Supporting document for the CO2OLHEAT technical poster presented during the Supercritical CO_2 Power Cycles Symposium (21 Feb – 24 Feb 2022, San Antonio, Texas, USA)

Authors of the document

Matteo Baggiani (SimeROM), Paolo Bruttini (Baker Hughes), Albannie Cagnac (EDF), Yves De Vos (Bosal), Stefan Glos (Siemens Energy), Renaud Le Pierres (HEATRIC), Giuseppe Messina (ENEA), Giacomo Persico (Politecnico di Milano), Jitka Spolcova (ETN Global), Savvas Tassou (Brunel University London)

Project Consortium

Introduction

CO2OLHEAT will demonstrate in the CEMEX cement manufacturing plant in Prachovice (CZ) the operation of a 2 MW Waste-Heat-to-power (WH2P) skid based on a 2MW-sCO_2 cycle able to efficiently valorise local waste heat at a significant temperature of 400°C. The Project will demonstrate the EU MW scale first-of-a-kind waste heat-sCO_2 plant towards a cheaper/more flexible waste heat valorisation.

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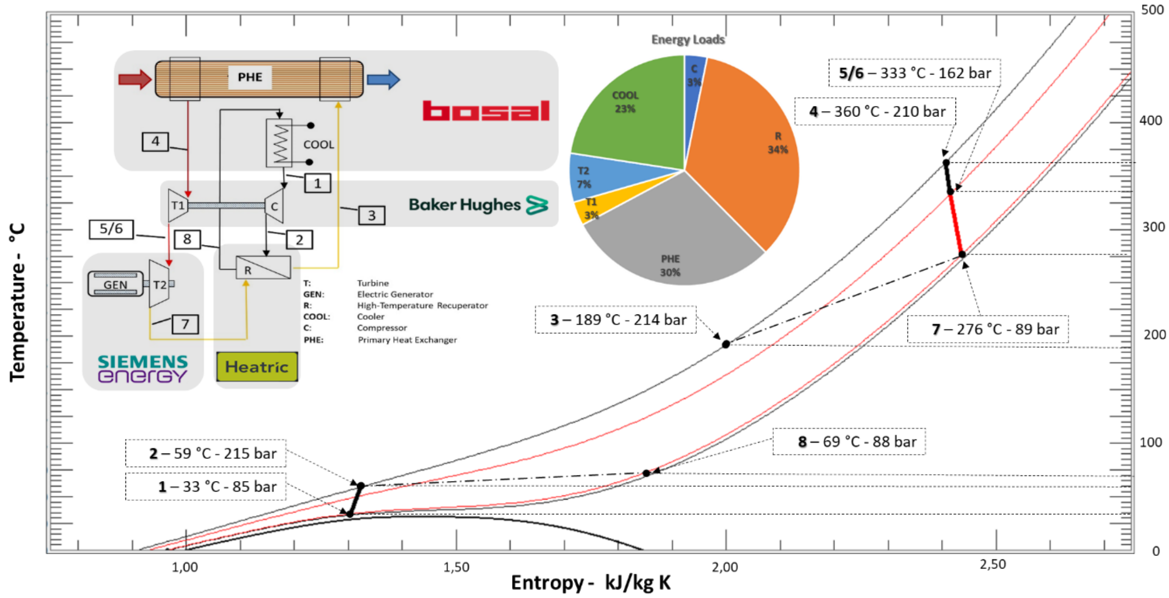

Figure 1 – CO2OLHEAT demo cycle layout, temperature-entropy diagram and pie chart of the main components' energy loads in percent

Regarding the general concept shown in Figure 1, the selection of the final layout took into consideration the following specification and constraints.

Compressor inlet section: 85 bars and 33°C. BH suggested such conditions to avoid significant variations of sCO_2 density close to the nominal inlet point, which would affect the compressor's performance dramatically and, therefore, of the overall system. In addition, these inlet conditions are far enough from the saturation line to preserve the compressor from gas-liquid two-phase flow state at the compressor inlet section. **Maximum temperature of the cycle: 360°C**. Such a temperature was fixed considering an average temperature of the flue gases entering the WHRU of almost 400°C. It was considered a difference of 40°C between the flue gases temperature entering the WHRU and the maximum sCO_2 temperature at the exit of the PHE, guaranteeing a ΔT= 20°C per heat exchanger. **Maximum pressure of the cycle: 215 bar.** All the partners involved agreed in selecting such a pressure for the demo cycle since it represents a good compromise among all the requirements and constraints of the key cycle components. **Machinery nominal efficiency: compressor 0.75; turbine of the turboexpander 0.84; power turbine 0.82.** Such values were given by the OEMs (BH and SIE). These preliminary estimated values will be refined during the further design of the machines and systems in the cycle. **Mechanical efficiency of turboexpander and power turbine: 0.95. Recuperator pinch point temperature difference: 10°C.** Such a value was set according to suggestions from Heatric, to maximise the cycle internal recovery and, consequently, the cycle efficiency. **Recuperator pressure drops: 1 bar for each side** (low-pressure and high-pressure side). These are preliminary values that will be updated iteratively during the recuperator design process. **PHE pressure drops: sCO_2 side 3.5 bar.** This is an initial value taken according to BOSAL information for the PHE pre-design. It will be updated iteratively during the recuperator design process. **Cooler pressure drops: sCO_2 side 3.0 bar.** This is a preliminary value taken according to BOSAL information for the cooler pre-design. It will be updated iteratively during the recuperator design process. **Output power: 2.2 MW with 43 kg/s**

nominal mass flow rate. As reported in the Grant Agreement with the European Commission, the minimum demo plant design electric power is 2 MW. Therefore, since there are many uncertainties in the evaluation of nominal losses for each machine/equipment in the preliminary cycle set-up and some sub-systems (e.g. auxiliaries) are not considered yet, the expected output power value was increased (+10%). The thermodynamic properties of the sCO_2 were taken from the database Refprop v10.

2. sCO_2 turboexpander unit

Baker Hughes is developing the turboexpander, consisting in a compressor driven by an electric motor through a gearbox and by an expander that provides the power to balance the compressor power plus the mechanical losses. This design development is leveraging on previous or ongoing projects on the turbomachinery working in plant that use CO2 in supercritical conditions as working fluid. These projects are **STEP**, funded by **DOE**, **sCO_2-Flex** and **SOLARsCO2OL** funded through EU **Horizon 2020**.

Based on these previous R&D experiences, and especially the one on the sCO_2-Flex project, where a 5.6 MW centrifugal compressor was designed, manufactured and fully tested at both design and off-design conditions, the inlet conditions of the CO2OLHEAT compressor has been set at **85 bar and 33°C**. This thermodynamic point allows to stay very close to the supercritical point bringing all the benefits coming from these conditions (reduced compressor absorbed power and reduced compressor footprint due to the high density of the fluid) and at the same time, guaranteeing stable compressor operation. On this last point it's important to highlight that the variations of the density due to the variation of temperature at the inlet of the compressor increase dramatically moving on the right of the p-T diagram bringing criticality on the stability and operability of the compressor and so of the overall plant. For this reason, is important to maintain a very limited range of variation of the temperature at the inlet of the compressor and so at the outlet of the cooler.

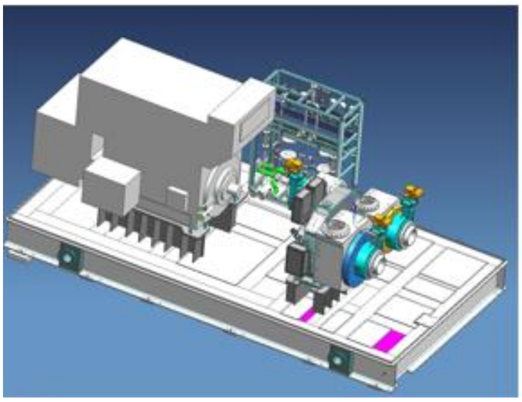

Figure 2 – Preliminary concept of the Turboexpander shaft line

The turboexpander will be defined as an **integrated machine** with a two-stage compressor and a two-stage expander. An electric motor, coupled with the turbomachinery through a gearbox on the same shaft line, has also been considered. This electric motor has two main scopes; the first one is to act as starter of the turboexpander and so of the CO2OLHEAT plant; the second one is to act as a helper during the operations keeping compressor and expander at constant speed. For this second scope the variations of load, temperatures, etc in the loop will be handle with the Inlet Guid Vane and a defined control strategy of this helper motor. The design of the turbo-expander has completed the conceptual phase, and this has been performed in compliance with the design best practices and development process of the Baker Hughes turbomachinery. The preliminary aerodynamic and mechanical design have been performed as well a preliminary rotordynamic and manufacturability assessment has been completed. The performance maps have been issued together to a preliminary analysis on the off-design conditions. The turboexpander concept has been carried out considering CAPEX optimization and the overall footprint minimization.

The turboexpander design seeing a lot of **challenges** to address that asking for leverage on deep expertise and backgrounds on this turbomachinery operating with CO2 and that must be carried to the edge of the technology to manage the critical conditions of the fluid at the inlet of the compressor (very high density) and the high values of pressure coupled with the high temperature at the inlet of the expander.

Here below are reported the main challenges that will be addressed within the WP2. For the ones pertaining to the aerodynamic design, these will be carried out with the scientific support of Politecnico di Milano:

- Definition of a dedicated Computational Fluid Dynamic (CFD) model of the compressor **capable** to take into consideration both the non-ideal thermodynamics of the supercritical fluid as well as local phase change phenomena occurring in the intake region of the compressor, which could have an impact on the performance and on the rangeability of the machine. This activity is in progress in collaboration with Politecnico di Milano.
- Set-up of a shape-optimization procedure, tailored for sCO_2 compressor aerodynamic design, developed by Politecnico di Milano and targeted for the increase of performance and rangeability of the compressor, by minimizing phase-change effects.
- High-fidelity analysis of the compressor and expander aero-thermodynamics, and evaluation of the turbomachinery maps. This activity will be performed in collaboration with Politecnico di Milano.
- Turbomachinery mechanical design and manufacturability process optimized to manage the **small dimensions** that could affect the performance.
- Turboexpander **operability & controllability** in all the operating conditions (transients included).
- Thermo-mechanical design of the expander to guarantee to deal with the defined boundary conditions at the inlet that are **360°C, 210.5 bar**.

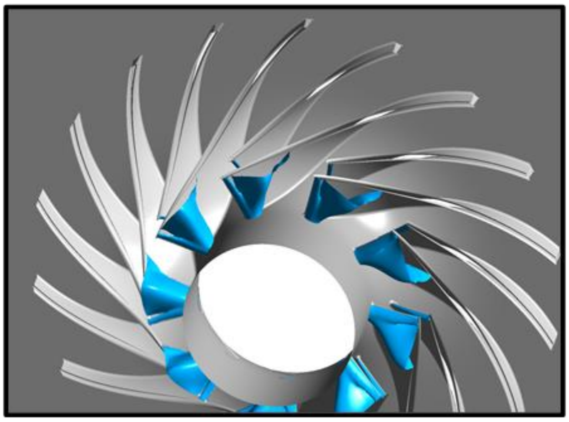

Figure 3 – CFD model results showing the area with vapour formation on the first impeller of the compressor

Once the design of the turboexpander will be finalized, the extension of the CO2OLHEAT concept and technology to full scale applications (e.g., for a cycle with power capacity higher than 5MW) in relevant environments will be investigated. This analysis will be devoted to evaluating the aerodynamic, structural, and technologic implications of upscaling.

Finally, within the turboexpander development and in collaboration with the University of Duisburg-Essen, will be performed an activity oriented to improve an existing industrial CFD code for numerical simulation at conditions close to the critical point or pseudo critical line considering real gas properties.

3. sCO_2 turbine

Within the framework of a previous R&D project (CARBOSALA project funded by the German Federal Ministry of Economics (BMWI)) three alternative concepts for an sCO_2 turbine were investigated by **SIEMENS-Energy** with regards to manufacturing and assembly aspects, rotordynamic and mechanical criteria, costs and scalability. In general, barrel-type turbines exhibit lower radial deformations and are therefore particularly suitable for high-pressure applications. However, production and assembly are comparatively complex. In this respect, turbines with a horizontal parting line are more favourable, but they react less favourably to high pressure differences.

The evaluation results in the barrel type concept being the most favourable design, i.e. a single-flow, double-shell design with inner and outer casing. The outer casing is of the barrel type with a circumferential split which allows rotational-symmetrical design without local material build up even for high gas temperatures and pressures thus minimizing unsymmetrical deformation and thermal loading. Since the inlet temperature of the CO2OLHEAT project is relatively low this design is assumed to be conservative and provides potential for further cost optimization or supports the use in other replication cases.

Based on the initial CO2OLHEAT cycle calculation, carried out in WP 1, a blade-bath design comprising 5 reaction stages was developed whereby the exact degree of reaction has been optimized individually for each individual stage (3DVTM).

Within WP3, **University Duisburg-Essen** is investigating the fluid dynamic within as sCO_2 turbine for flow phenomena that are clearly different from that within conventional steam turbines and which might have a potential beneficial or adverse impact on the design of the turbine. The investigations are carried out with operating parameters and geometry dimensions as expected by Siemens for turbines applied for residual heat utilisation through the Joule cycle operated with carbon dioxide in the supercritical state (sCO_2). The results will be considered during the detailed design phase of WP3.

The selected materials in the sCO_2 turbine are conventional, steel based materials, as usually applied for steam turbines and in compliance with European standards. Due to the moderate temperatures in the CO2OLHEAT project no additional measures or nickel based alloys had to be chosen.

4. Cycle heat exchangers

4.1 Waste heat Recovery Unit, Primary Heat Exchanger and Cooler

Three heat exchangers for the cycle are developed and built by Bosal:

- The Waste Heat Recovery Unit (WHRU) extracts heat from the exhaust flow of the Cemex plant, and indirectly heats the compressed sCO2, upstream of the power turbine's inlet. Indirect heating was chosen, so that the standardised sCO2 skid can operate at a substantial distance from the WHRU. The heat between the skid and the WHRU is transported by pumping hot Heat Transfer Fluid (HTF) from the WHRU to the sCO2 rig.

- The Primary Heart Exchanger (PHE) heats the pressurised sCO2, extracting 10 MW thermal energy from the HTF.
- The Cooler extracts heat from the low pressure side of the sCO2 cycle, upstream of the compressor's inlet.

Both the PHE and the Cooler use the same design, a shell containing the low-pressure fluid (water or HTF), and a tightly packed array of U-tubes containing sCO2. The tubes are arranged in modular cells, with each component containing approximately 20 cells. This allows for a straightforward sizing of these components for the replication sites (aluminium, steel, power plants and waste incineration).

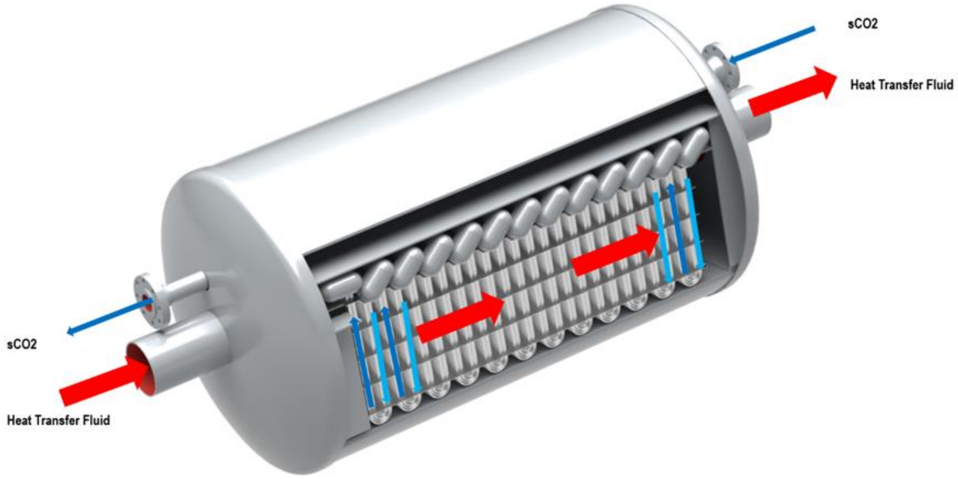

Figure 4 – Primary Heat Exchanger, preliminary design for CO2OLHEAT

The WHRU sits in the exhaust flow of the CEMEX plant, downstream of the Kiln preheater tower and the cyclone gas cleaners. The system contains a bypass, and is designed for handling hot gas with high dust load without clogging risk or substantial fouling.

The stationary, thermodynamic behaviour and performance of the Cooler and the PHE has been modelled, meeting the required performance specifications (pressure drop, exchanged heat, endurance). The assembly process of the cells - the modular building block - has been validated. Cells will be built and tested in 2022, prior to the assembly of the components, scheduled for 2023.

The WHRU gas been designed, and numerically validated. The solution for dust and fouling will be validated by testing in 2022.

4.2 PCHE sCO2 Recuperator

The CO2OLHEAT project is developing and installing a first-of-a-kind supercritical CO2 (sCO2) waste heat recovery (WHR) power conversion cycle in the Cemex industrial Cement plant in Prachovice.

Whilst there are existing power conversion cycles already in use for WHR, such as steam or organic ranking cycle (ORC), sCO2 power conversion cycles are considered as a suitable replacement due to unique benefits packaged with this cycle, which provides a better solution compared to other cycles.

The main benefits associated with the sCO2 cycle are the high-power density-per-volume given the sCO2 properties, which enables high efficiency in a very compact footprint, with associated CAPEX and OPEX savings such as:

CAPEX:

- Lighter / smaller components with reduced transport and structural installation cost
- Easier retrofitting options
- Smaller components with potential savings in material of constructions

OPEX:

- Reduced fuel consumption / higher waste heat conversion
- Reduced water usage depending on locations
- Faster start to optimum operating conditions

However, in order to achieve these benefits, the cycle components such as turbines, compressors and heat exchangers must enable them; by being more efficient in a more compact space envelope.

One of the key area where the sCO2 power cycle greatly influences process efficiency is the recuperator heat exchanger.

The recuperator is an economizer that transfers heat from the exhaust of the sCO2 power turbine, which needs to be cooled prior to compression to the compressed sCO2 that will be heated by the Waste Heat Recovery Unit (WHRU) via the Primary Heat Exchanger.

The use of the recuperator heat exchanger allows for the reduction in size and required performance of the other 3 heat exchangers (WHRU, PHX and Cooler) in the system. It also ensures system efficiency as it uses heat energy that would be removed from the system, most likely to atmosphere, to replace energy that would need to be added to the system by another means, such as burning fuel or using electricity.

This offers the system both reduced capital costs associated with the reduction in hardware requirements and operational benefits due to reduction of parasitic energy requirements.

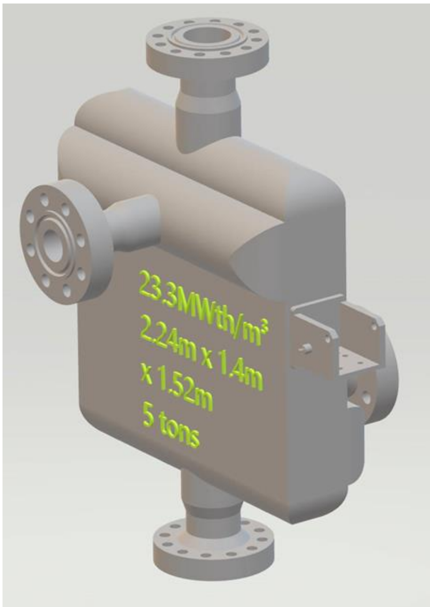

Figure 5 – CO2OLHEAT Preliminary PCHE Recuperator

Printed Circuit Heat Exchanger (PCHE) technology was chosen for the recuperator, due to its track record in other large scale sCO2 test facilities and proven benefits in performance and size reduction, when compared to other heat exchangers technologies such as Shell & Tubes (S&T).

However, given the retrofitting requirement for the Cemex plant and the aim to look into adapting the cycle to many various other industrial plants, such as glass, refinery or remote gas power plants, the aim of this project is to:

- Fully engage with the cycle optimization and provide guidance towards optimization that could influence the design of the recuperator

- Establish a better understanding of the behavior of the sCO2 power conversion cycle and its components interactions with the recuperator
- Define a control methodology for the cycle and the recuperator including operational range limits
- Develop a modular skid base plant to standardize as much as possible in-line with other replication cases
- Gather real world experience of operating the plant and associated learning against hypothesis / modeling

We have already reached a preliminary design for steady state operation of the plant. The next stage is to look into part loads and off-design conditions their impact on the design. This second phase will be supported by the design and manufacture of a representative test mock-up, to be tested by Brunel University to support the development of a control model for the Cemex plant.

5. Dynamic simulation and control optimisation

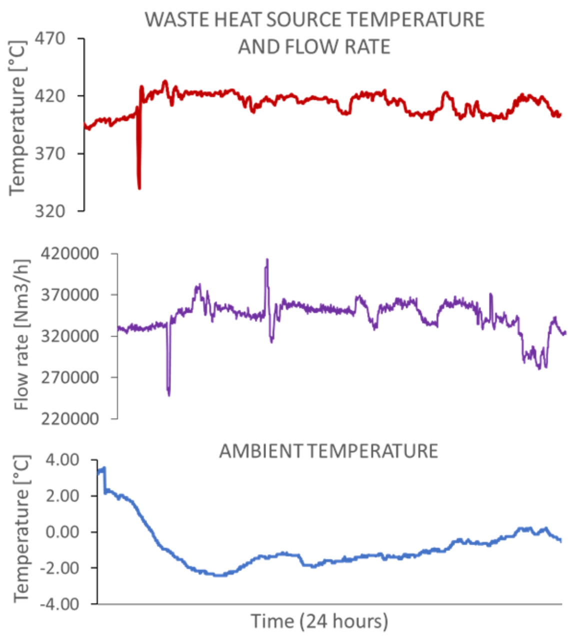

Figure 6 – Variation of waste heat parameters

The fluctuations in the temperature and flowrate of exhaust gases from cement plant are a function of the control of the manufacturing process. An example of these fluctuations at the CEMEX Prachovice plant together with the variation of the ambient temperature over a 24 hour period is shown in Figure 6. These parameters influence the design of the sCO_2 power block but also the heat to power conversion efficiency.

The main objective of WP5 is the development and implementation of a control strategy that accommodates the fluctuations of exhaust gas conditions, and capacity of rejecting heat at different ambient temperatures whilst maintaining optimum compressor and turbine inlet temperatures during steady state and transient operation.

This involves:

- Dynamic simulation of the integrated CO2OLHEAT system response to changes in thermal load- heat recovery, power block and heat rejection, to understand the challenges of control at start-up, shut down and fluctuations in waste heat source temperature and flowrate.
- Control architecture that integrates individual turbomachinery and heat exchanger controls to optimise performance and ensure safe operation (Figure 7).

- Control strategy that maintains turbine and compressor inlet temperatures close to design values over a range of waste heat conditions and ambient temperatures.

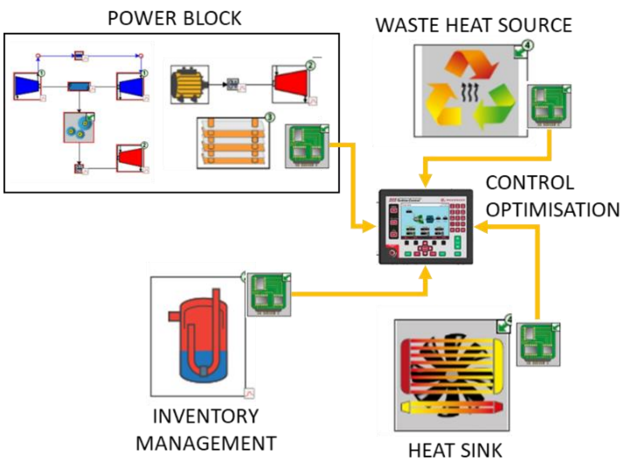

Figure 7 – Control architecture

The dynamic simulation methodology is based on a combination of zero (0D) and one-dimensional (1D) thermofluid formulations for the sCO_2 equipment. These low order models are an optimal trade-off between accuracy of the simulations and computational effort, which is a key requirement in performing optimization studies as well as the integration of suitable control approaches in the dynamic modelling platform. To ensure the integrity of the (1D) simulation approach, the simplified dynamic models will be validated against results from complex discretized modelling of heat exchangers, and mock-up testing in the test facilities of Brunel University London.

Knowledge of the dynamic responses of the major equipment and the integrated CO2OLHEAT system to step and slow changes in operating conditions, will facilitate the detailed design of the sCO_2 powerblock and the development of start-up and shut down procedures and controls to ensure safe and efficient operation of the system and its optimum integration in the CEMEX plant and local power grid.

6. Prachovice demo campaign

The Work Package 6 target is to test a full scale CO2OLHEAT plant in a real industrial environment, specifically in a CEMEX existing plant in the site of Prachovice in the Czech Republic.

This will imply the evaluation of all the HSE impacts of the plant and also of all economic and environmental performance in comparison to other type of WHRU.

Engineering Design

Starting from the project design basis and data defined in WP1, and taking into account the technical requirements for each supplied equipment (such as compressors, turbine, heat exchangers, defined in WP2-3-4) Simerom as EPC contractor will lead the development of the Engineering Design from FEED to detail, completing it with the requirements coming from control system and instrumentation of WP5.

Modular Approach

Using an innovative industrial approach, the design will be based on a modular approach: the entire plant will be subdivided into multiple skids and modules in order to maximize a fast and safe installation, and also its installation flexibility.

All modules will be then installed and integrated with the existing CEMEX plant through agreed tie-in and in compliance with Cemex plant shutdown for annual maintenance. After the installation, mechanical completion and preliminary control tests will be performed, and eventually the commissioning and start-up of the Demonstration Plant

Health & Safety analysis

In the same Work Package, dedicate effort will be given in the definition of appropriate safety measures and procedures for securing the safe performance of the sCO_2 technologies, with particular reference to the presence of under-pressure equipment like sCO_2 power block components and integration of the cycle in an industrialized area (with all its specific HSE rules).

According to European standards, a Risk Analysis will be developed to evaluate qualitatively the possible event sequences which could transform a potential hazard into an accident. After this, a second step will be to identify possible improvements or preventive measures for each undesirable events or hazards.

Full Scale Experimental Campaign

After the installation of the CO2OLHEAT system, a monitored experimental campaign will take place in Prachovice with an estimation of at least 2500 operating hours (12 months –considering that the plant is 24/7 operating). All the partners will be involved to achieve a successful monitoring campaign: the technical partners will be also devoted to perform maintenance/inspections on the pilot site and during the demonstration period.

7. Replication and impact analysis

Industry in the EU accounts for about 26% of the final energy consumption and for about 48% of the final CO_2 emissions. According to another EU-funded project, I-Therm, it has been estimated, that 70% of total energy use in the EU industrial sector is for thermal processes (furnaces, reactors, boilers and dryers) and up to a third of this energy is wasted through losses.

Total theoretical EU waste heat potential is estimated at approximately 920 TWh, out of which 30% represent waste heat suitable for CO2OLEHAT applications (T>300˚). If they could recover as little as 5% of this amount, a CO2OLHEAT plant could produce 230 GWh_{el}/year (considering average efficiency of 25% and an operating factor of 0,8), and thus saving 575 GWH/year of primary energy and over 100.000 tCO_2/year[1].

Figure 8 shows the share of waste heat per industrial sector. The most impactful sectors are Iron & steel, Chemical & petrochemical industry, and Non-metallic minerals, offering the highest WH temperatures.

[1] Primary Energy Factor for electricity at 2,51 $MWh_{,PES}/MWh_{,el}$ and 0,46 $tCO_2/MWh_{,el}$

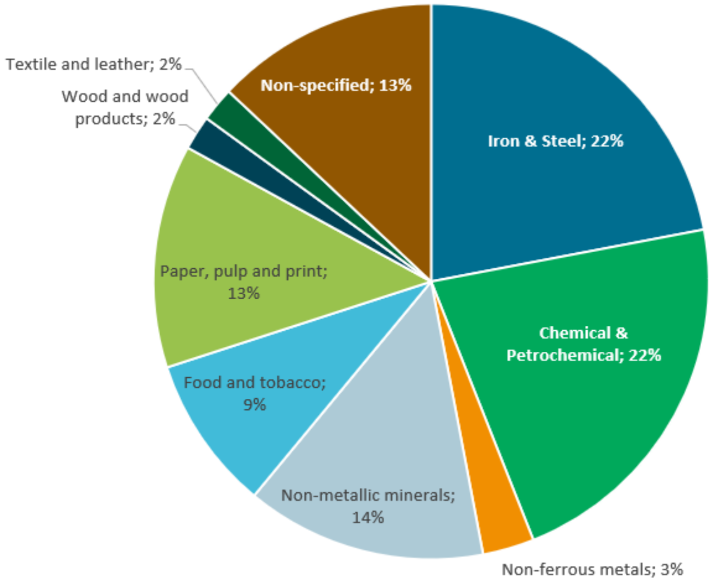

Figure 8 – Share of WH per industrial sector

CO2OLHEAT replication sites, recruiting from diverse resource and energy intensive industries (aluminium, glass, steel, waste incineration), and energy production (CCGT, CSP), will pave the way towards future R&D activities and strategies needed for the future replication processes (Figure 9).

To replicate CO2OLHEAT concept in other energy intensive industries…

Process:	**Maximum Waste Heat Temperatures**	**To be evaluated considering**
Aluminum production	**650-760 °C**	**Environmental aspects**
Steel production	**925-1050°C**	**Thermo-economic**
Glass processing	**1000-1550°C**	**Finance feasibility**
Cement facilities	**620-730°C**	**Regulatory framework**

…with a suitable replication plant size of about 1-5 MW (according to available waste heat)

Figure 9 – CO2OLHEAT replication strategy