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CO2OLHEAT

Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat

D 5.1 – Operational flexibility and control architecture requirements

Lead partner: BRUNEL UNIVERSITY LONDON

Consortium

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Executive summary

This deliverable has been prepared under the framework of Work Package 5 (WP5) of the CO2OLHEAT H2020 project. The report aims at providing an assessment of the transient and part-load operational requirements of the CO2OLHEAT power block along with the audit of current controls at the Prachovice CEMEX plant demonstration site relevant to the project. This includes preliminary definition of the control architecture for the CO2OLHEAT control system and interfaces with the sCO2 subsystems and the industrial process.

Transient data of the waste heat available from the flue gases at the CEMEX plant are presented along with insights on the transient response of the intermediate oil heat transfer loop between the flue gases and the sCO2 power block. The results of preliminary calculations of system CO2 inventory and inventory tank sizing are also presented to enable decisions on CO2 supply and management for the plant. Heating and cooling requirements for the control of the CO2 temperature in the inventory tank during filling, start-up and shutdown operations are also presented alongside control system architecture requirements. The strategy for system control will evolve as the major component operational and control requirements are finalised.

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List of Abbreviations

EU – European Union
HTF – Heat Transfer Fluid
PHE – Primary Heat Exchanger
sCO2 – Supercritical CO2
WH2P – Waste Heat to Power
WHRU – Waste Heat Recovery Unit

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1. Introduction

CO2OLHEAT will demonstrate at the CEMEX cement manufacturing plant in Prachovice (CZ) the operation of a 2 MW Waste-Heat-to-Power (WH2P) skid based on a 2 MW-sCO2 power cycle able to efficiently recover local waste heat at a temperature of approximately 400°C and convert it to high value electricity. The project will demonstrate the first-of-a-kind MW scale waste heat-to-power (WH2P) sCO2 system at TRL7, in an industrial environment, with the objective of taking the first steps towards a cheaper and more flexible valorisation of waste heat.

In the framework of the CO2OLHEAT project, Work Package 5 (WP5) aims at developing the control and monitoring system for the sCO2 plant, in order to ensure safe and efficient operation at both major component and system level. Critical control considerations include start-up, shutdown and emergency shutdown. Furthermore, the objective of the control action will be to ensure optimal performance of the system at part-load and during heat load transients, to demonstrate the operational flexibility of the sCO2 power cycle.

This report presents deliverable "D5.1 - Define flexibility requirements of the CO2OLHEAT power block to account for heat load fluctuations at the Prachovice demonstration site". It provides an assessment of the transient and part-load operational requirements of the CO2OLHEAT power block alongside an audit of current control arrangements for the plant. It includes preliminary definition of the control architecture for the CO2OLHEAT control system, interfaces with the sCO2 subsystems and the industrial process.

In the first section of the report, an analysis of transient waste heat temperature is presented covering the period December 2020 to November 2021. In the second section, the preliminary scheme of the sCO2 demo plant is outlined. Modelling activities performed for the intermediate oil heat transfer loop are discussed, and the preliminary sizing of system inventory, inventory tank volume and inventory heating/cooling capacity required are presented in Section 3. Preliminary control architecture requirements are outlined in Section 4.

2. CEMEX plant waste heat temperature data

The exhaust gas temperature data from the CEMEX plant have been analysed for a period of 12 months, from 1 December 2020 to 30 November 2021. In particular, the data considered are: i) the temperature of the gases at the two exhaust stacks ("Tower 1" and "Tower 2", points 1,2 and 3,4 respectively in Figure 1); ii) the total standard volumetric flow rate measured at point 7, and iii) the ambient temperature. Table 1 provides details of these measurements.

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Figure 1 – Top view of the CEMEX cement plant in Prachovice and measurement points

Table 1 - Measurement points at the CEMEX plant showed in Figure 1

No	Measurement point
1	Temperature before condition tower (Tower 1)
2	Temperature before condition tower (Tower 1)
3	Temperature before stab., No2 (Tower 2)
4	Temperature before condition tower, No2 (Tower 2)
5	Vacuum before stab, No1
6	Vacuum before condition tower, No2
7	Flow (total)
8	Coolant temperature, outlet
9	Coolant temperature, return

2.1. Waste heat temperature variation

The variation of the waste heat temperature for the period December 2020 to January 2021 is shown in Figure 2. The time resolution of the data is one minute. A temperature band between 380°C and 420°C has been highlighted with red lines to show the main range of variation of the exhaust gas temperature during normal operating conditions of the plant. As per December 2020 and January 2021 data, the temperature of the exhaust gas remains quite stable within the selected temperature band in both exhaust stacks. Some quick temperature drops occurred, especially during the first weeks of December. In the worst cases, temperatures dropped down to 225°C over a time period of 40 minutes. The temperature decrease rate (2.1°C/min) may be challenging for Waste Heat Recovery Unit (WHRU) materials and therefore further investigations are needed on this. During this period, the minimum ambient temperature was -8°C and the maximum +11°C.

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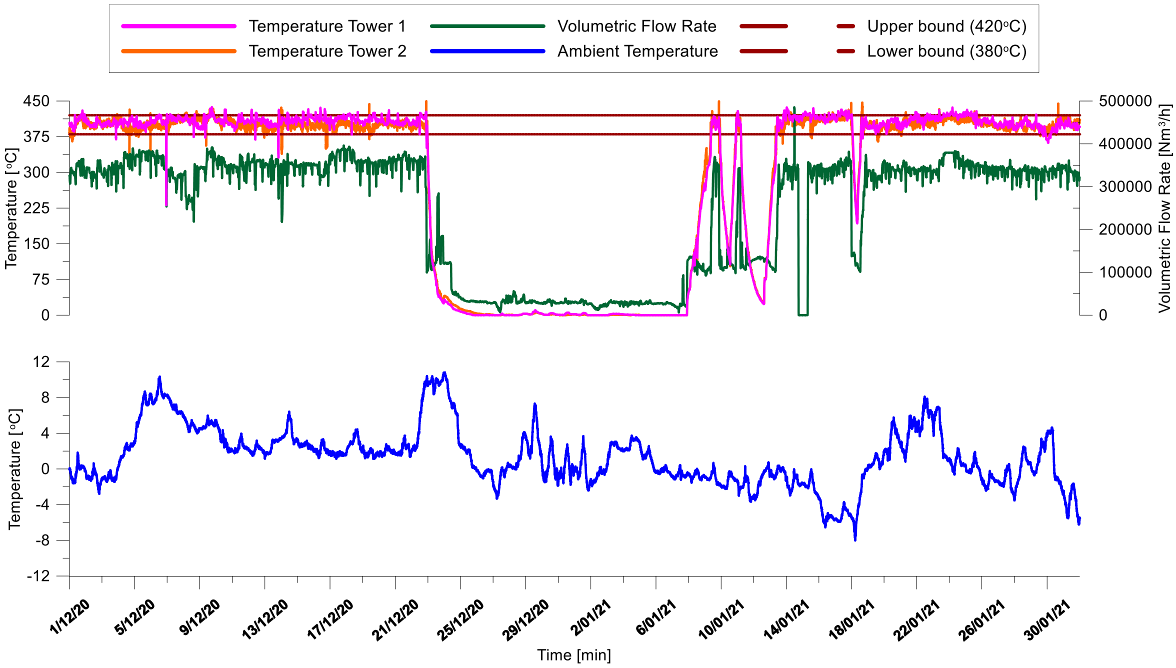

Figure 2 – Variation of: i) stack temperature and volumetric flow rate and; ii) ambient temperature, for the period 1 December 2020 to 31 January 2021.

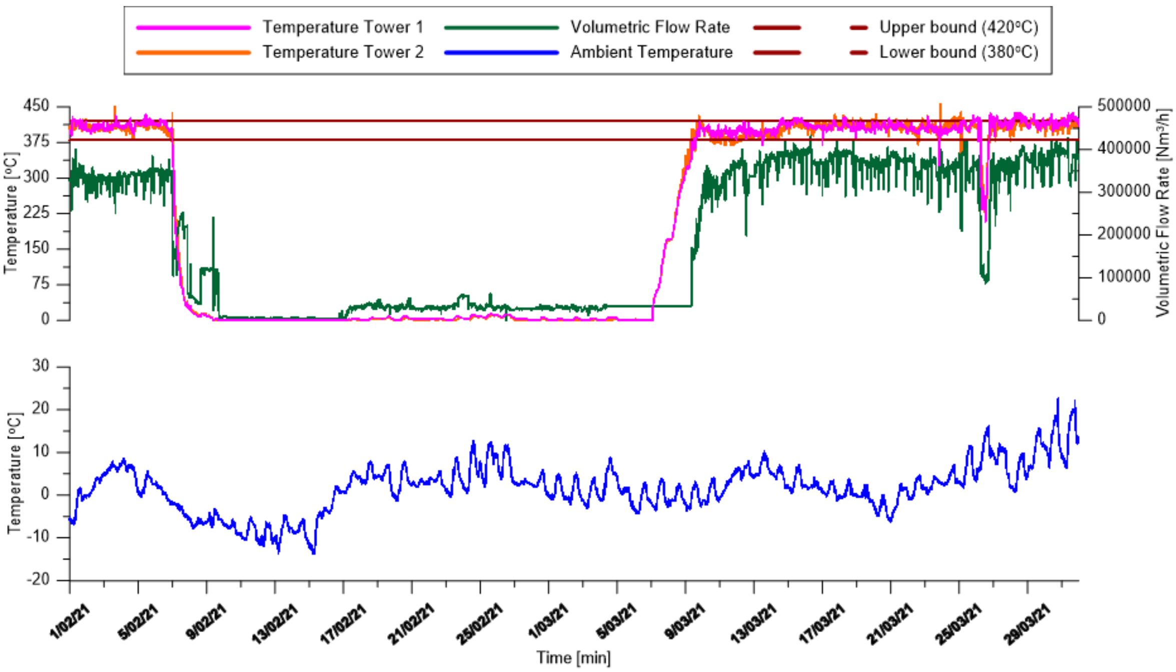

Figure 3 – Variation of i) stack temperatures and volumetric flow rate, and ii) ambient temperature for the period 1 February 2021 to 31 March 2021.

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Figure 3 shows the data for February and March 2021 during which there was a 35 day planned shutdown for maintenance of the plant.

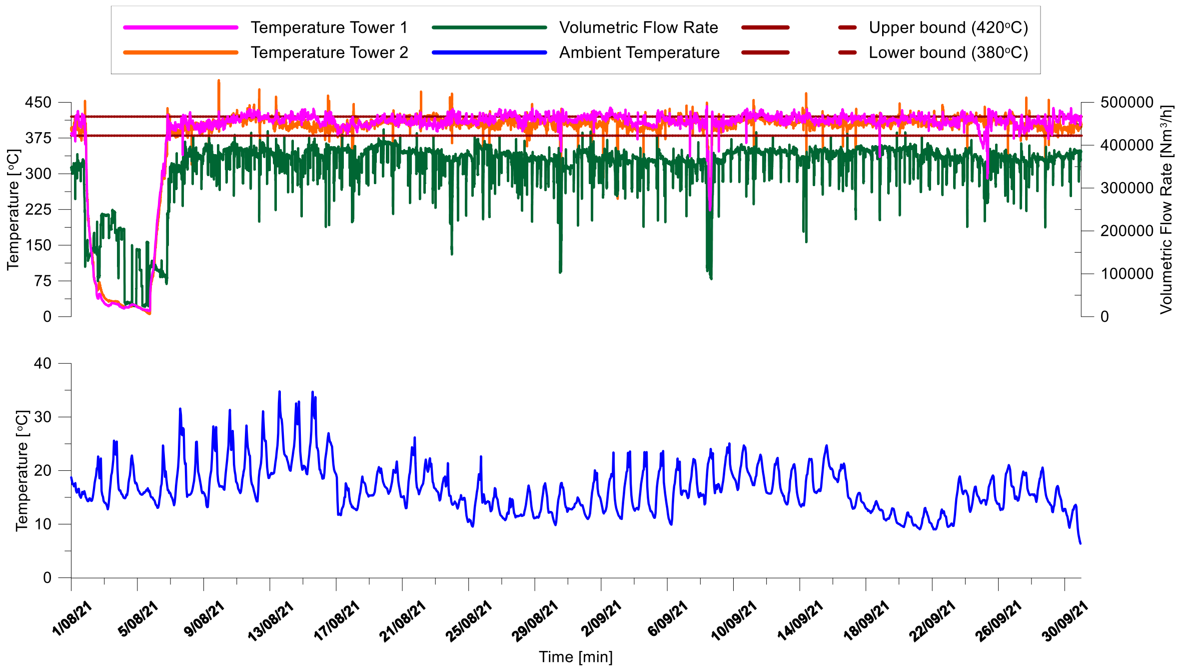

Figure 4 – Variation of: i) stack temperatures and volumetric flow rate, and ii) ambient temperature for the period 1st August 2021 to 30th September 2021.

Figure 4 shows the variation of stack temperatures, volumetric flowrate and ambient temperature in August and September 2021. It can be seen that in early August there was a near complete shut-down for 4 days. During the period there have also been a small number of occasions when the stack temperatures fell below 300 °C but only for a short period of time.

Table 2 summarises the number of events such as planned shutdowns, major and minor temperature variations (reductions in waste heat availability) and rates of temperature decrease. These variations and their potential impact are analysed in more detail in section 2.1.1 below.

Table 2 – Summary of exhaust temperature variation events in the period December 2020 - November 2021.

Event	No	Min Temp. [°C]	Max Temp. decrease rate [°C/min]	Risk for WHRU
Planned shutdowns	2	0	0.7°C/min	Low
Major temperature reductions/shut downs	5	0	0.7°C/min	Low
Slow major temperature reductions	6	150	0.7°C/min	Low
Quick temperature reductions	15+	220	>2°C/min	Medium

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2.1.1. Analysis of different case scenarios

Taking as reference the December 2020 and January 2021 months, particular scenarios have been analysed where the conditions of waste heat temperature and volumetric flow rate of exhaust gases changed from the nominal conditions considered for operation of the sCO2 demo plant at the design point (waste heat temperature of 400°C and mass flow rate of flue gases of 50 kg/s). The analysis showed that during shut-down, the overall volumetric flow rate dropped fast to approximately one third of the nominal flowrate. This was followed by a reduction in the exhaust gas temperature but at a much slower rate, not exceeding 0.7°C/min. The overall shut-down process of the cement manufacturing plant lasted for approximately 48 hours. The start-up process of the plant was the reverse of shut-down with the exhaust flowrate first increasing sharply to a third of the nominal flowrate. This increase was then followed by a much slower increase of the exhaust gas temperatures in the two stacks, reaching a value of 350 °C after approximately 40 hours. At this point the exhaust flowrate increased to its nominal value with the exhaust temperatures taking another six hours to reach 400 °C. The rate of temperature variation in this case does not represent a risk in terms of material stresses.

For the cases where the exhaust temperature (heat load) drops for short periods, further analysis is required to understand if, for these conditions, the sCO2 plant can be operated in idle mode. This means that the CO2 in supercritical state can be kept circulating in the loop with the power required for the compressor to provide circulation of the working fluid in the system, provided by the expanders with no power import from the grid.

2.2. Ambient conditions

The ambient temperature at the CEMEX plant is currently measured by two temperature sensors. One located close to the CEMEX air coolers which is partially shielded (T2) and the other mounted on a wall of a building which is not shielded (T1). The data from the two sensors are presented for the months January and February 2021 in Figure 5 (representation of winter conditions), and for the months June and July 2021 in Figure 6 (representation of summer conditions). It can be seen that there is not much difference between the data from the two sensors in the winter months. However, in the summer months there are fluctuations in temperature due to the influence of solar radiation. It is therefore important, for more accurate data, to install radiation shields round the temperature sensors to have more accurate data, particularly for the design and control of the cooler of the CO2OLHEAT system.

Figure 7 presents the variation of ambient relative humidity (RH). It can be seen that in the summer months RH reaches 100% on a number of occasions which may have an influence on the performance of the CO2OLHEAT cooler. As the sensor, though, is situated close to the evaporative coolers of the plant, the high local RH values may be due to water vapour from the coolers. This aspect will be investigated further over the next few weeks.

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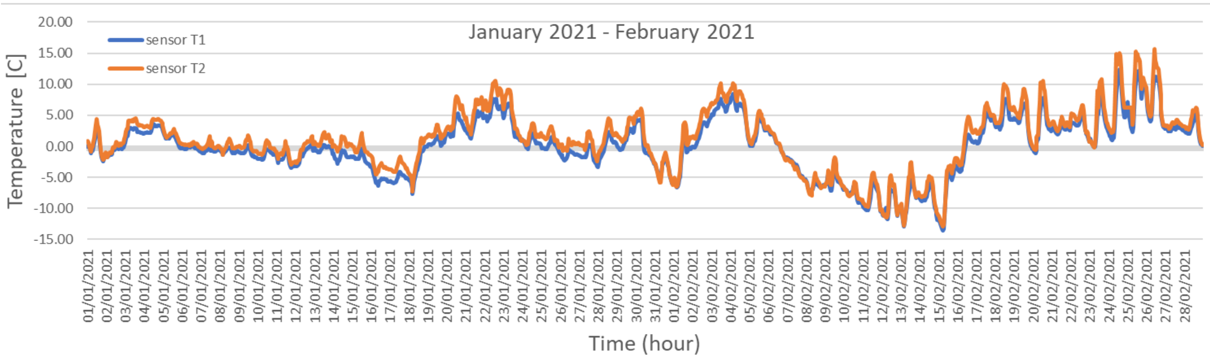

Figure 5 – Ambient temperature at CEMEX plant for the period 1 January 2021 to 28 February 2021.

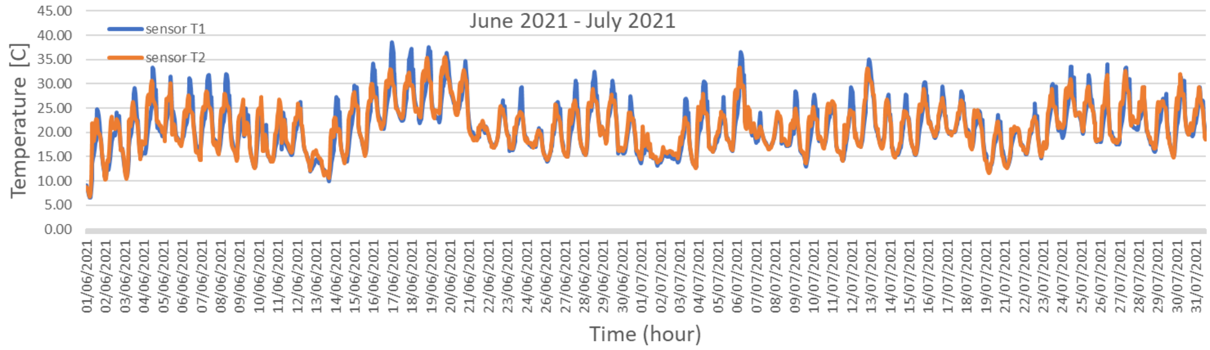

Figure 6 – Ambient temperature at CEMEX plant for the period 1 June 2021 to 31 July 2021.

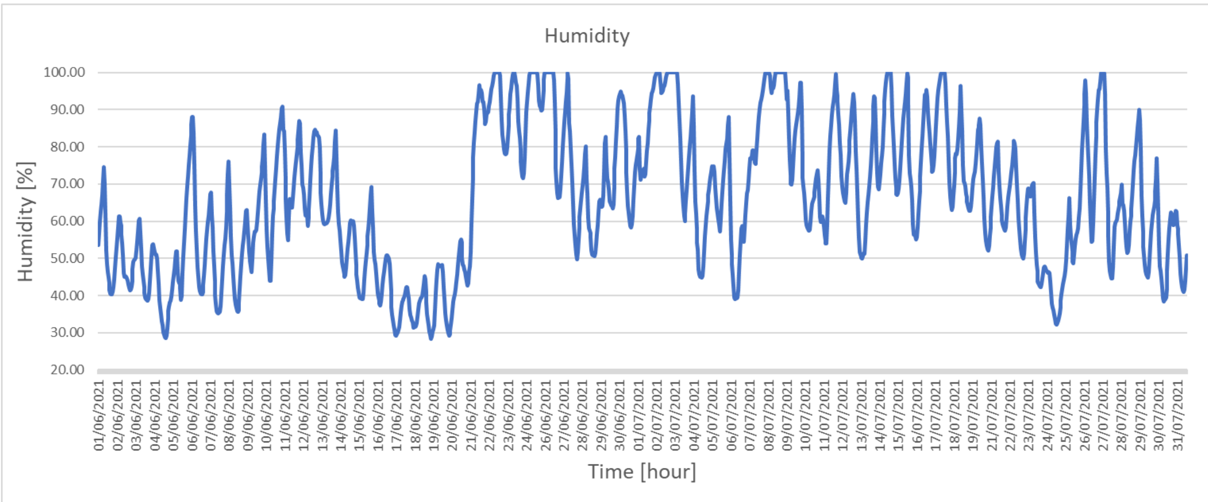

Figure 7 – Relative humidity data at CEMEX plant (sensor T2) for the period 1 June 2021 to 31 July 2021

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3. Preliminary Process Flow Considerations

Flexibility and operational requirements for the sCO2 plant have been considered to provide insights for a preliminary Process Flow Diagram (PFD) of the demo installation. In particular, the system has been split into three main parts:

- **The intermediate heat transfer loop:** connecting the Waste Heat Recovery Unit (WHRU) where the heat is recovered from the exhaust stacks to the main heat exchanger of the sCO2 plant (the Primary Heat Exchanger, or PHE), where the heat of the exhaust gases is transferred to the supercritical CO2. The proposal from the WHRU manufacturer is to use heat transfer oil, (Fragoltherm X76A) as the heat transfer fluid.
- **The sCO2 loop:** which embeds all the components required to transform the thermal energy recovered by the flue gas into mechanical and then electrical power.
- **The Inventory Management system:** used to handle the charge of CO2 required to operate the sCO2 demo plant during filling, emptying, start-up and shutdown operations.

3.1. Intermediate heat transfer loop

The preliminary PFD of the intermediate heat transfer loop includes:

- An expansion vessel to accommodate the oil density variation occurring between filling and nominal operation as well as transients.
- A storage tank to store the oil in case of normal or emergency shutdown of the system
- Two Waste Heat Recovery Units (WHRU) one in each waste heat stack.
- The Primary Heat Exchanger (PHE) where the oil transfers the recovered thermal energy to the sCO2 power block.
- A pump for the filling of the oil loop.
- Circulation pumps to establish and control the flow rate through the WHRUs.
- Valves and by-pass lines required for the control of the heat transfer loop.
- Pipes connecting the several components.
- An air-cooling unit to reject heat to the environment in case of oil overheating.

The information in the PDF and the proposed location of the sCO2 power block have been used to determine the approximate length of oil pipes and the total oil mass in the system. These data have been employed to perform preliminary simulations to gain insights on the dynamic response of the heat transfer fluid (HTF) circuit.

A preliminary step for the development of models to predict the transient response of the heat transfer loop has been the calculation of the mass and volume of the oil in the loop. The selected boundary conditions and heat exchanger sizes used for the calculations (Figure 8.a) have been based on the suggested design/operating conditions for the demonstration plant and some preliminary data from the design of the WHRUs. With the possibility of siting the demonstration plant away from the waste heat source, the pressure and heat losses from the insulated oil pipes have been considered. An insulation thickness of 80 mm has been assumed in the calculations. The calculations have been performed for different lengths of pipe from 5 m to 170 m. Figure 8.b shows the volume of oil in the loop for different lengths of pipes while the table in Figure 8.c shows the mass of oil in the loop for the pipe diameter selected.

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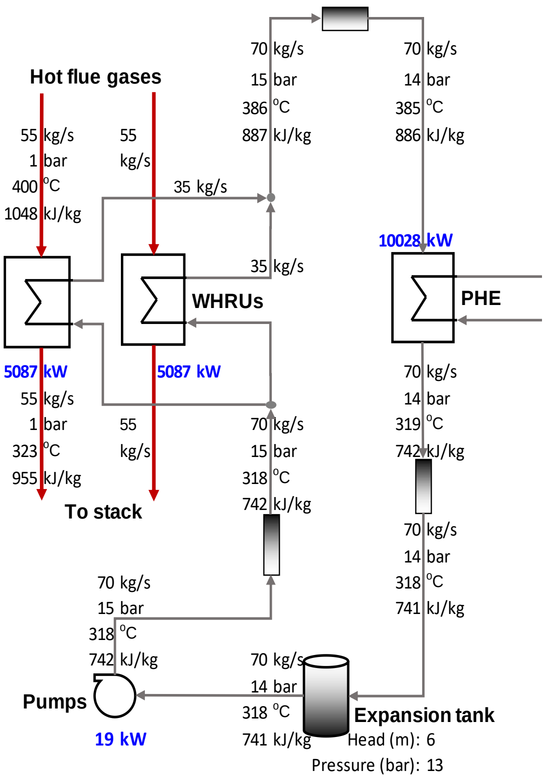
The mass and heat balance calculations as well as the modelling activity for this task have been based on a pipe length of 150 m. However, it should be noted that these are only preliminary results. Calculations and the dynamic models will be revised once the location and design conditions for the plant are finalised.

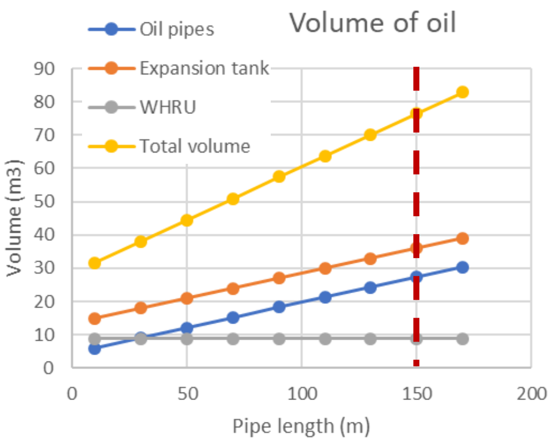
3.1.1. Modelling methodology

The dynamic models for the oil heat transfer loop in Matlab/Simulink and GT-SUITE environment are illustrated in Figure 9. The Matlab/Simulink models developed are used as benchmark for 1-D system models in GT-SUITE. The components modelled include the WHRUs, the PHE, the expansion drum, oil pumps, pipes and control valves. Mass, momentum and energy balance equations are solved for each component. Pressure loss in pipes and heat exchangers as well as heat loss to the ambient through the insulated pipes are considered.

The thermo-physical properties for the flue gas mixture and CO2 are obtained from the NIST REFPROP (version 10.0) software while the properties of the oil, FRAGOLTHERM X-76-A, are from the property information datasheet supplied by the vendor.



(a)



(b)

Pipe length [m]	Oil loop (pipe+HX) [kg]	Expansion tank [kg]	Total oil mass [kg]
130	20299	21512	45670
150	22164	23490	49868
170	24030	25469	54068

(c)

Figure 8 – Preliminary calculations for the oil heat transfer loop: (a) heat and mass balance; (b) volume as a function of pipe length; (c) total oil mass.

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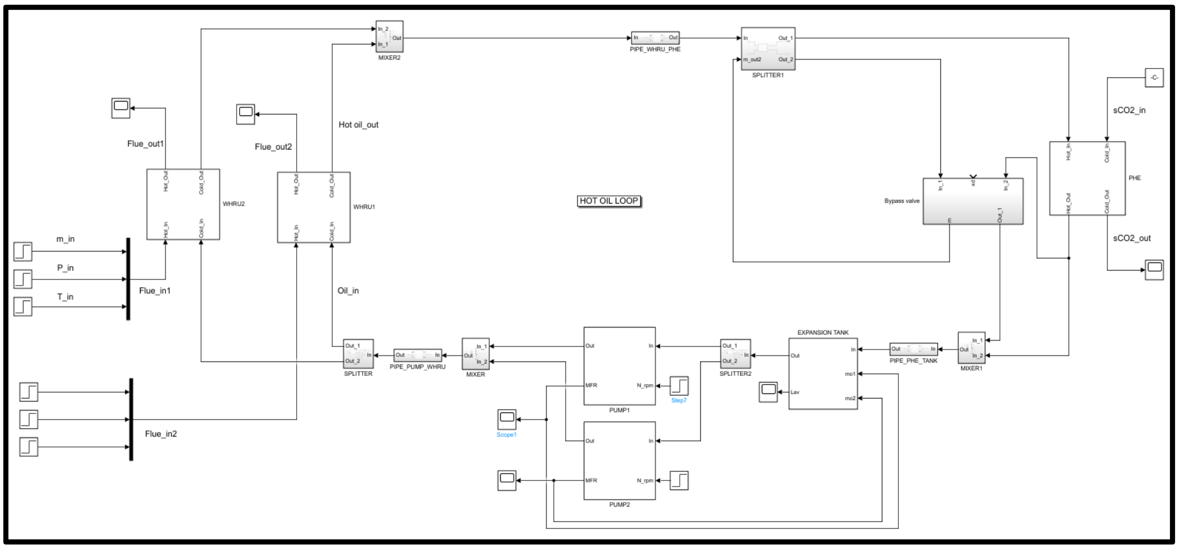
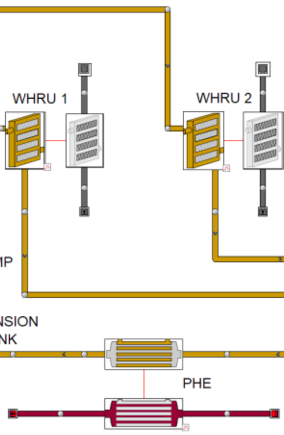
3.1.2. Simulation of transient response

The transient response of the hot oil loop to a 10% step change in exhaust gas temperature and its impact on the sCO_2 temperature at turbine inlet are illustrated in Figure 10. As can be seen from Figure 10.b, the time constant of the hot oil system, as reflected by the change in sCO_2 temperature at turbine inlet, is of the order of between 2 and 3 minutes whilst it takes approximately 10 minutes for the sCO_2 temperature to reach a new steady state value. This response time is reasonably fast compared to the rate of change in the exhaust gas temperature which is in the range 0.7 to ~2.0 ^{o}C/min. The time constant will depend on the final design of the heat recovery heat exchanger as well as the final oil pipe length and diameter.



(a)



(b)

Figure 9 – a) MatLab Simulink, (b) and GT-SUITE models of the oil intermediate heat transfer loop

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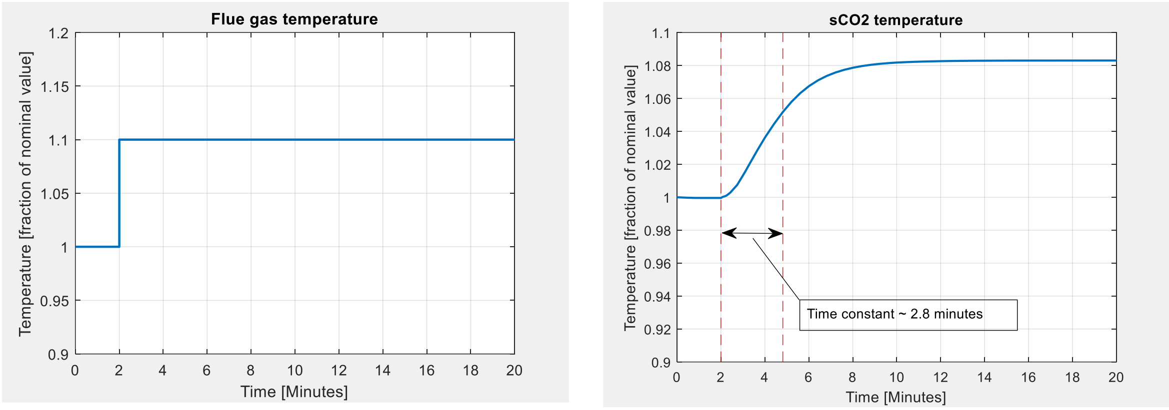
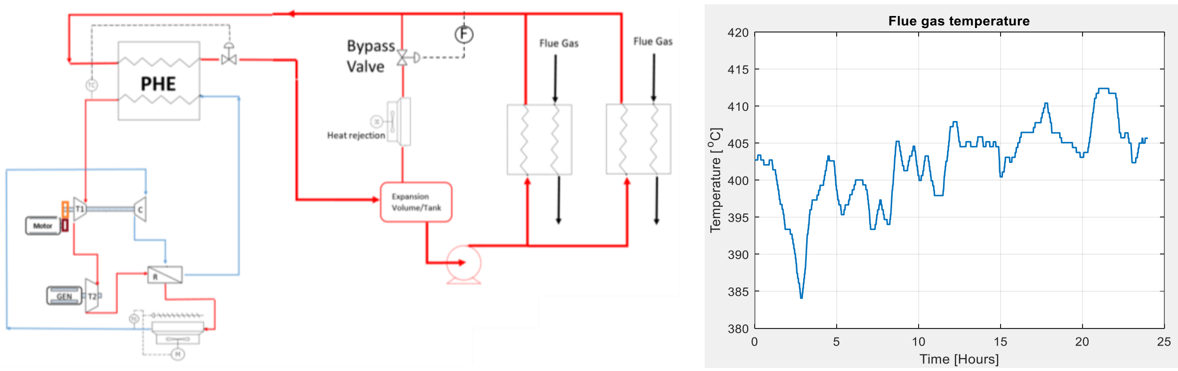


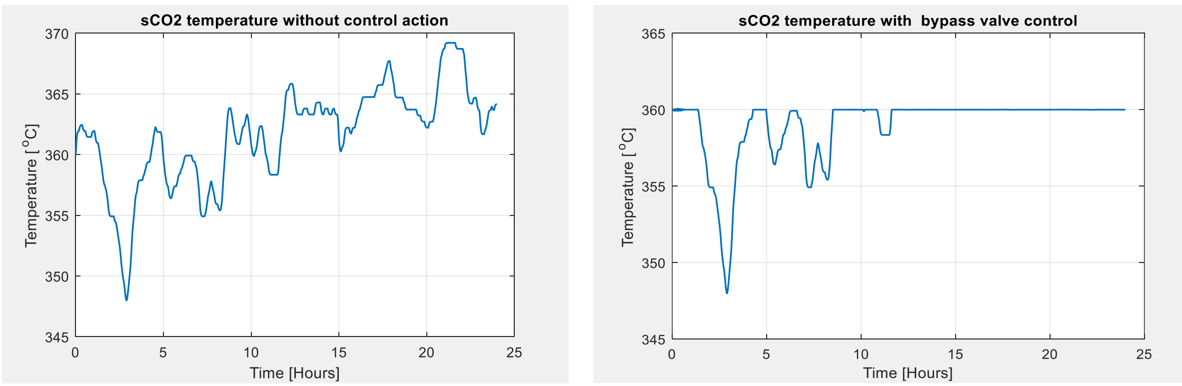
(a) (b)

Figure 10 – Transient simulation of the oil heat transfer loop: (a) step increase of 10% in the temperature of exhaust gas; (b) temperature variation of the sCO2 at the outlet of the Primary Heat Exchanger.



(a) (b)

Figure 11 – (a) Simplified scheme of the oil intermediate heat transfer loop and sCO2 system; (b) variation of exhaust gas temperature over a 24 hour period.



(a) (b)

Figure 12 – Dynamic simulation of sCO2 temperature at the Primary Heat Exchanger outlet (a) non-controlled system ; (b) controlled system.

The actual CEMEX plant data were used to simulate the transient response of the oil loop for a typical 24-hour variation in exhaust gas temperature (Figure 11.b). The transient response of the sCO2

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temperature without any control action is shown in Figure 12.a. The control of the sCO2 turbine inlet temperature with hot oil bypass valve was also simulated. As shown in Figure 12.b, for periods when the exhaust gas temperature is above the design operating point, the sCO2 temperature can be maintained at the design point value of 360°C by regulating the flow of hot oil through the PHE. However, when flue gas temperature drops below the design operating point, hot oil bypass cannot be used to control the sCO2 temperature. These periods will require the control of the sCO2 cycle in order to keep the turbine inlet temperature within the desired operating range.

3.2. sCO2 power cycle

The preliminary design of the sCO2 power cycle considers:

- One Primary Heat Exchanger to recover heat from the hot oil and transfer it to the supercritical CO2 in the power cycle.
- One turboexpander unit comprising a two-stage compressor connected on the same shaft with a motor and a two-stage expander.
- A power turbine.
- A Printed Circuit Heat Exchanger (PCHE) to be used as recuperator.
- A cooling unit (COOL), to reject heat to the ambient.

The inventory mass of CO2 in the CO2OLHEAT system was calculated to be approximately 1284 kg.

3.3. sCO2 Inventory management system

A preliminary arrangement for the inventory management system of the sCO2 power block consists of:

- An inventory tank equipped with a heating and cooling system to regulate the sCO2 temperature and support the filling, start-up and shutdown procedures of the plant.
- An expansion tank located after the inventory tank to accumulate liquid CO2 that may form during the filling process.
- A booster station to increase the CO2 pressure and manage the filling and replenishment of CO2 during operation.

To determine the size of the inventory tank, the following procedure has been followed. Since the entire inventory of CO2 required for the plant's nominal operation should be contained in the inventory tank, the mass of 1284 kg has been considered as a starting requirement. An oversizing coefficient of 1.5 has been considered to account for additional CO2 that could be injected into the system during operation. To calculate the volume of inventory tank required, a worst-case scenario has been considered using the maximum storage temperature achievable during the summer (35°C based on the data provided by CEMEX) and a maximum pressure achievable in the tank of 90 bar (dictated by process limits). Under these conditions, the volume required for the tank was found to be equal to 4.6 m^3 (Table 3).

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Table 3 – Summary of Inventory tank sizing results

Inventory Tank Sizing		
Max mass required	1284	kg
Oversize	50.0	%
Mass in inventory	1926	kg
Storage Temperature	35.0	C
Density at storage	419.1	kg/m^3
Volume required	4.6	m^3 (~5000 litre)

Based on the volume of the inventory tank, the capacity of the heating/cooling auxiliary system required to control the temperature of the CO2 in the tank has been determined. This is the energy required to bring the CO2 in the tank from cryogenic conditions (pressure and temperature of 20 bar and -20°C respectively) to the minimum supercritical conditions needed at the compressor inlet (pressure and temperature of 74 bar and 33°C respectively). The time assumed for the transfer of this energy to the CO2 was 30 minutes, leading to a power input requirement of 170 kW. Table 4 summarises the input and output data used in the calculations.

Table 4 – Summary of inventory tank heating/cooling system sizing

Starting conditions (Cryogenic)			**Supercritical conditions (compressor off)**		
Temperature	-20	°C	Temperature	33	°C
Pressure	20	bar	Pressure	74	bar
Density	1031.8	kg/m^3	Density	288.2	kg/m^3
Specific enthalpy	154.4	kJ/kg	Specific enthalpy	389.3	kJ/kg
Specific enthalpy change				234.9	kJ/kg
Mass				1284	kg
Thermal Energy Required				301562	kJ
Time in minutes				30	min
Time in seconds				1800	s
Thermal Power				170	kW

4. Control system architecture requirements

For monitoring and operation purposes a fully capable HMI system will be delivered with the control system. The HMI system will allow the operator to have overall supervision of the process and to give high level commands. All the elements that will compose the proposed system will be of an industrial type certified to operate as required in the foreseen environment, with robust and reliable specifications. The proposed HMI will comprise of a system with the following minimum specifications:

- One 15 inch industrial panel PC to be used as operator station.

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- High availability managed network routers.

Hardware (e.g. CPU, RAM, graphics card, etc.) shall be selected so as to run the HMI application with ease and fast screen switching and fast data loading from disk (e.g.1-2 sec for loading a graph with historical information). Disk storage shall provide adequate storage for needed historical data.

The Operating system will be latest industrial MS Windows. The applications software will be based on a specially produced MAS application which will provide extended monitoring and processing features to fully cover the needs of this project and future expansions. The HMI application package will support as a minimum the following:

- Local user interface
- OPC server able to provide real time information to other systems (e.g. plant DCS or SCADA system).
- Short term historian providing short-term information (1 sec resolution) about all operational parameters for trending and troubleshooting purposes.

The HMI system shall not play an active role in the control and protection logic (all logic shall be in the respective hardware controls). Its main role will be to acquire, record and present actual data of the functional situation of the machine. All operational information and possible commands of the machine control and protection shall be available locally. Embedded application protection logic will prevent users from sending inapplicable commands to the control systems. HMI/DCS (MAS Control Panel) will have the high level of control of the logic/commands only for the equipment without their own controllers.

Main HMI platform offers extended capabilities including but not limited to:

- The collection, processing and storing of all IO data in real time
- Multi password protected system (two users at least: operator and engineers)
- Graphical representation with movement, color, etc. for the easiness of operation.
- Instant navigation between all information (screen selection).
- Extended logging facility (status, alarms, warnings, operators commands, system states etc.)
- Extended Alarm filtering, including the facility to group alarms.
- Live and historical trending of multiple values and historical depth.

The delivered application will offer at least the following pages / information:

- Operation Summary
- Mimic screens
- Status Screens
- Mechanical Parameters
- Parameterization screens
- Alarm and event logs
- Historical reference Screens

During the Site Survey performed on November 23rd 2021 MAS found out and proposes the following.

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1. Cement plant DCS is Allen Brandley.
2. There is a central control room where all cement plant operations are monitored. There are several, PC based, operator stations installed for this purpose.

Two possible locations were presented for the installation of the facilities.

A. On the roof of building beneath the Flue Gas Ducts.
   Pros: facilities will be very close to WHRUs
   Cons: The location is dusty and vibrating. The available space is limited.
B. In a separate area distant from the Flue Gas Ducts.
   Pros: The location is cleaner, non-vibrating with more space.
   Cons: Facilities will be away from WHRUs

Suggestions:

1. Control equipment is highly recommended to be installed in a dust free, temperature-controlled area.
2. Control equipment area is preferrable to be close to the facilities. A new container may be provided if an existing building, that is fit for the purpose, is not available nearby.
3. MAS control system shall provide its own SCADA. It will be useful to provide CEMEX, a PC based, operator station with MAS SCADA in central control room to get high level control and monitoring of the facilities.
4. *It will be very useful to get remote access (through internet) at control equipment. CEMEX cybersecurity requirements and restrictions must be reviewed.*

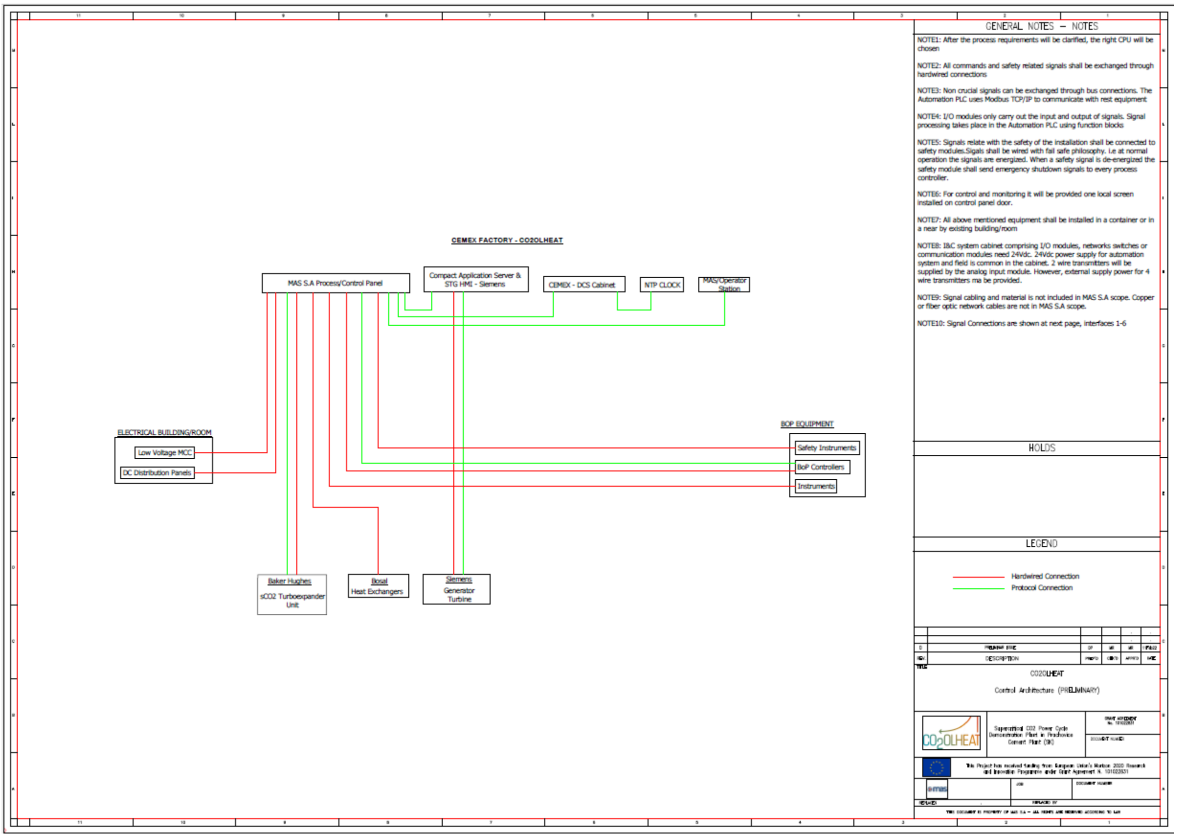

Figure 13 – Preliminary control scheme of the different controllers integration in the sCO2 demo plant

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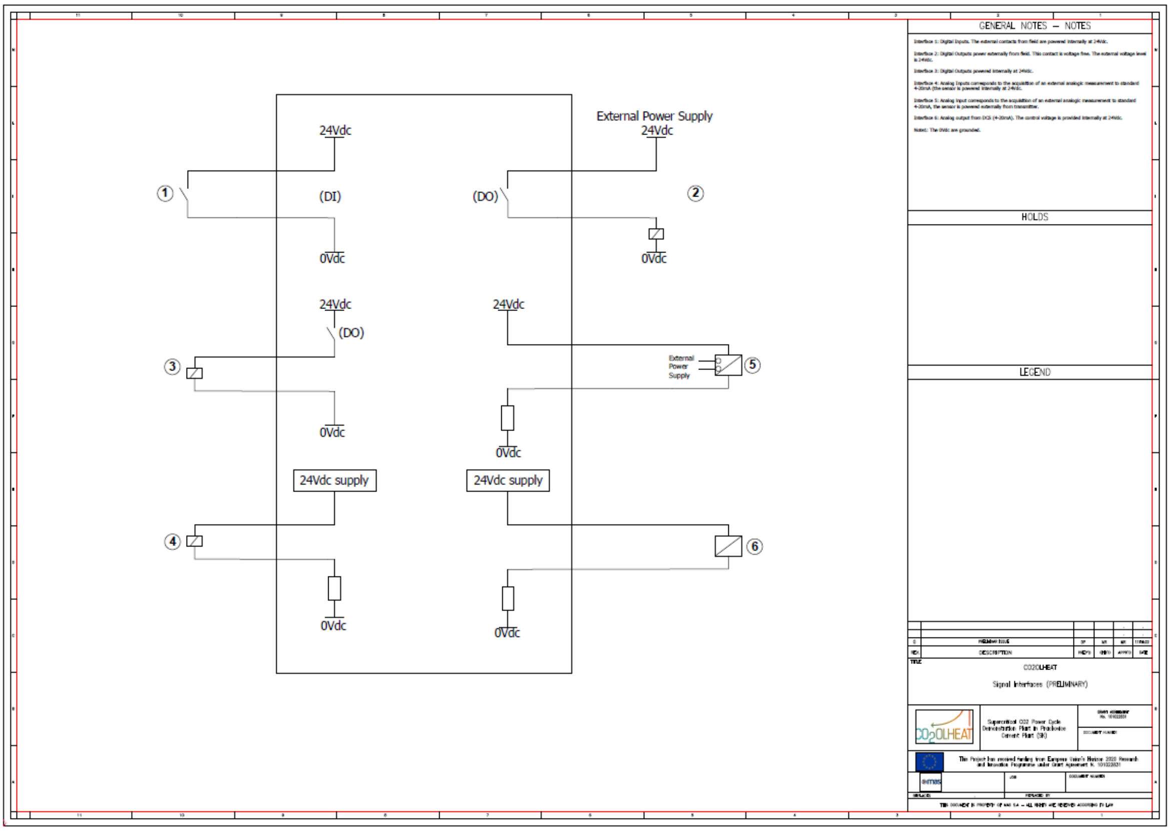

Figure 14 – Preliminary electrical drawings of the control architecture.

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