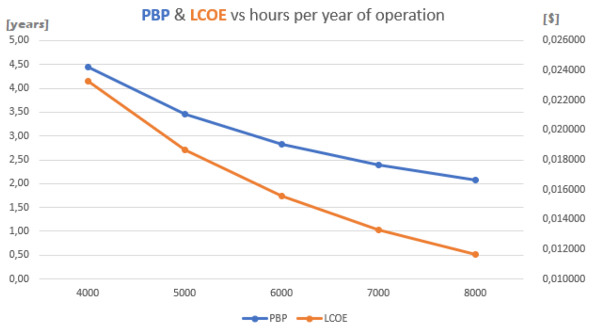
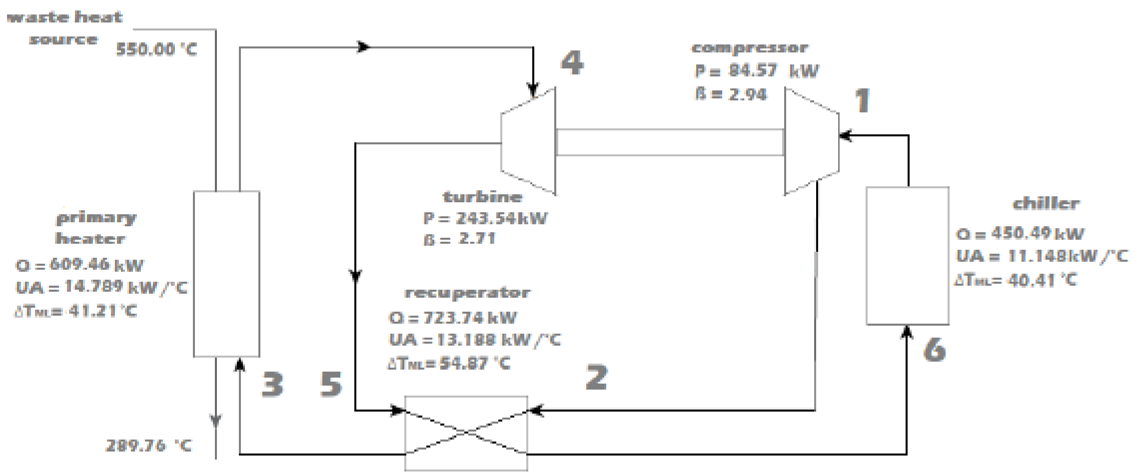


Figure 10 - PBP & LCOE vs hours per year of operation

2.1.2 Simple Recuperated Brayton Cycle – D5 Layout



D5	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
1	37.000	8.5000	504.09	334.79	1.4344	18.061
2	85.020	25.000	660.88	370.91	1.4598	2.2580
3	269.76	24.500	253.76	680.03	2.1740	1.3110
4	476.18	24.010	164.38	940.34	2.5847	1.2439
5	374.38	8.8504	72.871	836.32	2.6256	1.1576
6	109.16	8.6730	148.63	527.20	2.0123	1.3364

Plant parameters

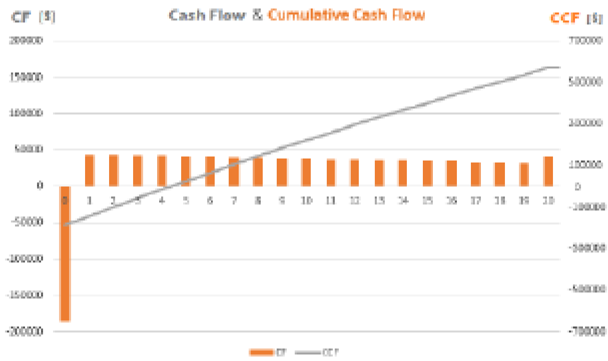
Pmin/Pmax = 8.5/25 MPa

ṁ = 2.3413 kg/s

η = 26.08% η_t = 80.00% η_c = 75.00%

P = 158.97 kW

WHR_{eff} = 49.15%



Capital costs

Turbomachinery: 28 847 $

Heat exchangers: 107 316 $

Generator: 7 121 $

BOP: 42 986 $

Total: 186 270 $

Assumptions:

discount rate = 5%

life of the plant = 20 years

cost of electricity = 8.00 c$/kWh

yearly activity = 4000 hours/year

Economic performance indicators
(expected case, best case, worst case)

	Expected case	Best case	Worst case
NPV	299 349 $	366 523 $	194 921 $
IRR	21.59 %	32.51 %	12.78 %
PBP	4.38 years	2.98 years	6.81 years
LCOE	2.3073 c$/kWh	1.6078 c$/kWh	2.9905 c$/kWh
cash position	576 700 $	651 588 $	464 558 $

Figure 11 - Simple Recuperated Brayton Cycle D5 Layout

Sensitivity analysis for configuration D5

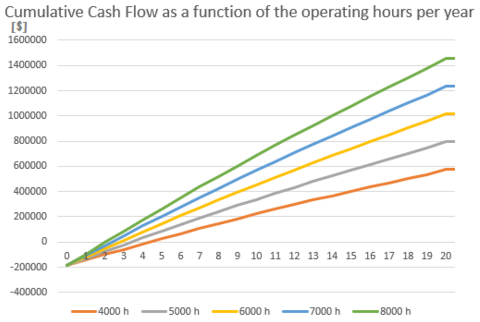


Figure 12 - Cumulative cash flow as function of the operating hours per year

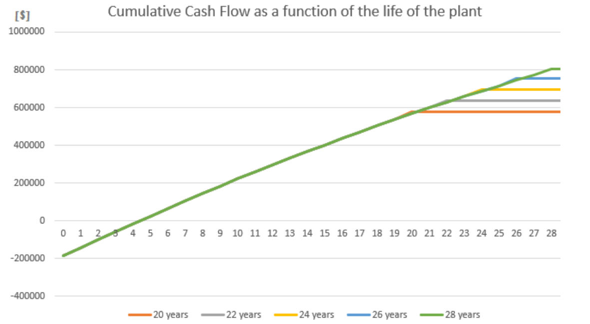


Figure 13 - Cumulative cash flow as a function of the life of the plant

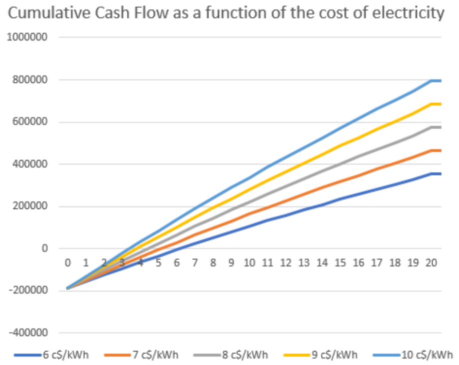


Figure 14 - Cumulative cash flow as a function of the cost of electricity

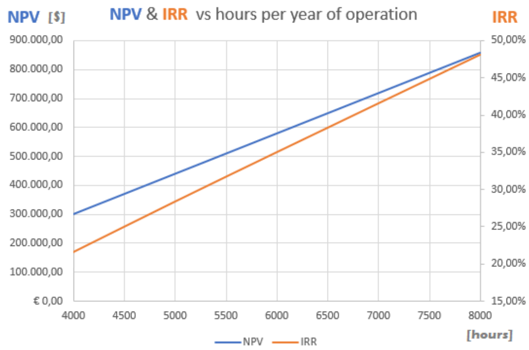


Figure 15 - NPV & IRR vs life of the plant

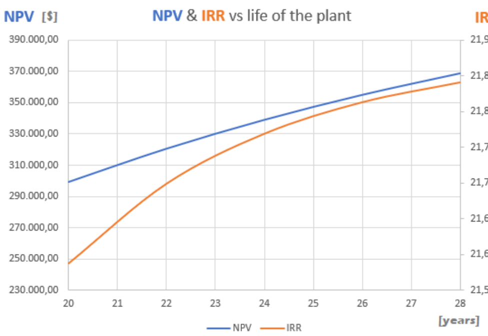


Figure 16 - NPV & IRR vs cost of electricity

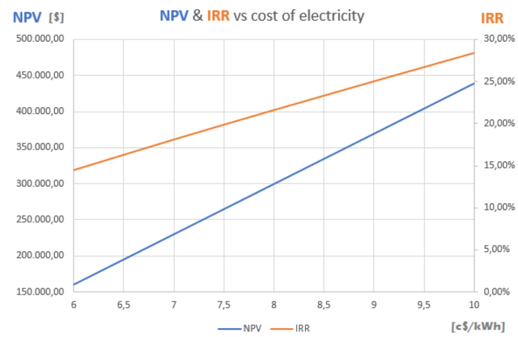


Figure 17 - NPV & IRR vs hours per year of operation

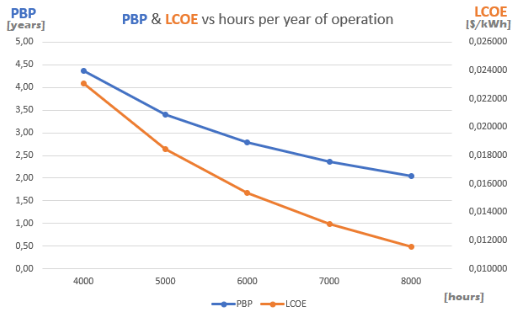
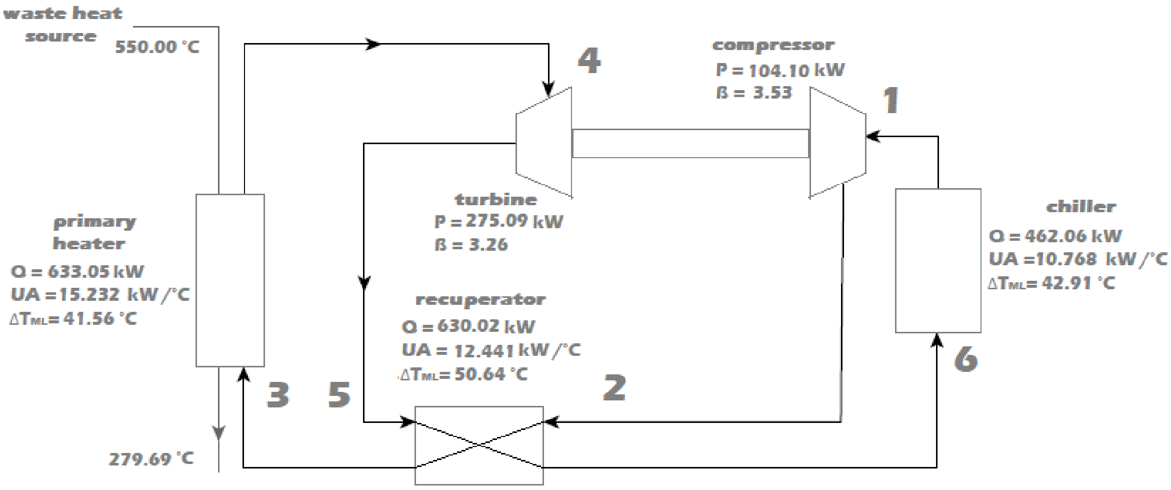


Figure 18 - PBP & LCOE vs hours per year of operation

2.1.3 Simple Recuperated Brayton Cycle – H5 Layout



H5	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)
1	37,000	8,5000	504,09	334,79	1,4344	18,061
2	94,508	30,000	684,43	380,50	1,4657	2,0558
3	259,69	29,400	311,50	657,14	2,0991	1,3673
4	475,14	28,812	195,39	935,11	2,5420	1,2595
5	355,33	8,8504	75,367	814,32	2,5911	1,1529
6	117,12	8,6730	142,66	537,68	2,0394	1,2980

Plant parameters

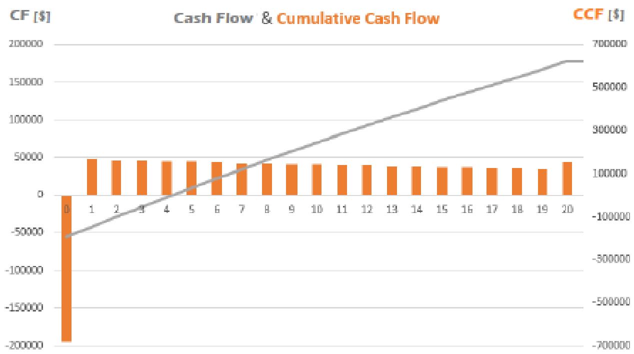
Pmin/Pmax = 8,5/30 MPa

$\dot{m}$ = 2.2774 kg/s

η = 27.14% ηt = 80.00% ηc = 75.00%

P = 170.99 kW

WHReff = 51.05%



Capital costs

Turbomachinery: 34 501 $

Heat exchangers: 107 649 $

Generator: 7 631 $

BOP: 44 935 $

Total: 194 718 $

Assumptions:

discount rate = 5%

life of the plant = 20 years

cost of electricity = 8.00 c$/kWh

yearly activity = 4000 hours/year

Economic performance indicators
(expected case, best case, worst case)

	Expected case	Best case	Worst case
NPV =	327 514 $	398 076 $	218 008 $
IRR =	22.29 %	33.51 %	13.28 %
PBP =	4.25 years	2.90 years	6.61 years
LCOE =	2.2651 c$/kWh	1.5788 c$/kWh	2.9283 c$/kWh
cash position =	625 660 $	704 519 $	507 857 $

Figure 19 - Simple Recuperated Brayton Cycle H5 Layout

Sensitivity analysis for configuration H5

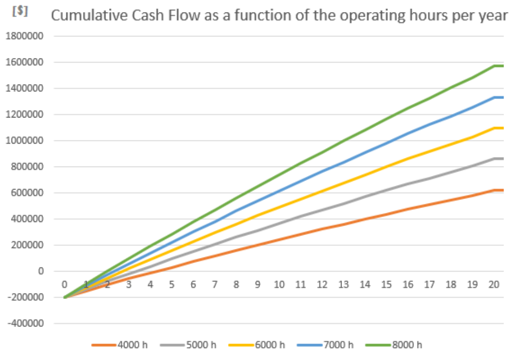


Figure 20 - Cumulative cash flow as function of the operating hours per year

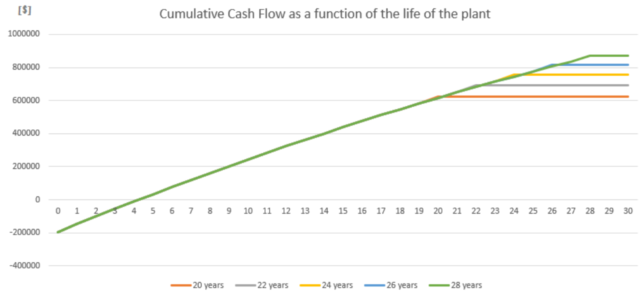


Figure 21 - Cumulative cash flow as a function of the life of the plant

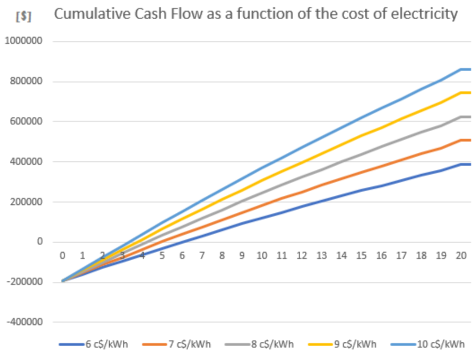


Figure 22 - Cumulative cash flow as a function of the cost of electricity

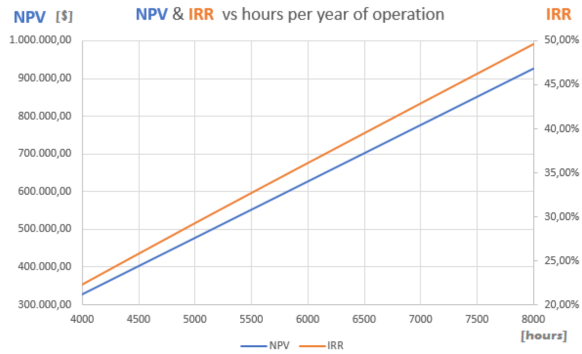


Figure 23 - NPV & IRR vs life of the plant

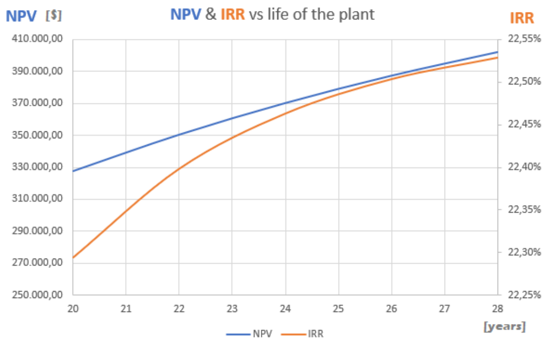


Figure 24 - NPV & IRR vs cost of electricity

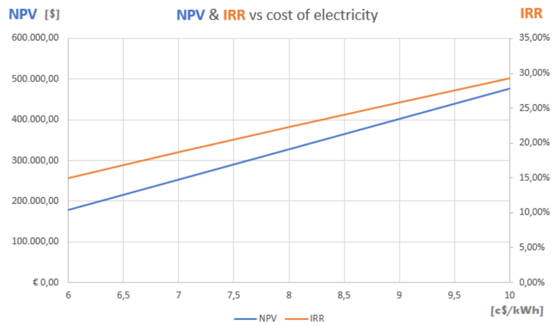


Figure 25 - NPV & IRR vs hours per year of operation

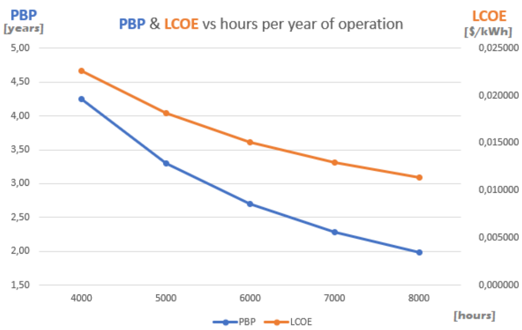


Figure 26 - PBP & LCOE vs hours per year of operation

3 CONCLUSIONS

Fifteen different configurations of a WHR systemin relation to a specific business case have been proposed with the following economic performances:

- NPV between 235 000 and 376 000 $
- IRR ranging from 11 to 22%
- PBP between 4.25 and 7.66 years
- LCOE in the range between 2.26 and 3.35 $cent/kWh.

A sensitivity analysis was carried in order to evaluate the economic performance of the plant when operated with different conditions than those related to the specific business case. The number of operating hours per year proved to be the most influent factor as the following performance has been estimated for a total of 8000 hours/year (doubled if compared to the original business case):

- NPV up to 1 100 000 $
- IRR up to 45.00%
- PBP down to 2 years
- LCOE down to 1.11 $cent/kWh.

As a result, the technology is expected to be profitable. Rate of returns (RoR) in the 8-10% range is usually regarded as desirable for power generation and the greater RoR obtained could compensate for the risk associated with the investment. The final cash position and the NPV of the investment are roughly 3 and 1.5 times the starting expenditure, respectively. The LCOE is surprisingly low, especially if compared to the LCOEs relative to large-scale power generation, due to operation costs not accounting for fuel consumption. Finally, the estimated PBPs are considered short enough for the investment to attract heavy industry companies to make their production more profitable and cost-effective.

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