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Project 101122231 — ASTERIx-CAESar

D1.1 - Specifications of the ASTERIx-CAESar prototypes

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Summary

This document describes the specifications of the ASTERIx-CAESar prototypes to be installed at CIEMAT-PSA as well as at IMDEA Energy institute.

At CIEMAT-PSA, small-scale solar receiver experiments will be performed at the solar furnace at an existing thermal characterization loop.

Furthermore, at CIEMAT-PSA, an already existing 300kWth research prototype [1] will be modified and equipped with a compressed air energy storage (CAES) unit, demonstrating a volumetric solar receiver unit that delivers heat to pressurized air that in turn expands in a hot air turbine unit (the ASTERIx-CAESar main demonstration prototype). Additionally, a reverse osmosis desalination unit will be connected to the CAES unit. Here, the objective is to power the water pump with compressed air instead of electricity.

On the other hand, at IMDEA-Energy, a small-scale solar receiver unit will be tested at a experimental high-flux solar tower plant.

All required components are fully specified and described in this document. Orders can now be placed to be able to start prototype installation as soon as possible. The installation of the solar turbine loop and CAES system is planned to be done during the year 2025. Wiring and control system modifications are foreseen to start at the beginning of 2026.

Nomenclature

ACRONYM	DESCRIPTION
P&ID	piping and instrumentation diagram
PSA	CIEMAT Plataforma Solar de Almería (E-04200 Tabernas)
CAES	Compressed air energy storage
PI feedback loop	Proportional Integral feedback control loop
OVAR	Open volumetric air receiver
TI	Temperature indicator (sensor)
FI	Flow indicator (sensor)
PI	Pressure indicator (sensor)
GL-PX	Gas-liquid pressure exchanger used in desalination system
RO	Reverse Osmosis

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1 Introduction

This document describes the specifications of the ASTERIx-CAESar prototypes to be installed at CIEMAT-PSA as well as at IMDEA Energy institute.

At CIEMAT-PSA, small-scale solar receiver experiments will be performed at the solar furnace at an existing thermal characterization loop. Furthermore, at CIEMAT-PSA, an already existing 300kWth research prototype [1] will be modified and equipped with a compressed air energy storage (CAES) unit, demonstrating a volumetric solar receiver unit that delivers heat to pressurized air that in turn expands in a hot air turbine unit (the ASTERIx-CAESar main demonstration prototype – see Figure 14).

On the other hand, at IMDEA-Energy, a small-scale solar receiver unit will be tested at a experimental high-flux solar tower plant.

This document is organized as follows:

- Section 2 describes the testing setup at the solar furnace at CIEMAT-PSA.
- Section 3 describes the testing setup at the high-flux tower plant at IMDEA.
- Section 4 describes the ASTRIx-CAESar main demonstration prototype at CIEMAT-PSA, composed of solar receiver, compressed air energy storage unit, hot air turbine and desalination unit.

2 Solar absorber testing at the solar furnace at CIEMAT-PSA

The principal aim of the planned experiments is to evaluate the thermal performance of specific absorber samples in terms of thermal efficiency and thermal stability (oxidation). In order to do so, the absorber samples will be exposed to concentrated solar flux and a thermal air loop will force cooling air through the samples to simulate the operation of a full-scale volumetric solar receiver. Figure 1 shows a cross-sectional view of the CAPTure receiver prototype (300 kWth), highlighting one absorber module (cup). Figure 2 shows the open volumetric air receiver concept and a scheme of one representative absorber module.

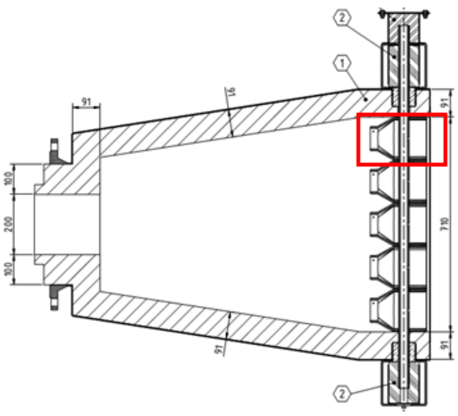


Figure 1: CAPTure receiver prototype drawing with one absorber module selected

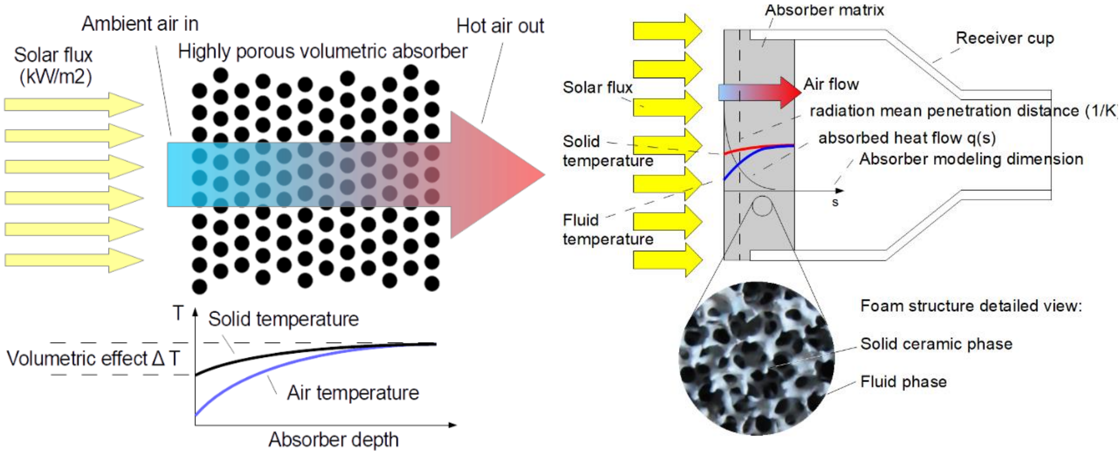


Figure 2: Open volumetric air receiver working principle and ideal temperature profiles (left); Absorber module (cup) exposed to incident solar flux (right)

With the objective to reproduce the working conditions of a solar absorber installed in a full-scale solar receiver, a single absorber module will be evaluated in a specifically designed thermal air loop as shown in Figure 3. The volumetric absorber module (1) is mounted at the inlet of the air duct/receiver pipe (2). The ambient air is forced through the experimental circuit by a blower (6). In particular, the air is forced through the absorber module (1), the receiver pipe (2), the air/water heat exchanger (4) and the flow meter (5). This OVAR thermal test loop will be placed in the focal plane of the solar furnace and the input thermal power and the maximum solar flux will be regulated by a shutter. Simultaneously, a blower will force the movement of the ambient air through the new absorber foams.

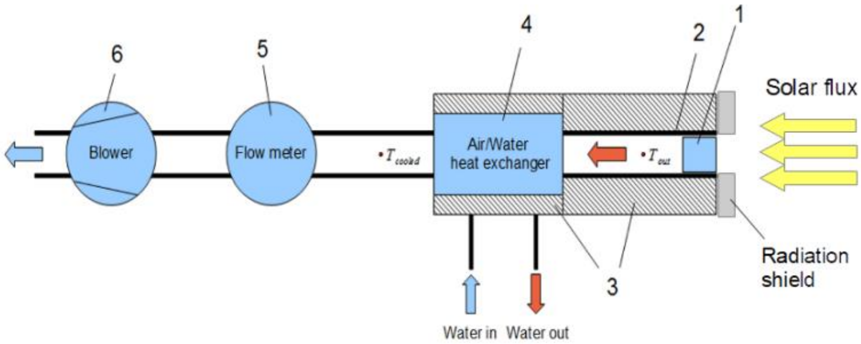


Figure 3: Scheme of thermal air loop for solar absorber characterization

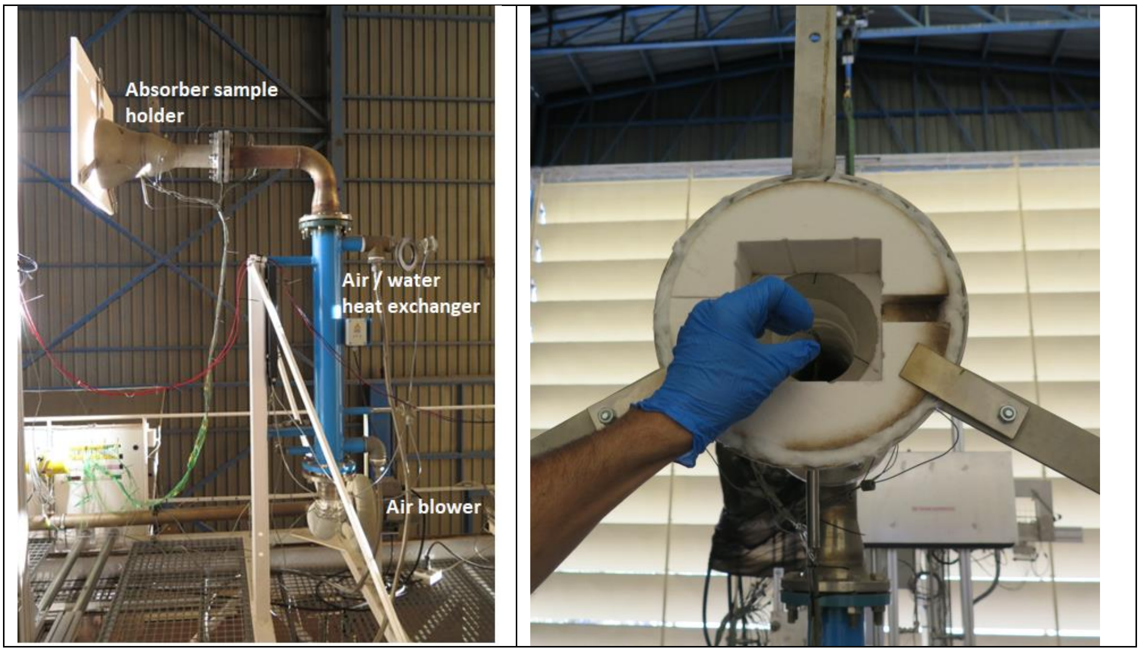


Figure 4: Solar furnace thermal air loop (sample holder, air water heat exchanger and air blower)

2.1 Absorber module geometry

The design of the absorber module to be tested in the solar furnace is predefined by the existing thermal loop design. The solar receiver module consists of the absorber holding structure (the cup) and the solar absorber itself (the foam). The cup that holds the solar absorber has the following dimensions as shown in Figure 5.

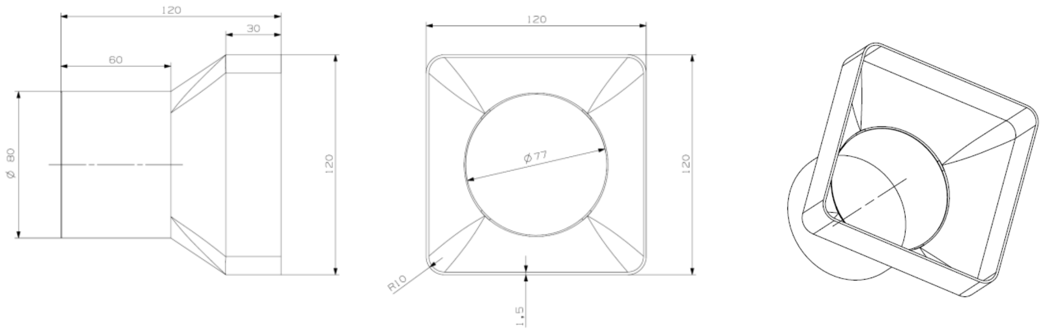


Figure 5: Cup dimensions for the solar furnace testing

The solar absorber has the following dimensions as shown in Figure 6.

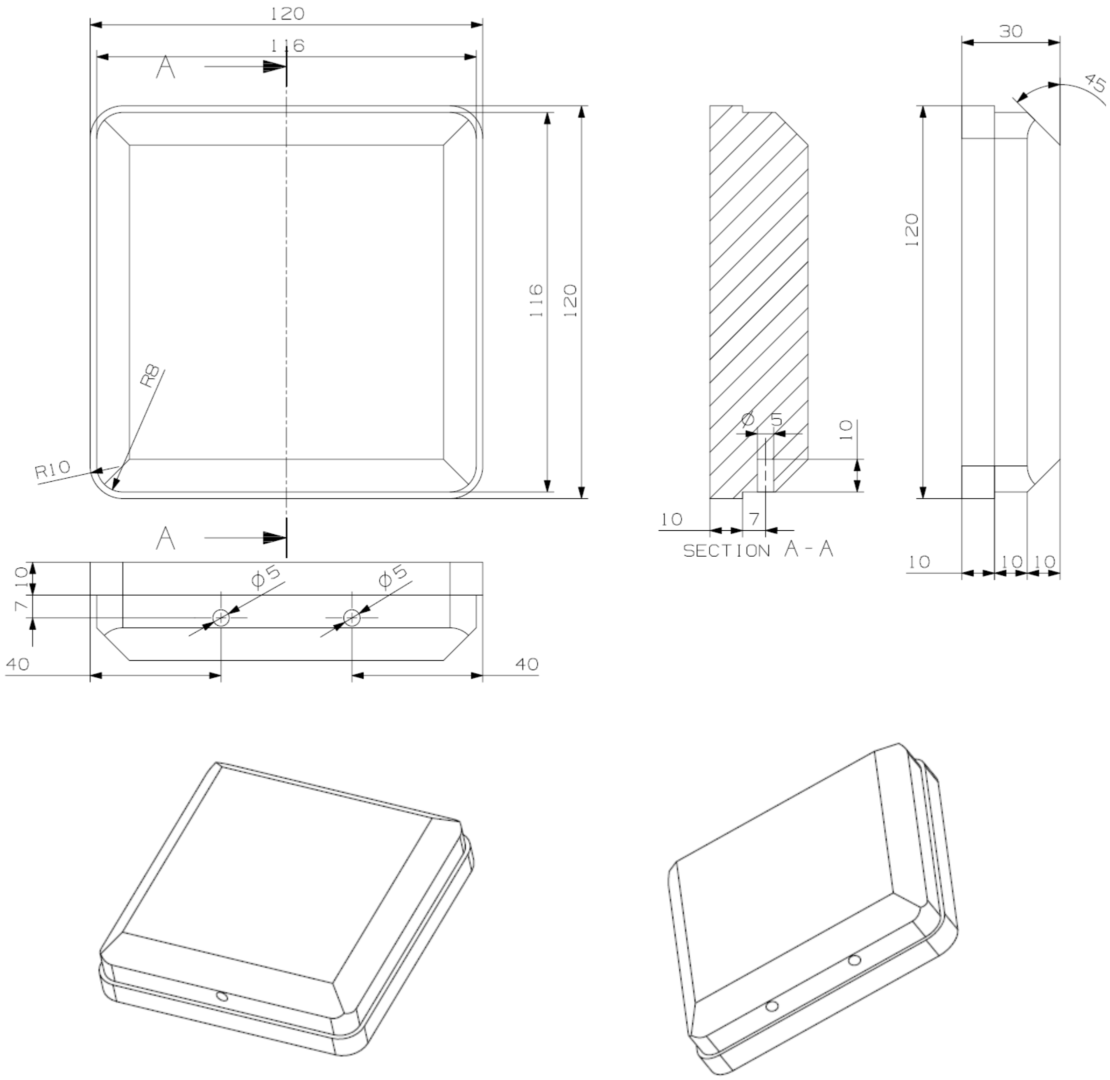


Figure 6: Solar absorber foam dimensions for solar furnace testing

2.2 Absorber samples

A total number of 16 foam samples was prepared by partner IKTS. The following table gives all important foam parameters. The parameter selection was based on the CAPTure project results [2].

Table 1: Foam samples and parameters for solar

Sample	Cell size	Weight	Length	Width	Height	Total porosity	Fixing
	ppi	g	mm	mm	mm	%	
S230-169	30	161.6	120.0	119.4	30.0	86.8	drill holes
S230-165	30	122.0	120.1	120.0	30.1	90.1	drill holes
S230-164	30	154.1	120.1	120.3	30.1	87.4	drill holes

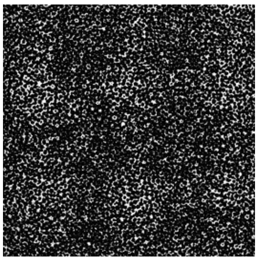
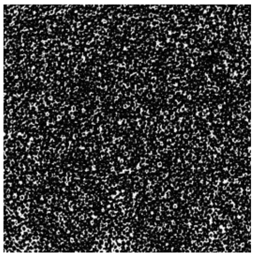
S230-168	30	152.7	120.1	120.0	30.1	87.5	
S230-166	30	146.2	120.0	120.0	29.5	88.1	drill holes
S230-170	30	147.9	119.8	119.9	30.1	87.9	
S230-167	30	142.2	120.0	120.0	29.9	88.4	
S230-163	30	109.5	120.0	120.0	30.1	91.1	drill holes
S237-2	30	147.7	120.1	120.0	30.0	88.0	drill holes
S237-4	30	153.2	119.9	120.0	30.2	87.5	drill holes
S237-3	30	148.3	119.5	119.8	30.1	87.9	
S237-1	30	138.7	120.2	120.2	30.1	88.7	
S237-7	30	154.2	120.0	120.1	30.1	87.4	drill holes
S237-5	30	120.9	120.1	120.1	30.1	90.1	
S237-8	30	119.3	120.0	120.0	30.2	90.3	drill holes
S237-6	30	118.7	120.0	119.9	30.2	90.3	drill holes

The estimated specific surface area of the foams, with a mean cell size of around 1300 µm, is between 2500 to 3000 m^2/m^3. The expected accessible porosity (cell porosity) is in the range of 81-84 %.

A CT characterization was performed of the foam samples at IKTS giving the results as indicated in Table 2.

Table 2: CT results of foam sample groups S230 and S237

Average geometrical values		**unit**	**S230**	**S237**
Cell diameter:	dc	(µm)	1470	1680
Strut diameter:	ds	(µm)	210	185
Window diameter:	dw	(µm)	490	560
Porosity total	ε	(%)	88.4	88.8
Cell porosity (accessible)	εc	(%)	85.0	85.4

specific surface area	Sv	(m^2/m^3)	2322	2017
Example Cross section through the middle of the foam in flow direction based on CT reconstruction				

2.3 Orifice dimensions

The air mass flow needs to be adjusted for each absorber module to achieve similar outlet temperatures despite the non-homogeneous solar flux profile at receiver scale. To study the impact of orifice diameter on air flow and absorber cooling, three orifice dimensions have been defined (60 mm, 40 mm and 30 mm diameter – see Figure 7).

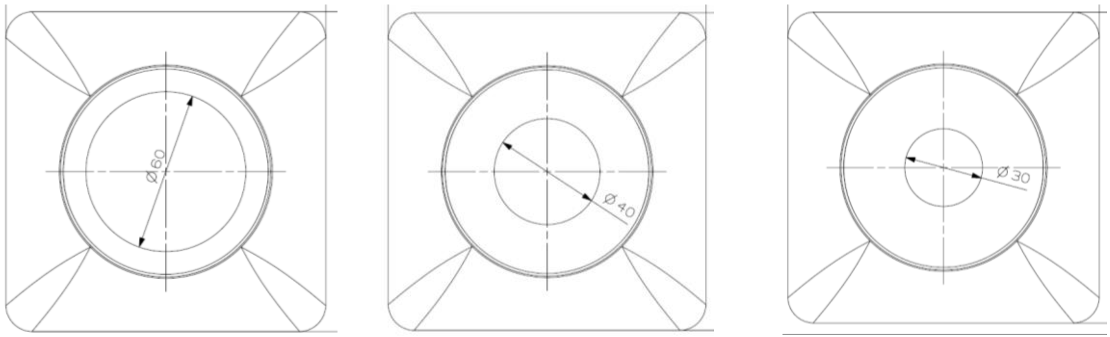
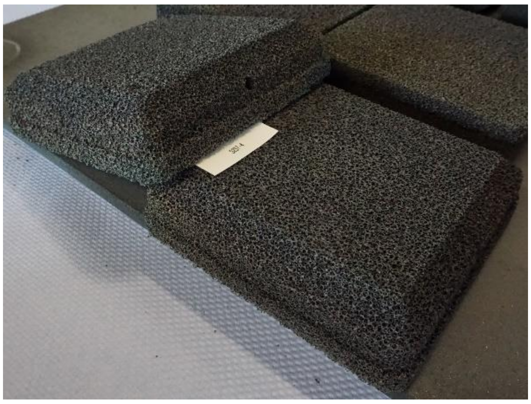


Figure 7: Orifice dimensions for solar furnace testing

The following figure shows manufactured absorber modules and foams. The absorber cups were manufactured by partner WPS using a lightweight and highly temperature resistant ceramic composite material.



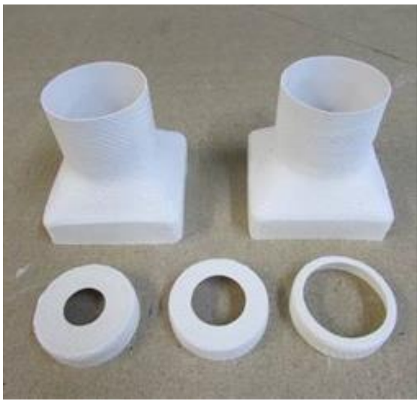


Figure 8: Manufactured samples for solar furnace testing

3 solar absorber testing at the high-flux tower plant at IMDEA

As intermediate step before the receiver testing at the modified CAPTure prototype (see Section 4), an experimental evaluation of one single absorber cup is planned at the experimental solar tower at IMDEA in Madrid. The estimated thermal power of the receiver module will be approximately between 20 and 30 kW, heating ambient air to high temperatures (800 – 900ºC).

A **tailored transportable thermal loop** for absorber module testing (see Figure 3 and Figure 10) will be used to test advanced ceramic foam modules at the IMDEA experimental tower (at slightly larger scale than at the solar furnace). A simple scheme of the test loop is shown in Figure 3. The volumetric absorber module (1) is mounted at the inlet of the air duct/receiver pipe (2). The ambient air is forced through the experimental circuit by a blower (6). In particular, the air is forced through the absorber module (1), the receiver pipe (2), the air/water heat exchanger (4) and the flow meter (5). The absorber sample (1) will be irradiated by concentrated light of IME's heliostat field (see Figure 9). The heat exchanger and the receiver unit are insulated (3) in order to keep thermal losses negligible. The air temperature is measured in a plane right after a following double membrane air mixer (3 K-type class 1 thermocouples in diagonal staggered configuration). The air mixer is of orifice type [3] and is needed in order to achieve a homogeneous mixing temperature of the air flow for correct representative air temperature measurement. The air temperature is also measured at the heat exchanger exit (cold end) with a single K-type class 1 thermocouple. The air/water heat exchanger is a simple shell and tube design, having the water flow on the shell side and the air flow on the tube side. To allow high receiver operating temperatures, the receiver air duct is not welded to the heat exchanger shell, in fact it is only attached in loose manner with one single bolt at the top center, such that the connection is statically determined and the inlet air duct can expand freely according to its temperature. Thus, no thermal stress is caused at the inlet section of the heat exchanger shell due to thermal expansion of the hot inlet duct. Both, the heat exchanger outer shell and the receiver inlet air duct are thermally insulated externally with layers of micro porous high-performance insulation material [4]. Thermal losses to the ambient are therefore negligible.

Figure 9: Experimental tower at IMDEA in Madrid

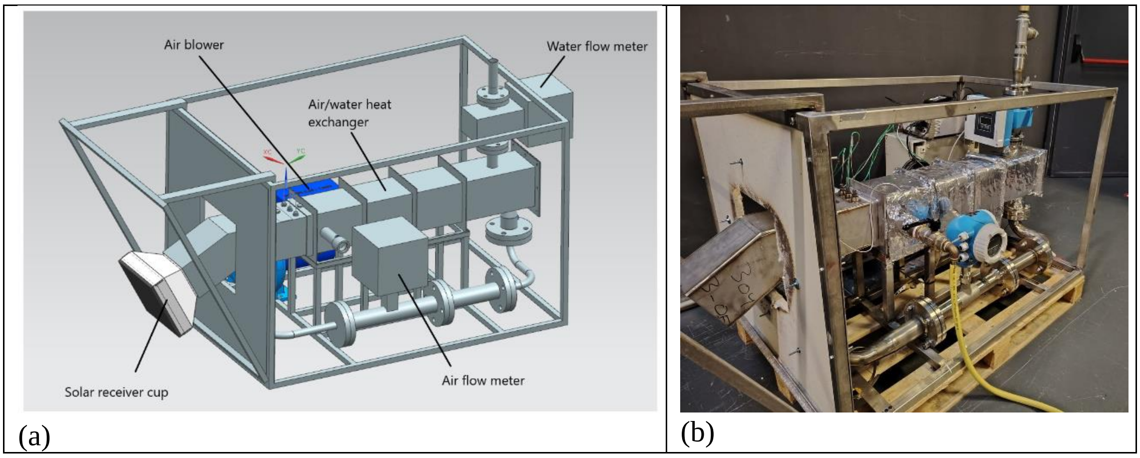


Figure 10: Transportable thermal test loop 30 kWth (800 x 1200 mm approx.); Receiver duct not yet insulated; 3D-model (a); Mounted test loop at CENER laboratory (b)

The air and cooling water mass flow are measured with a hot wire type flow meter and an electromagnetic flow meter, respectively (see Figure 11). The accuracy of the hot wire air flow meter is approximately 1% of measured value. The accuracy of the electromagnetic water flow meter is approximately 0.2% of measured value.

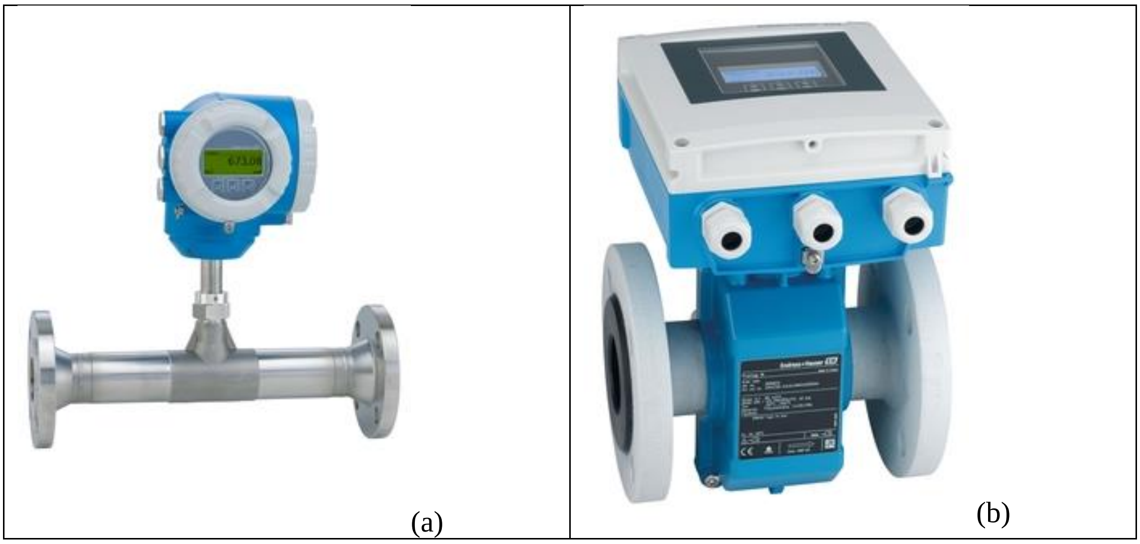


Figure 11: Hot wire air flow meter E+H model t-mass F 300 (a); Electromagnetic water flow meter E+H Promag W 400 (b)

3.1 Absorber module design

The module size for the experimental activity at IMDEA will be increased to 25 x 25 cm of aperture area. This will give valuable feedback regarding the performance of larger absorber tiles, when compared to the 14 x 14 cm tiles used in the CAPTure project. The proposed cup design is shown in Figure 12.

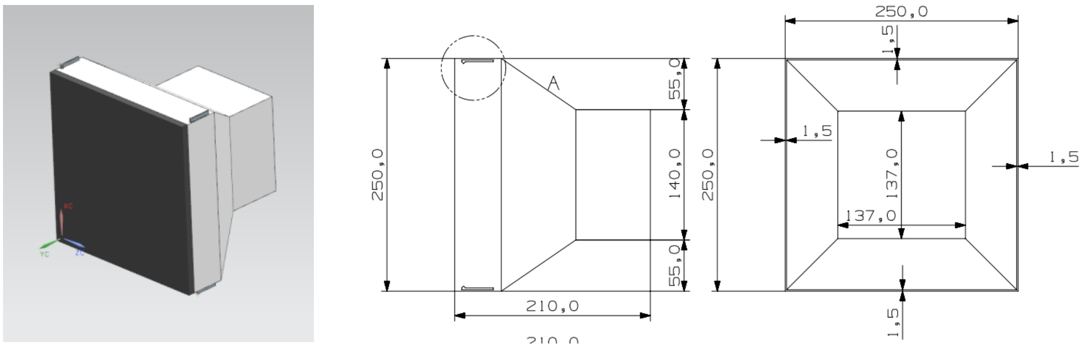


Figure 12: Absorber module design for testing at IMDEA

4 The ASTERIx-CAESar main demonstration prototype at CIEMAT-PSA

This section describes the prototype of a solar powered air turbine system, its design and specifications, operating modes, the corresponding control loops, as well as operator interfaces. The system is to be installed and operated at CIEMAT-PSA. The prototype is an extended research prototype that has been originally implemented during the CAPTure Horizon 2020 project [1].

The CAPTure (Competitive SolAr Power Towers) H2020 project lasted from May 2015 to July 2020 and focused on an innovative central receiver CSP plant configuration, investigating the application of an open volumetric air receiver (OVAR) for heat generation at highest temperature to power a combined cycle (CC) – topping Brayton, plus bottoming steam Rankine cycle – for efficient and competitive renewable power generation. The power plant key components, most critical for future commercial implementation, are (i) the CAPTure open volumetric air receiver (OVAR), and (ii) the CAPTure regenerative system coupling the high-temperature atmospheric air stream with the pressurized air loop of the topping Brayton cycle. A 300 kWth prototype was implemented, connecting the solar receiver with the regenerative heat exchange system and a small-scale Brayton cycle. Figure 13 shows the original CAPTure prototype.

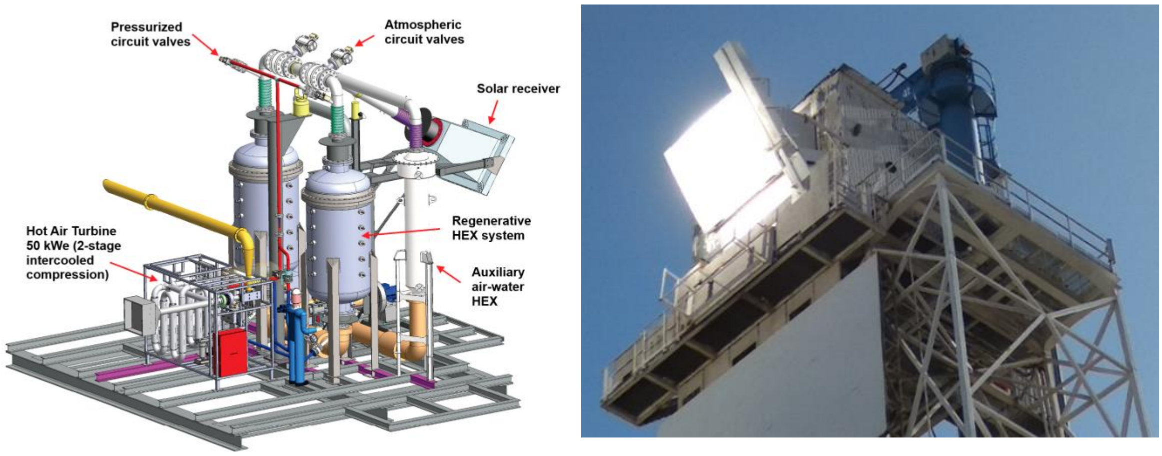


Figure 13: CAPTure validation prototype 3-D view (left); Receiver during on sun testing (right)

Unfortunately, the turbine start-up was not achieved during the CAPTure project due to several problems and limited testing time [1].

The ASTERIx-CAESar project is now modifying the existing prototype and will add a small-scale compressed air energy storage (CAES) unit to demonstrate the operation of the combined CAES-CSP concept. In particular, the CAPTure regenerative system will be replaced by a conventional shell-and-tube heat exchanger, the CAPTure hot air turbine will be reduced to a two-stage hot air expander, and the system at the top of the tower will be supplied with compressed air, coming from the CAES system, installed at the bottom of the tower.

The corresponding piping and instrumentation diagram (P&ID) is shown in Figure 14. The new prototype components are indicated in Figure 16 in colour (new air-air heat exchanger: red, new piping: yellow, new preheat/start-up blower: blue).

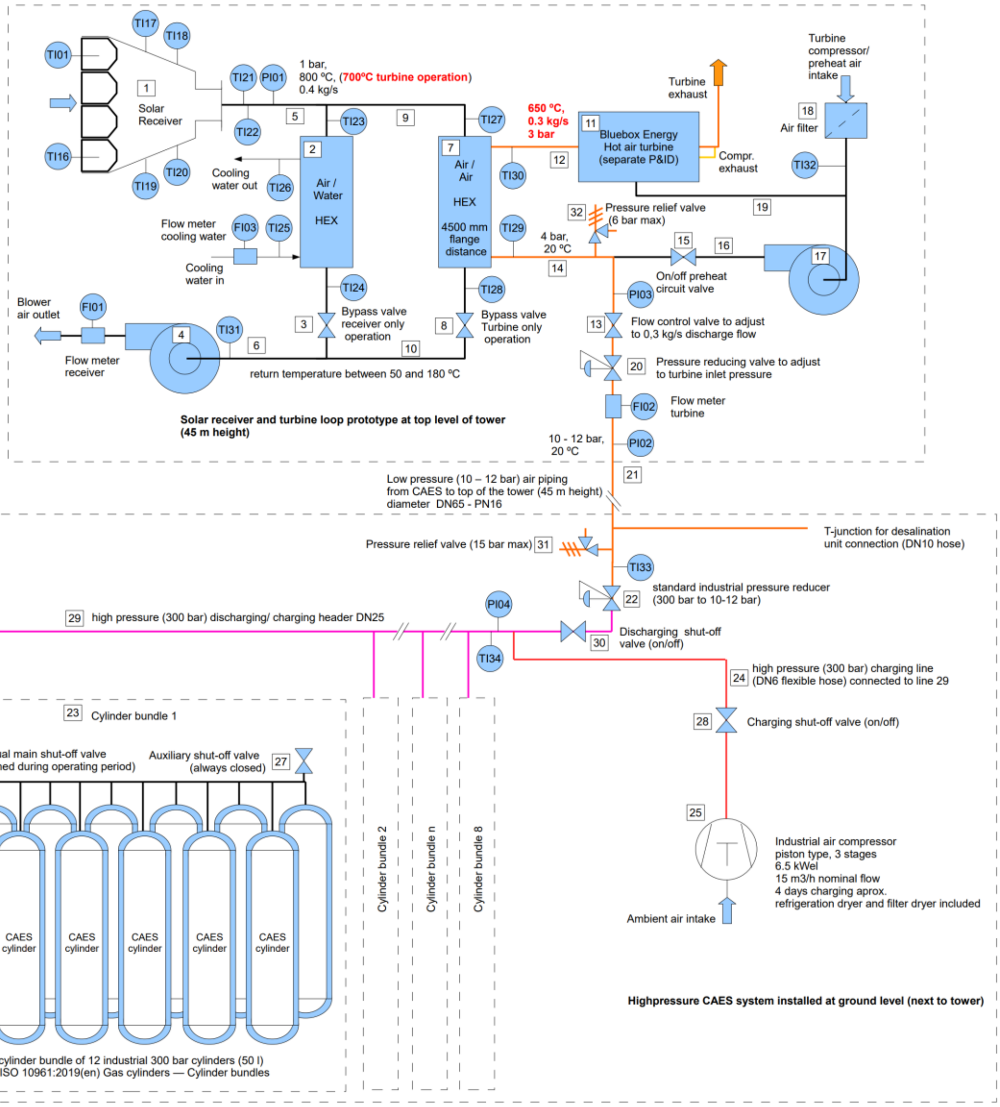


Figure 14: P&ID of solar powered air turbine and CAES system to be installed and operated at CIEMAT-PSA

The prototype consists of two installation areas, one at the top of a tower (45m height), and the other at the ground level.

At the top of the tower, the **solar receiver loop** as well as the **hot air turbine loop** is located.

At ground level, the **compressed air energy storage (CAES) system** is located, consisting of the compressed air storage volume as well as the air compressor.

These prototype installation areas will be connected via a compressed air piping (DN65 PN16) line going from ground level up to the top level of the tower (see Figure 15).

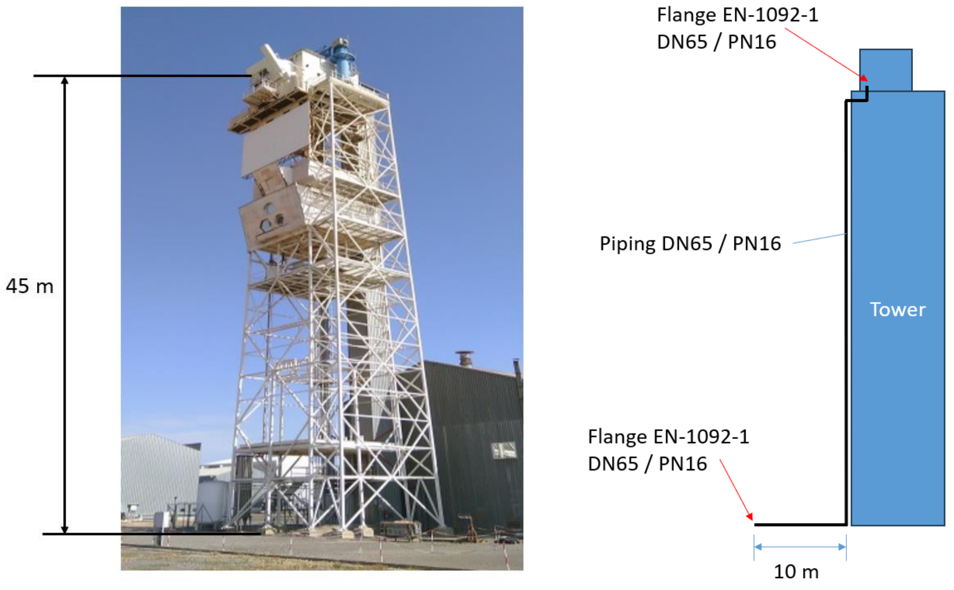


Figure 15: Experimental tower at CIEMAT-PSA and scheme of connection piping

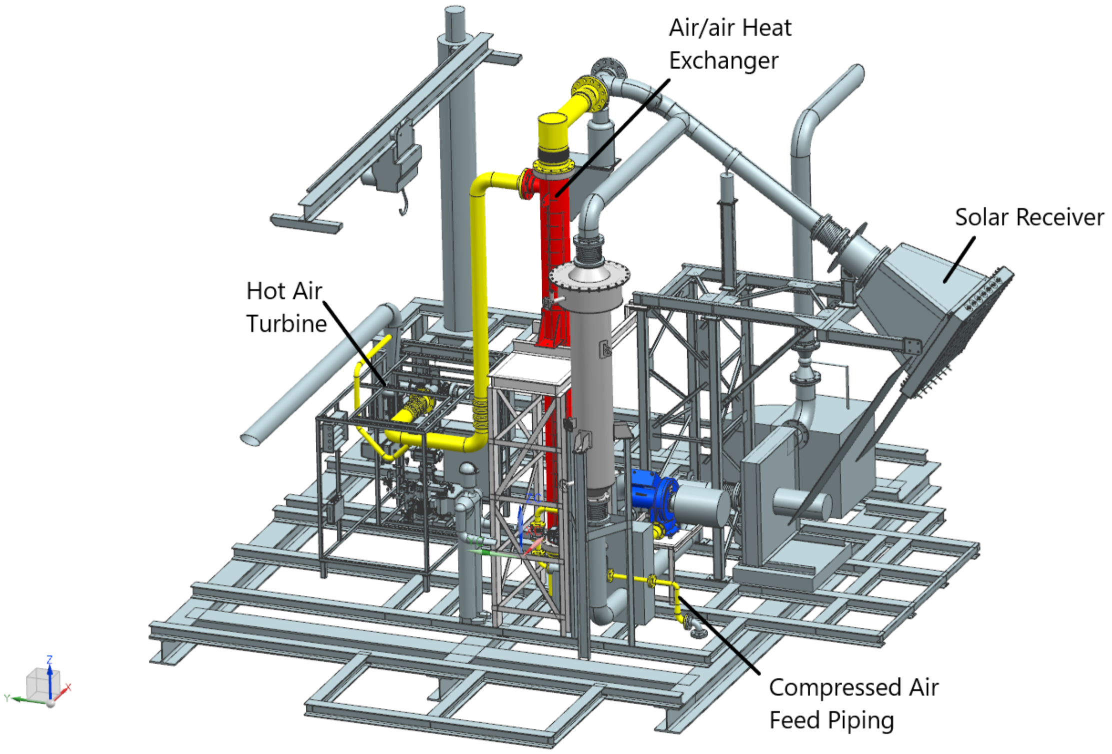


Figure 16: 3-D model of the ASTERIx-CAESar prototype solar receiver and turbine loop at the top of the tower

4.1 The solar receiver loop

The solar receiver loop consists of the solar receiver (300 kWth) that heats ambient air to high temperature (up to about 800ºC). For detailed information, the interested reader is referred to Ref. [1]. The basic working principle is that the incoming concentrated solar flux (from the solar field's mirrors – see Figure 17) heats a porous ceramic structure. At the same time, the ceramic structure is cooled by ambient air that is forced through the receiver using an air blower. By cooling the ceramic structure, the air can reach very high temperatures. Figure 18 shows the receiver working principle.

Figure 17: Experimental solar receiver in operation – The heliostat field concentrates solar flux onto the receiver aperture area

The porous ceramic structure is designed modular, each module consisting of a ceramic foam absorber and a ceramic cup, which holds the absorber in place and guides the air flow. The whole receiver consists of a certain number of identical modules that are stacked on top of each other (see Figure 18 – left hand side). The ASTERIx-CAESar project will apply larger receiver modules than the CAPTure project, in order to reduce cost. The exact module dimensions will be determined later in the project. The CAPTure receiver casing will be reused.

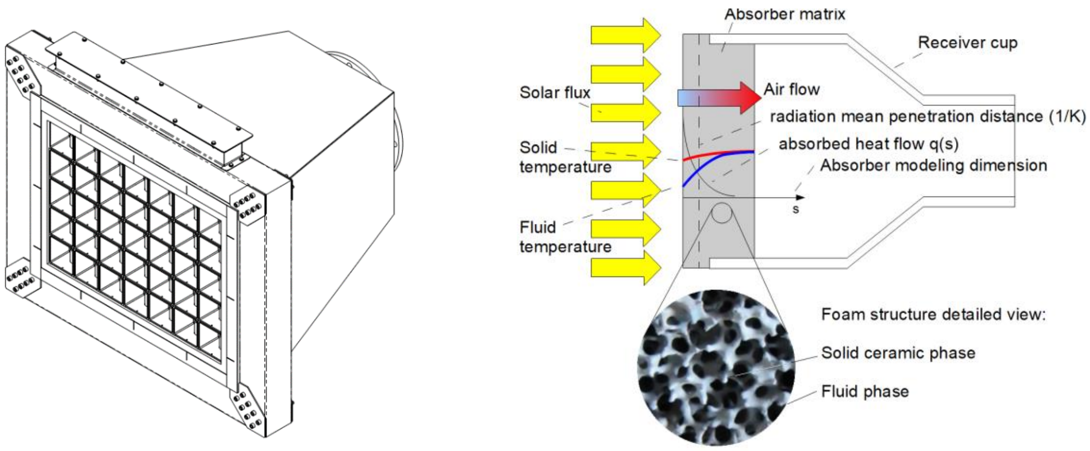


Figure 18: CAPTure Open volumetric air receiver (OVAR) 3-D view (left) and its operating principle (right)

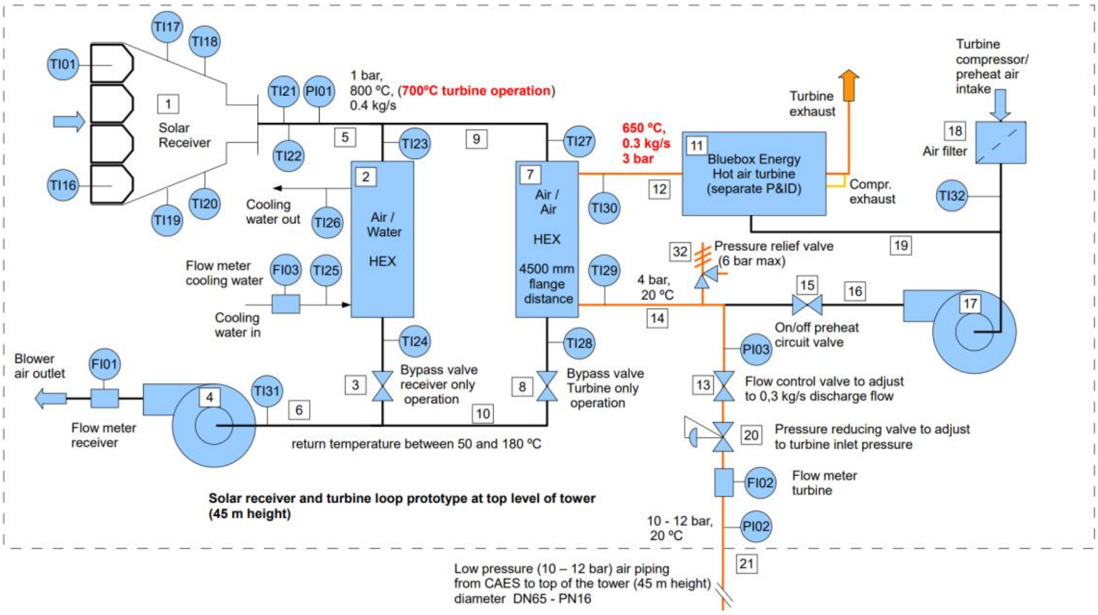


Figure 19: Prototype solar receiver loop and turbine loop P&ID at the top of the tower

The solar receiver loop further consists of the air blower (item number 4 in Figure 19) that forces the air through the receiver and the piping system. The hot air exiting the solar receiver can either be directed over an air/water heat exchanger (2) (where it is cooled down to below 200ºC), or it can be routed over an air/air heat exchanger (7) (where it is also cooled down to below 200°C) that thermally connects the hot air turbine loop. Two valves (items 3 and 8) are used to direct the air flow either over the air/water heat exchanger or the air/air heat exchanger.

4.2 The hot air turbine loop

The loop of the turbine (at the top level of the tower) consists of the compressed air piping (item number 21) entering the testing level, the flow control valve (item number 13), the air/air heat exchanger (7), as well as the turbine block itself (item number 11). Piping (14) and (12) connect the flow control valve and the turbine system to the air/air heat exchanger. Valve (15) is closed in normal turbine operation.

To preheat the turbine system during the start-up procedure, an auxiliary blower is going to be installed (item number 17). This blower moves ambient pressure air through the air/air heat exchanger, where it is warmed up and then enters the turbine system to preheat the air expander stages in the start-up process. During this warm-up procedure, the compressed air control valve (13) is closed, and valve number (15) is open.

An additional necessary feature is the intake air piping (item number 19) for the turbine system. This air intake is required because the turbine system is composed of a re-used small-scale Brayton cycle with radial turbo machinery, based on modified truck turbo-charger components. The first air expansion stage is that of a turbocharger. Hence, the air intake is the inlet of the turbocharger compressor wheel. The outlet air of the compressor stage is then simply rejected to the environment without further use. This is the most economical solution for demonstrating the air expander at small scale in the above-mentioned prototype.

4.2.1 Hot air turbine P&ID

Figure 20 shows the hot air turbine P&ID, which is the detailed view of item number 11 in Figure 19.

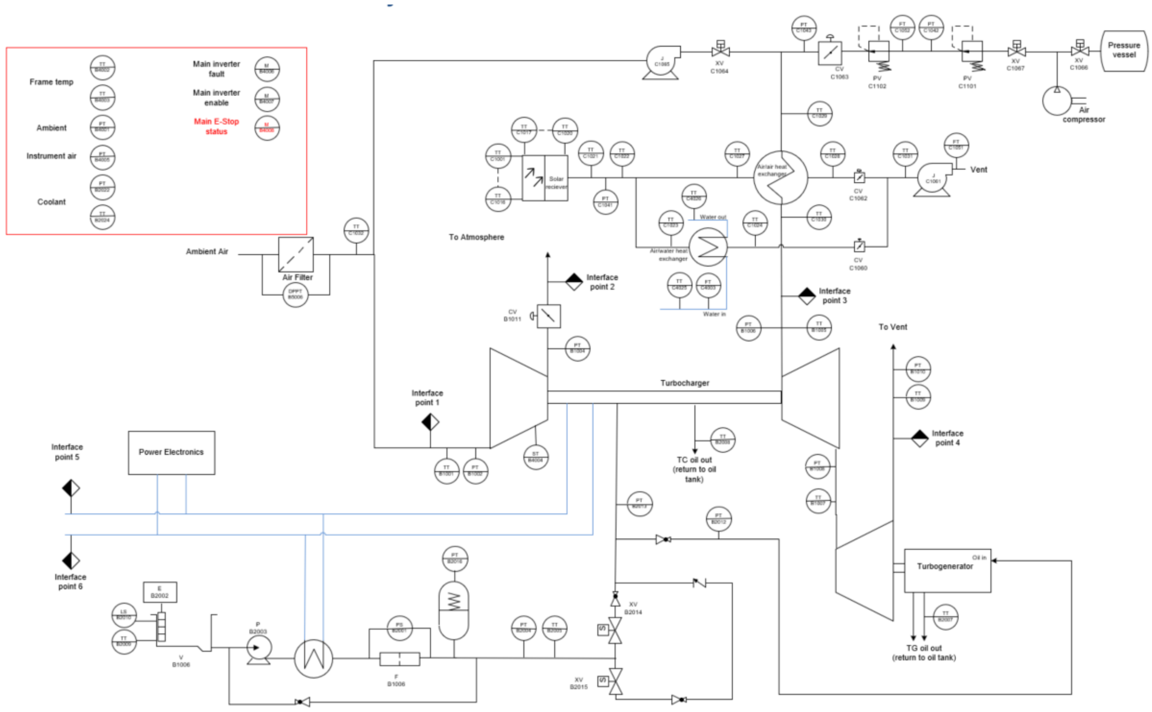


Figure 20: Hot air turbine P&ID – Two-stage air expander

4.3 Detailed information of new prototype components

This section will describe all new components that will be added to the CAPTure prototype.

4.3.1 Air-air heat exchanger for heating the compressed air before expansion in the turbine

The existing CAPTure prototype will be modified to work in combination with a CAES system. A new air-air heat exchanger will be installed and connected to the existing receiver loop. It will have a thermal rating of about 200 kW. The heat exchange area will be about 56 m^2. The geometrical details and design parameters are given in Figure 21.

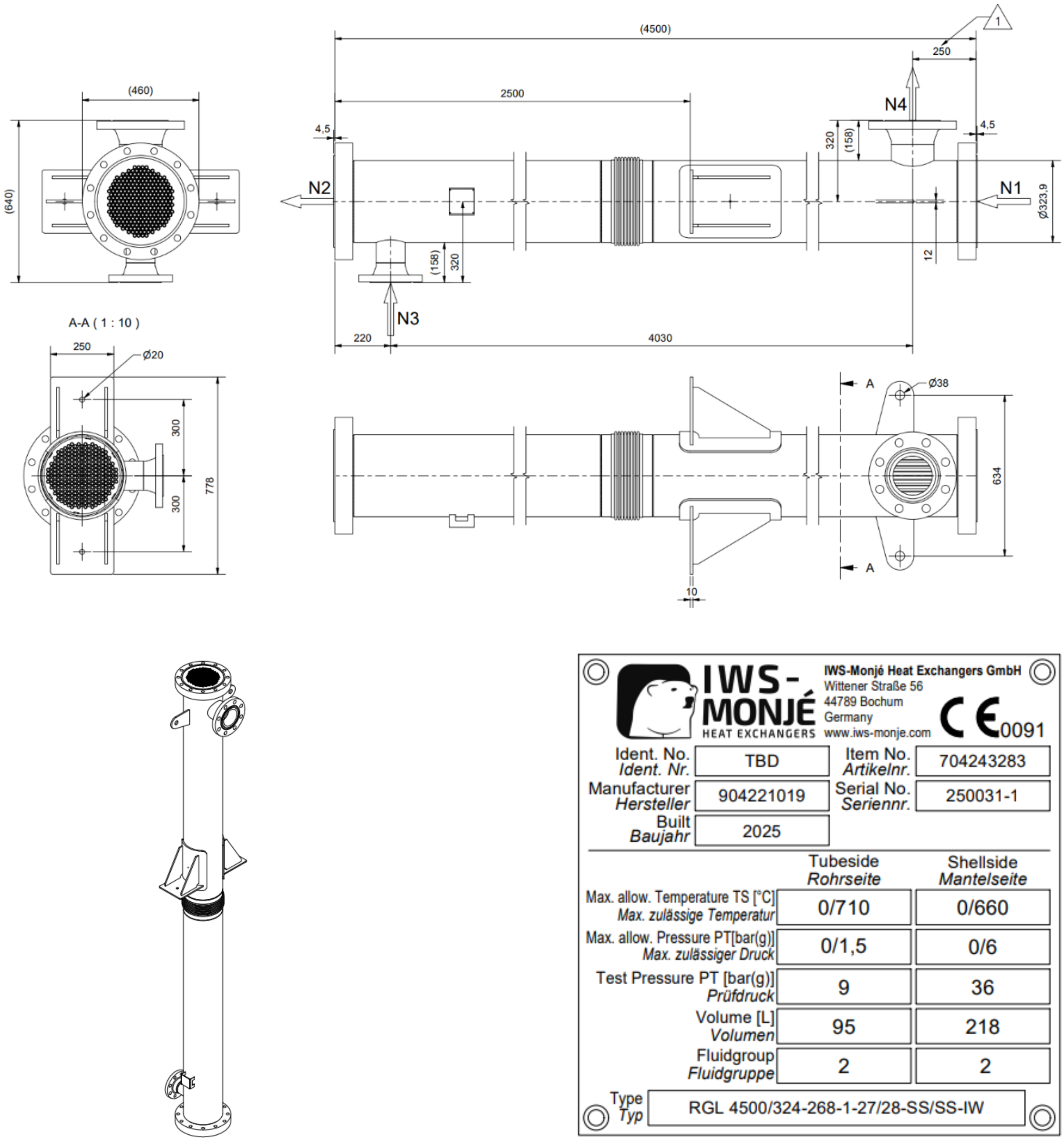


Figure 21: Air-air heat exchanger for heating the compressed air before expansion in the turbine

4.3.2 Air-air heat exchanger connection piping

The air-air heat exchanger will be connected to the existing receiver air loop with two piping sections with welded axial corrugated expansion joints (see Figure 23). The connection piping is composed of a DN200 pipe section and a DN300 pipe section. The DN200 pipe has an outer diameter of 219.1 mm. By selecting schedule 10 (wall thickness 3.76 mm), the inner diameter would be 211.58 mm. The DN300 pipe has an outer diameter of 323.8 mm. By selecting schedule 10 (wall thickness 4.57 mm), the inner diameter would be 314.66 mm.

The necessary expansion bellows with weld ends to be welded into the pipes are one with DN200, and one with DN300 specifications. The maximum thermal expansion is expected at the top (hot end) horizontal connection piping. Assuming a thermal expansion coefficient of about 18.1e-6 K^{-1}, and a maximum temperature change of 800 K, then the thermal expansion per meter of pipe length would be 14.48 mm. Thus, a thermal expansion of the horizontal pipe section would be about 15 mm in the worst case. The vertical section would have to compensate for the expansion of the heat exchanger above the mounting point with about 2 meters of heat exchanger length. The total HEX expansion above the mounting point would be about 25 mm (delta T 650 K).

Axial expansion joints for low pressure (PN1) would have the following dimensions (HKS corrugated expansion joints) for DN200: BL: 210 mm, da: 219.1 mm, Da: 265 mm, Lb: 90 mm, s: 2 mm. The DN300 bellow would have the following dimensions: BL: 215 mm, da: 323.9 mm, Da: 375 mm, Lb: 82 mm, s: 7.1 mm (see Figure 22).

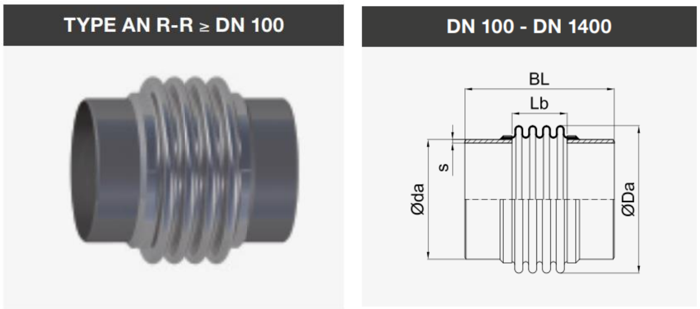


Figure 22: Welding ends corrugated expansion joints

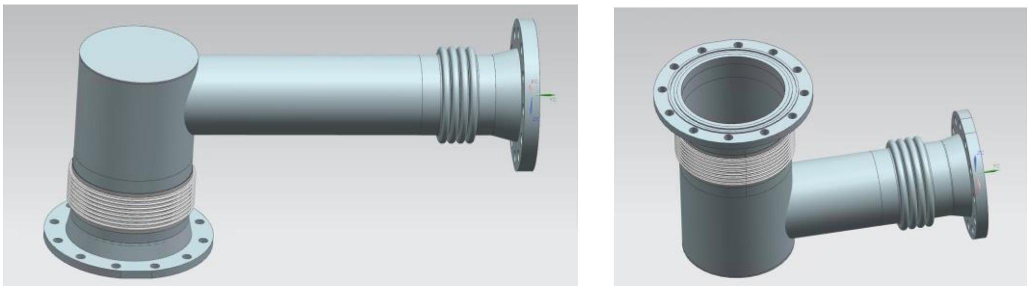


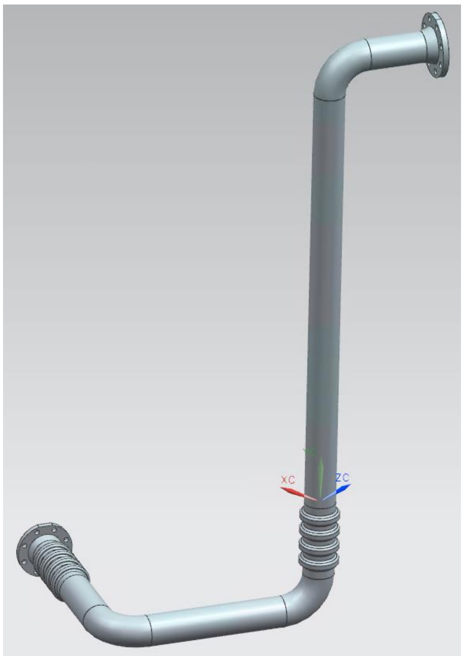
Figure 23: Air-air HEX connection pipe at top (hot): left; connection at bottom end (cold): right

As can be seen in Figure 23, both connection piping configurations have an L shape and expansion compensators are integrated in both legs. Once the heat exchanger or piping heats up, the expansions will mainly result in angular adjustments of the bellow, rather than axial adjustments. The proposed material of all the low-temperature piping is conventional AISI 304, the high-temperature piping will be made of AISI 316

4.3.3 Hot air turbine and connection piping

The hot air turbine inlet is connected to the air/air heat exchanger via a DN150 pipe with three 90-degree bends and two expansion bellows of an axial absorption potential of about 64 mm. The dimensions of the expansion bellow would be as follows: da = 168.3 mm, BL = 415 mm, s= 4.5 mm, Lb = 303 mm, Da = 212 mm (see Figure 24). The vertical pipe part needs to be supported right above the lower 90-degree bend in order to absorb the force, generated by the vertical thermal expansion.

The air-air HEX outlet flange is of type EN1092-1 / DN150 PN63-D. The proposed material of the connecting piping is EN 1.4828 (DIN X15CrNiSi20-12, AISI309), the same material as chosen for the air-air heat exchanger. The nominal operating pressure will be about 3 bar. The nominal operating temperature is 650ºC. DN150 has an external tube diameter of 168.3 mm. According to ASME code[5, 6], tube wall thickness of 3.4 mm (schedule 10) would be sufficient under such operating conditions.



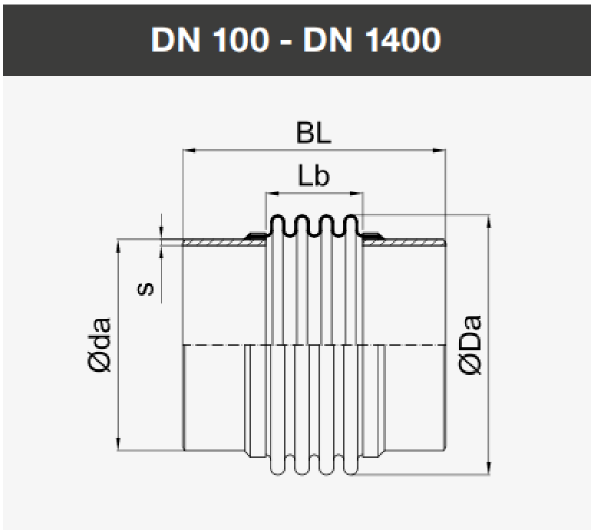


Figure 24: Hot air turbine connection piping 3D view (left); Expansion bellow drawing (right)

4.3.4 Compressed air transport piping and connection with air/air heat exchanger

The CAES system will be connected to the ASTERIx-CAESar prototype at the top of the tower via a low-pressure compressed air transport piping (DN65, PN16). This piping goes partially underground until reaching the base of the tower. The vertical piping (45 m) is clamped to the tower structure and enters the top testing level from below. The top flange is located at the north-east corner of the testing level. The compressed air transport piping is installed since December 2024 (see Figure 25).

The DN65 low-pressure piping is suggested with schedule 5 (OD 73 mm; wall thickness 2.11 mm), which results in an internal diameter of about 68.78 mm. According to ASME boiler and pressure vessel code [5, 6], when using a piping material with maximum allowable stress around 90 MPa, operating pressures of up to 50 bar shall be possible.

The DN65 piping that goes up to the tower is then reduced inside the tower to a DN40 pipe, since pressure drop is not an issue and the mass flow sensor and the additional pressure reducer (to achieve turbine inlet pressure) are of DN40 dimension. In this case, the pipe can also be schedule 5, having OD 48.3 mm and internal diameter of 45 mm.

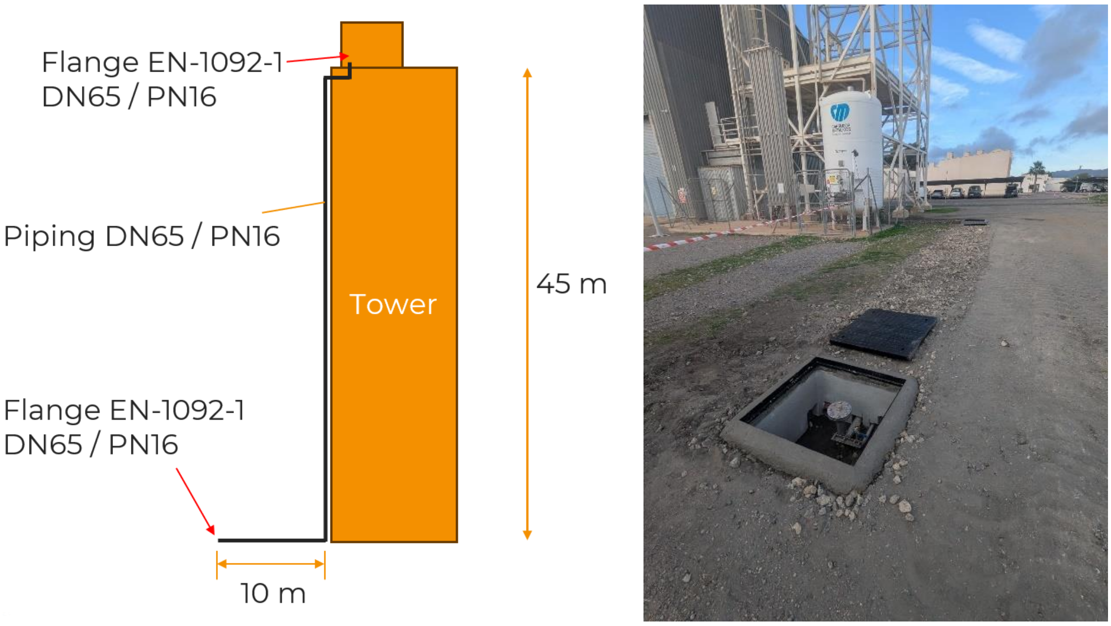


Figure 25: Scheme of compressed air transport piping

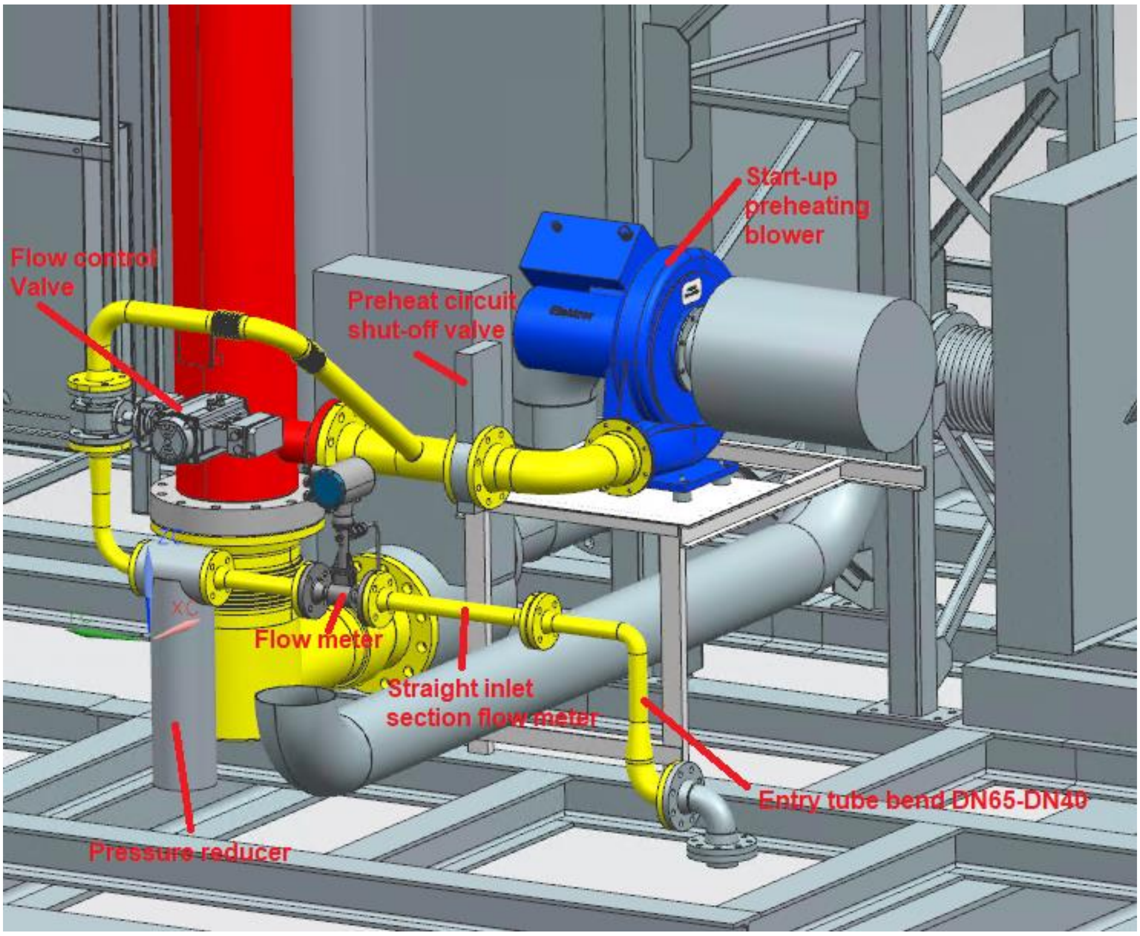


Figure 26: Compressed air line entry piping in tower testing level

The transition pipe from DN65 to DN40 is connected to a straight DN40 tube section with integrated flow rectifier since the minimum straight pipe length cannot be achieved in the available space (see Figure 26 and Figure 27).

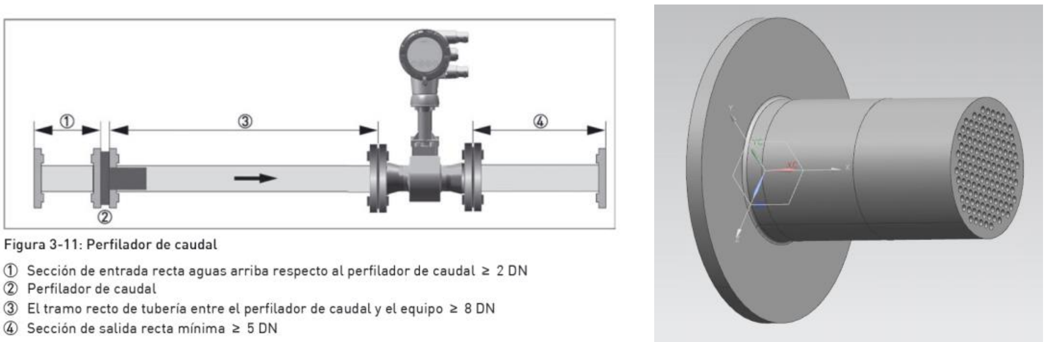


Figure 27: Flow meter and necessary straight tube sections before (>=8DN) and after (>=5DN); flow rectifier DN40 to be mounted between flanges (right)

A vortex-type flow meter (Krohne OPTISWIRL 4200) with pressure and temperature compensation has been chosen. The expected accuracy is at about 1.5% of measurement value.

The flow meter is followed by a straight tube section. The next component is a secondary pressure reducer, which reduces the pressure to the target turbine inlet pressure. Prior to turbine operation, the pressure reducer needs to be manually adjusted such that the real pressure drop in the entire compressed air line is taken correctly into account.

The secondary pressure reducer’s flange diameter is DN40 (Model SAMSON model Type 41-23, PN 16 , kvs 20, adjustable pressure range from 2 to 5 bar g).

The pressure reducer is followed by a 90 bend and a straight tube section which changes from DN40 at the inlet to DN50 at the outlet to connect the DN50 control valve that can be reused from the former CAPTure project.

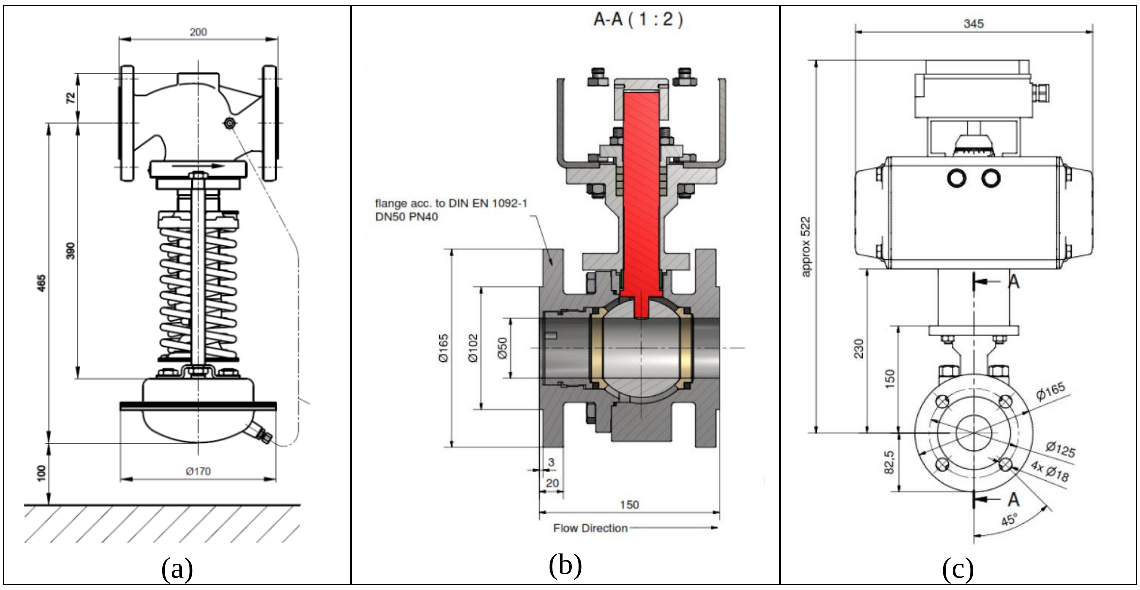


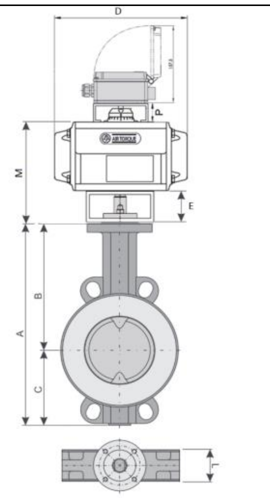
Figure 28: SAMSON pressure reducing valve (a); CERA-SYSTEM ball valve for flow control (b, c)

After the control valve, a tailored DN50 piping connects to the DN100 line that connects to the air/air heat exchanger inlet flange, as well as to the preheat circuit shut-off valve.

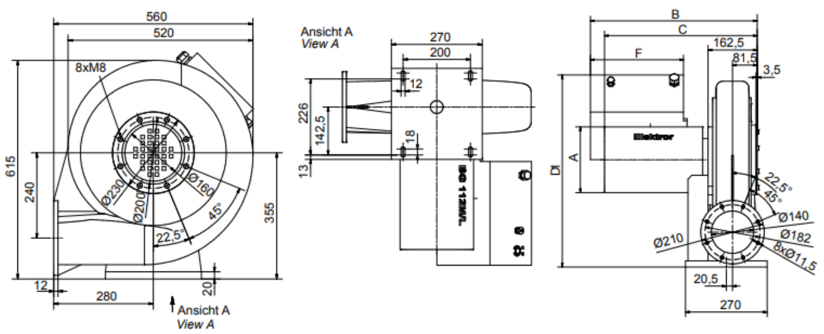
A DN100 pipe is required to connect the auxiliary start-up blower with the air/air heat exchanger. The maximum operating pressure will be 6 bar. Flanges will be selected according to PN16. The outer tube diameter will be 114.3 mm. Selecting schedule 10, leads to 3.05 wall thickness (108.2 mm ID). According to ASME code, this should allow up to 50 bar operating pressure with 90 MPa stress limit.

The preheat circuit shut-off valve (valve 15 in P&ID - Figure 14/Figure 19) is closed during operation with compressed air. A simple butterfly valve can be used for this application (see Figure 29-a).

An important feature of the DN100 piping, which connects auxiliary preheat blower and the compressed air feed piping, is a safety blow-off valve that opens in case the pipe pressure reaches 6 bar. This is needed as the maximum operating pressure of the air-air heat exchanger is 6 bar (see item 32 in Figure 19, and Figure 31).



(a)



Typ	A	B	C	D	D1	E	F
HRD 65 FU-100/5,5	Ø218	-	505	-	-	-	-
HRD 65 FUK-100/5,5	Ø218	551,7	505	286	636	223	308
HRD 65 FU-100/7,5	Ø218	-	505	-	-	-	-
HRD 65 FUK-100/7,5	Ø218	551,7	505	286	636	223	308

(b)

Figure 29: SAMSON 3335 DN 100 Wafer (a); Elektror blower HRD-65-FUK-100-7.5 (b)

The preheat circuit shut-off valve connects to the turbine preheat blower (item number 17 - in P&ID - Figure 14/Figure 19) The model HRD-65-FUK-100-7.5 from Elektror is available from the CAPTure project and can be reused in ASTERIx-CAESar as preheat blower.

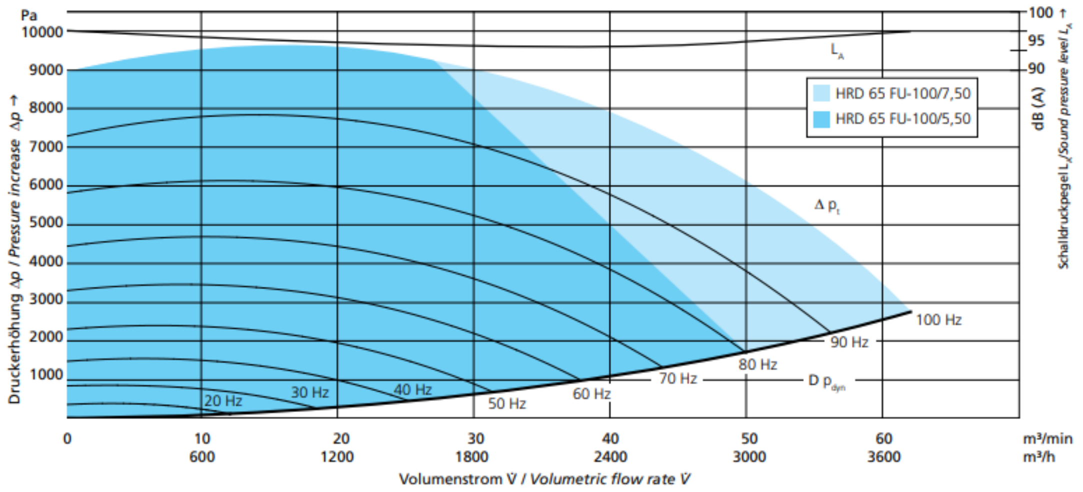
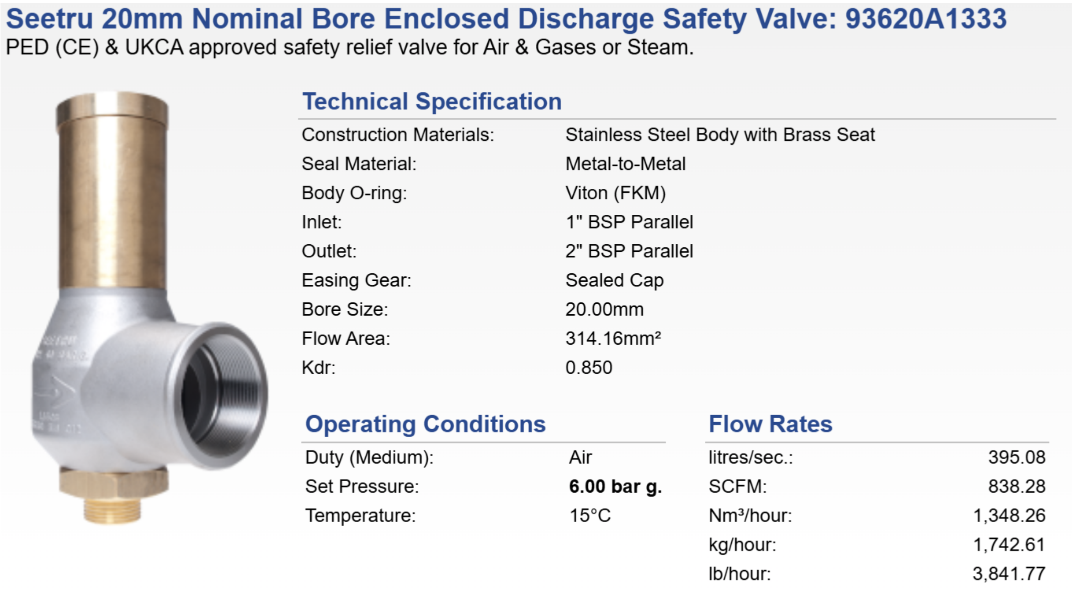


Figure 30: Turbine preheat blower characteristics (Elektror HRD-65-FUK-100-7.5)



Seetru 20mm Nominal Bore Enclosed Discharge Safety Valve: 93620A1333
PED (CE) & UKCA approved safety relief valve for Air & Gases or Steam.

Technical Specification

Construction Materials:	Stainless Steel Body with Brass Seat
Seal Material:	Metal-to-Metal
Body O-ring:	Viton (FKM)
Inlet:	1" BSP Parallel
Outlet:	2" BSP Parallel
Easing Gear:	Sealed Cap
Bore Size:	20.00mm
Flow Area:	314.16mm²
Kdr:	0.850

Operating Conditions

Duty (Medium):	Air
Set Pressure:	**6.00 bar g.**
Temperature:	15°C

Flow Rates

litres/sec.:	395.08
SCFM:	838.28
Nm³/hour:	1,348.26
kg/hour:	1,742.61
lb/hour:	3,841.77

Figure 31: Pressure relief valve 6 bar for use after secondary pressure reducer (before air/air HEX)

4.4 The compressed air energy storage (CAES) system

The CAES system is installed at ground level, next to the tower. It consists of 8 bundles of 12 pieces of 50 litre gas cylinders each, connected together (see Figure 33). The nominal storage pressure of these industrial gas cylinders is 300 bar. The total storage volume is 4.8 m^3.

The cylinder bundles will be temporarily immersed in warm water to limit temperature reduction during air expansion. At least one above-ground pool will be needed with adequate sizing. To allow dry storage of high-pressure cylinders during down-time, the water will be pumped to a second auxiliary pool or closed water storage tank next to the CAES system (see Figure 32). A closed water storage tank will be the preferred option to avoid contamination of the water during down-time.

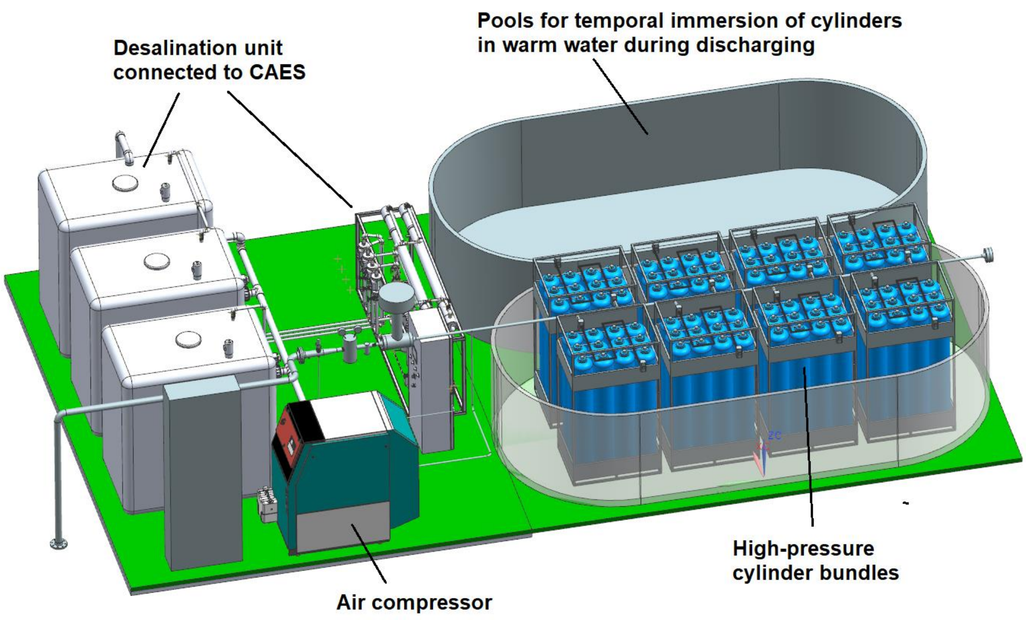


Figure 32: ASTERIx-CAESar prototype at ground level: CAES and desalination system overview

Each cylinder bundle features two manual shut-off valves (see Figure 33 (b)), one being connected to the charging/discharging header (item number 29), the other is always closed. The discharging/charging header (29) is connected to shut-off valves (item number 28 for charging, and item number 30 for discharging). After the discharging valve (30), a standard industrial pressure reducer (item number 22) reduces the pressure to the level of the low-pressure piping (21) connecting the CAES system with the turbine loop at the top of the tower.

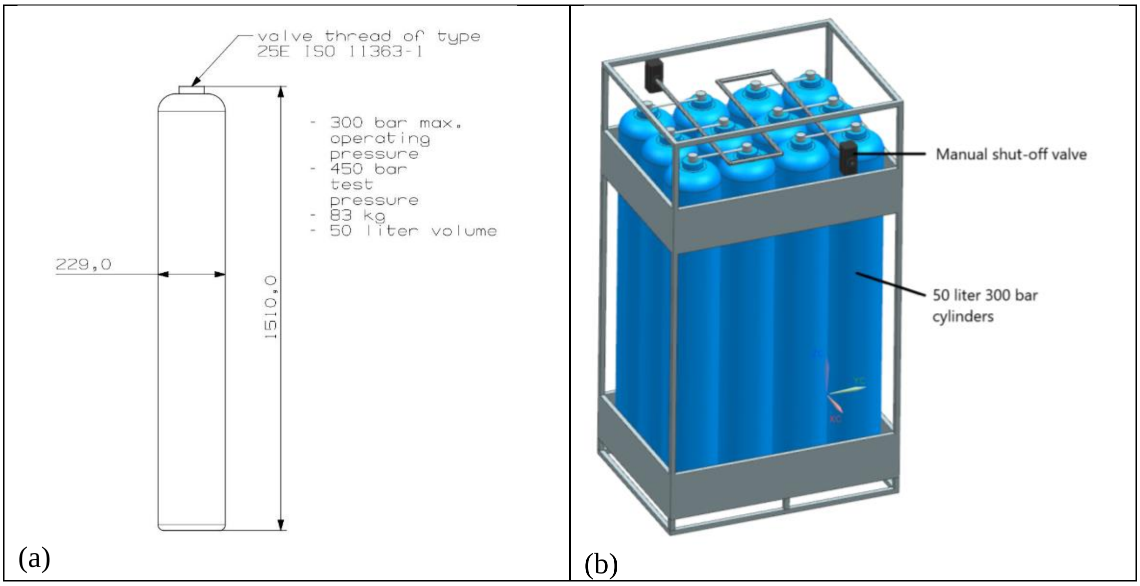


Figure 33: Cylinder dimensions (mm) and data (a); Cylinder bundle example 3D view (b);

The shut-off valves (30 and 28) of the cylinder bundles are to be actuated either remotely over the PLC. Alternatively, also a manual operation may be considered in order to reduce costs (see Figure 45 – (d)).

The industrial piston compressor (item number 25) charges the system during approximately 3 to 4 days of continuous operation. Thus, the charging time is considerably longer than the discharge time. The planned discharge time is approximately 1 hour with nominal flow of 0.3 kg/s.

The compressed air energy storage unit will be composed of bundles of industrial high-pressure cylinders. Each cylinder is connected with a steel pipe of 5 mm internal diameter. Then, a header pipe of 10 mm internal diameter connects each cylinder pipe and finishes with a manual main shut-off valve (see Figure 34). The main shut-off valve is typically equivalent to a cylinder shut-off valve with 25E ISO 11363-1 conical thread, the only difference is that the valve is fitted to a main-valve holder (Figure 34 (d)) that connects to the bundle tubing.

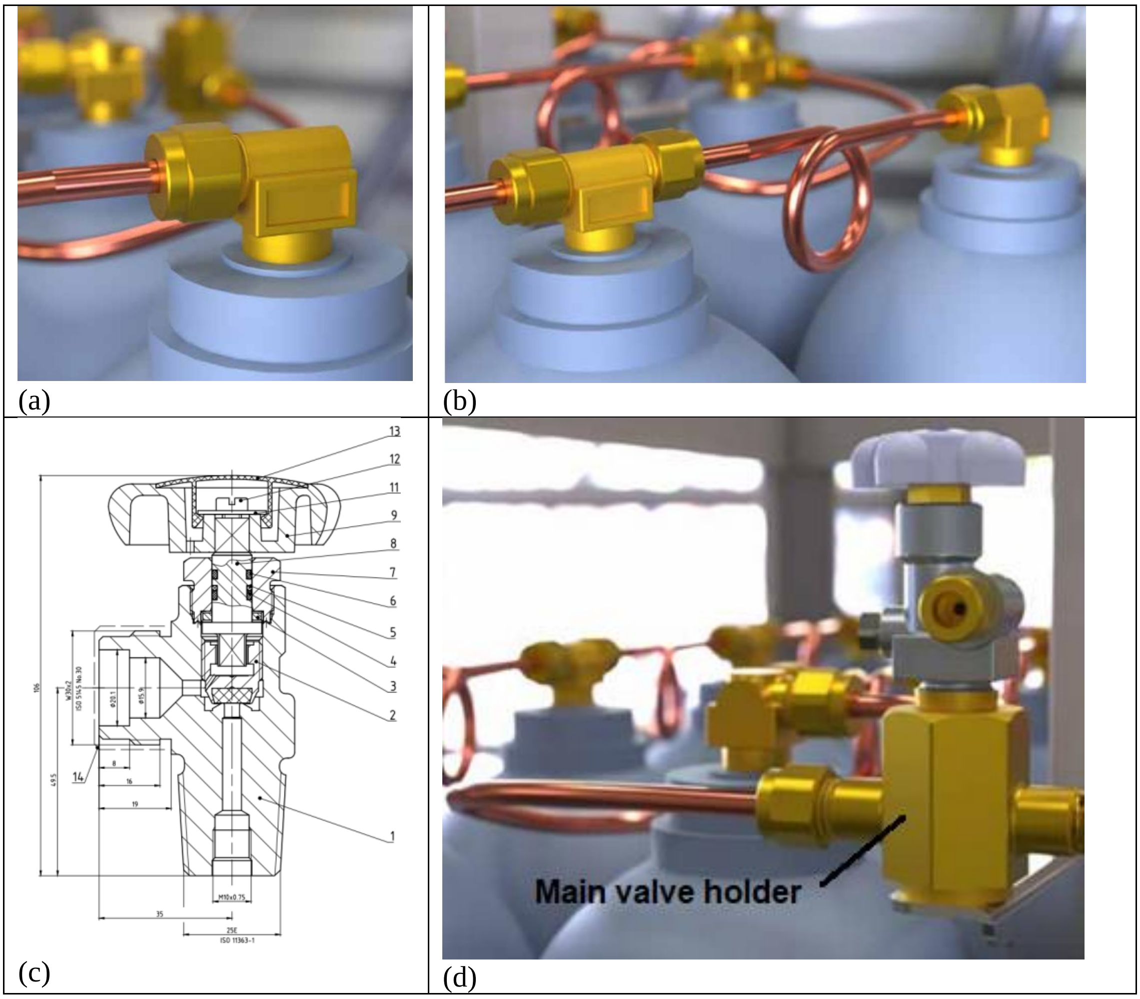


Figure 34: Cylinder bundle detailed views: One-way fitting connected to a cylinder (a); Two-way fitting connected to a cylinder (b); cylinder bundle main valve example – ISO 5145 No. 30 connection (c); Main valve holder with main valve thread of type 25E ISO 11363-1 (d) [7]

The outlet connection of the main shut-off valve can have different types, depending on the country, applied norm, and gas type. The connection threads are different for each gas type to avoid wrong connections. For example, ISO 5145 (Provisional standard, previously NEVOC) No. 30 (W30 x 2 (15.9-20.1) right-handed thread) could be an option (see Figure 34 (c)).

In Germany, valve connections for gas cylinders are covered by DIN 477. For the application of compressed air, connection number 52 (not inflammable gases and non-toxic gases until 300 bar pressure, M30 x 1.5 female right-hand thread), or connection number 56 (pressurized air – W30 x 2 (16.6 / 19.4) right-handed thread) would be possible.

In Spain, the requirements according to MIE-AP 7 B (Ministerio de Inudstria y Energia – Aperatos a Presión) would be applicable. Also ITC EP-6 (Instrucción Técnica Complemetaria - Equipos Presión) Type B (M30x1.75) would apply for air [7].

The connection type for the ASTERIx-CAESar prototype will depend on the supplier with the most competitive offer. A high-pressure stainless-steel hose (DN6) will connect each cylinder bundle with the high-pressure main line (DN25) (see Section 4.4.1). The DN25 main line will have G 1/4” high-pressure threadolets welded (one for each bundle) and an additional connection for the compressor. The compressor will be connected with a high-pressure hose as well. The standard connection for BAUER compressors is the so-called “Unimam / M16 x 1.5 nut & nipple” type (see Figure 35 (a, b)). When using a standard BAUER compressor hose, a fitting needs to be applied that connects the hose (female thread) to the main pressure line G 1/4” (female thread) (see Figure 35 (c)).

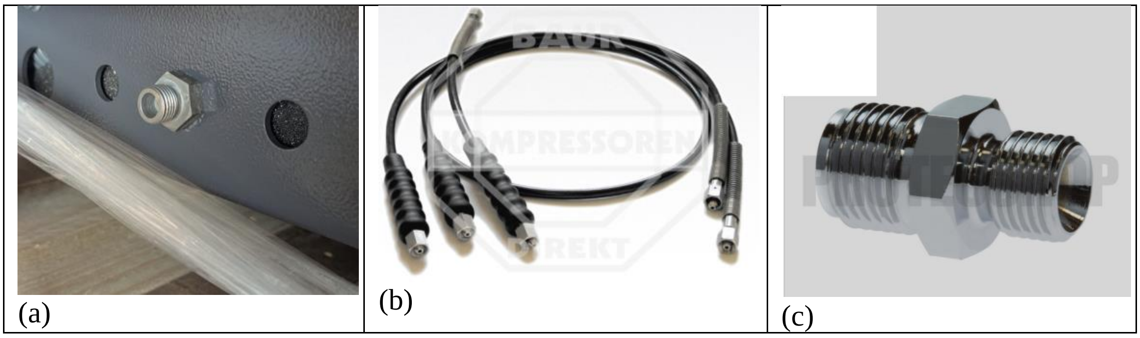


Figure 35: BAUER compressor connection: male M16x1.5 thread at compressor (a); Unimam M16x1.5 nut connection on high-pressure hose (b); Nipple fitting BAUER M16x1.5 male – G ¼” male (c)

One main header pipe is foreseen that connects all 8 bundles and finishes with a main shut-off valve for the air storage system. The main header is a DN25 line with maximum operating pressure of 300 bar.

Assuming 8 bundles (8 x 0.6 = 4.8 m3) and assuming a nominal discharge flow of 0.3 kg/s, the pressure drop and velocity parameters are as shown in Table 3. Each cylinder bundle is composed of tubing that connects each cylinder (5 mm internal diameter) and a header pipe (10 mm internal diameter) that connects all individual cylinder tubes and connects them to the bundles main shut-off valve (see Figure 34). As already explained above, each cylinder bundle is then connected to the main CAES header (DN25 line) using a flexible stainless steel high-pressure hose with DN6 as nominal diameter. Hence, the maximum flow velocity is to be expected in this connection hose, as well as in the bundles’ main shut-off valves with similar internal diameter. According to the high-pressure hose manufacturer, the flow velocity should not exceed 25 m/s. The flow velocity will be below that value until the pressure level reaches about 50 bar. During the last period of the discharge period, from about 50 bar down to 20 bar, the flow velocity will be higher and a higher noise level is expected (see Table 3). Since the operation with high velocities is short and the prototype will be operated only during a few months, this should not be an issue.

The pressure drop calculation model has been validated against the work of Carello et al. [8] as well as that of Abushakra et al. [9], showing good agreement with experimental and theoretical data. The model of friction losses in straight pipes is based on the Modelica Standard Library's (MSL) "detailed wall friction package" [10].

Table 3: Velocity and pressure drop parameters in CAES lines (cylinder bundles and main header)

Duct type (-)	Operating pressure (bar)	Mass flow (kg/s)	Velocity (m/s)	Pressure drop (bar)
Bundle header, 10 mm ID	300	0.0375	1.4	0.014
Bundle header, 10 mm ID	20	0.0375	20.1	0.2
Cylinder pipe, 5 mm ID	300	0.003125	0.45	0.035
Cylinder pipe, 5 mm ID	20	0.003125	6.7	0.53
Bundle DN6 connection hose	300	0.0375	3.7	0.098
Bundle DN6 connection hose	50	0.0375	22.3	0.6
Bundle DN6 connection hose	40	0.0375	27.9	0.73
Bundle DN6 connection hose	30	0.0375	37.2	0.97
Bundle DN6 connection hose	20	0.0375	55.8	1.5
Main CAES header pipe, 25 mm ID	300	0.3	1.7	0.06
Main CAES header pipe, 25 mm ID	20	0.3	26	0.93
Main header going up to the tower (DN65)	15	0.3	5.1	0.1
Main header going up to the tower (DN65)	10	0.3	7.6	0.11
Main header going up to the tower (DN65)	5	0.3	15.2	0.3

Besides the issue of maximum velocity and pressure drop in the air piping, the cool down behavior during discharge needs to be taken into account since the pressure reducers may cool below 0ºC causing icing problems.

To maintain the temperature of the air volume as stable as possible, it is proposed to immerge the cylinder bundles in a water basin, which is heated up before expansion to about 40ºC by solar energy or auxiliary electric water heaters. Figure 36 shows the conceptual scheme indicating one representative cylinder in a water basin. The problem has been modeled in

Modelica language applying CENER's inhouse library CSTLibrary, considering one representative air volume, the mass and thermal resistance of the pressure cylinders, the water volume of the basin, as well as the convective heat transfer at the cylinder wall (between air/cylinder wall and water/cylinder wall) as well as heat losses of the water basin to the environment. The method applied is equivalent to the one applied in Ref. [11]. Real gas properties of air are taken into account according to Refs. [12, 13].

When considering a total storage volume of 4.8 m3 (= 8 bundles of 12 cylinders of 50 liters each) and a nominal discharge flow of 0.3 kg/s, the discharge time is approximately 1.2 hours.

Figure 37 shows the simulated pressure decrease during a full discharge. Figure 38 shows the thermal behavior of the system. As can be seen, when starting at about 40ºC, the air inside the cylinders cools down to just below 38 ºC. However, the temperature drop in the pressure reducing valve is quite big (see lower plot of Figure 38) so that in the initial phase of the discharging, the outlet temperature in the pressure reducer falls to below 5ºC.

When starting at 35ºC of initial temperature, the outlet temperature of the pressure reducer approaches -3ºC, leading to icing condition during the first 15 minutes of the discharge simulation (see Figure 39).

When starting at 30ºC of initial temperature, the outlet temperature of the pressure reducer approaches -10ºC, leading to icing condition during the first 30 minutes of the discharge simulation (see Figure 40).

The best starting temperature will depend on the exact thermal inertia of the system. During first experimental discharge trials, the most suitable starting temperature will need to be found experimentally. Additionally, industrial heating blankets may be required to prevent icing and protect the valve.

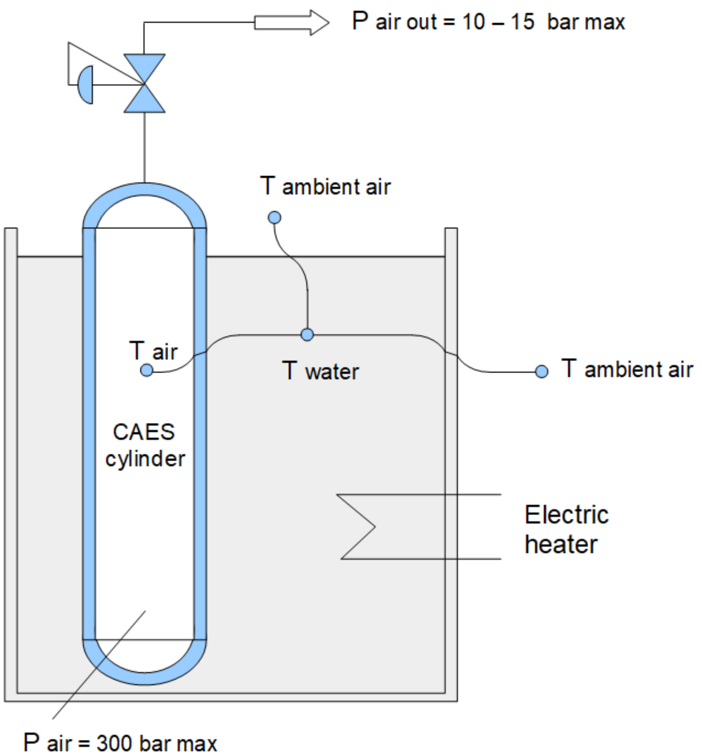


Figure 36: Scheme of the CAES system with immersed high-pressure cylinders

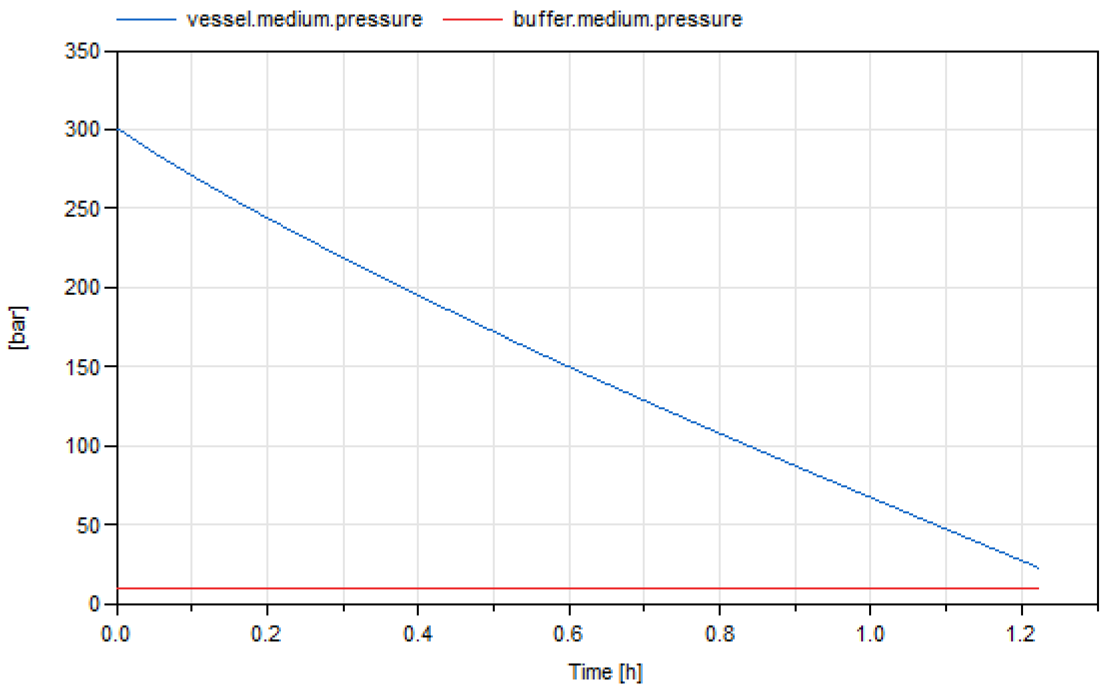


Figure 37: Simulated pressure decrease during discharge

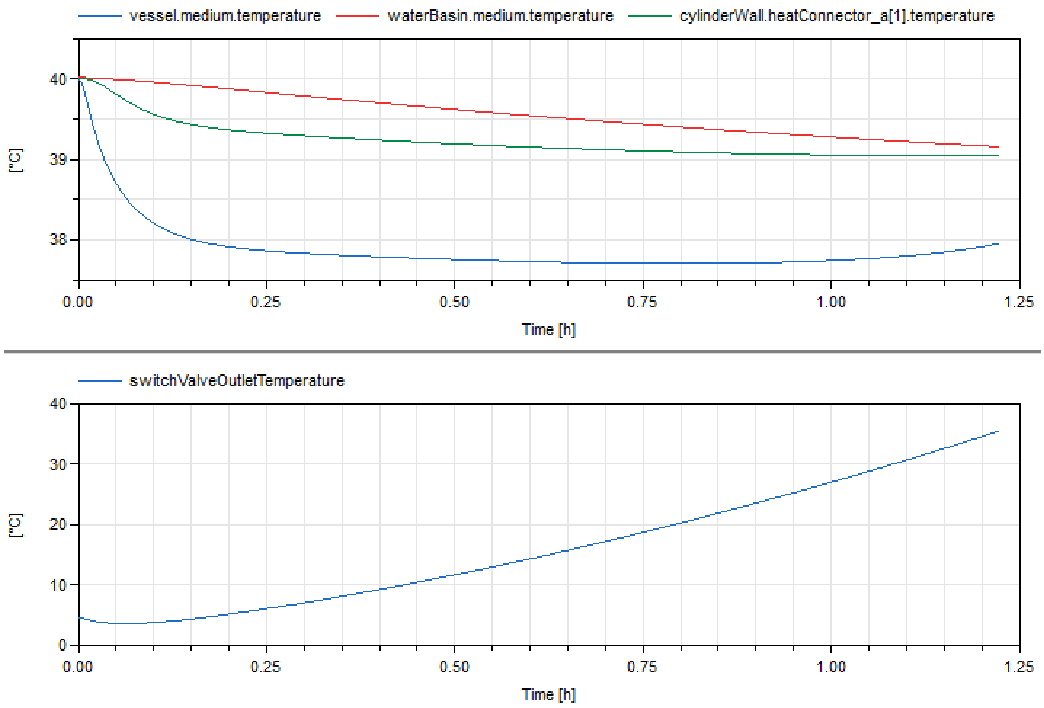


Figure 38: Simulated thermal behaviour of the CAES system (40ºC start temperature). The upper plot shows the temperature of the compressed air (blue), the cylinder wall temperature (green) as well as the water temperature of the basin (red). The lower plot shows the pressure reducing valve outlet temperature (blue).

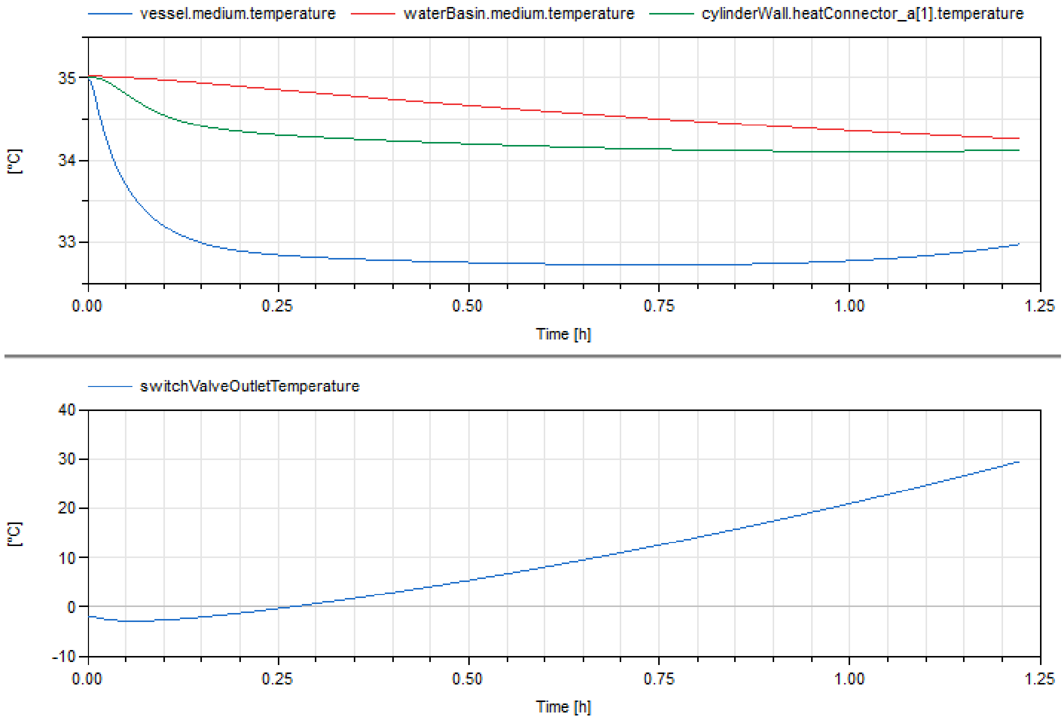


Figure 39: Simulated thermal behaviour of the CAES system (35ºC start temperature). The upper plot shows the temperature of the compressed air (blue), the cylinder wall temperature (green) as well as the water temperature of the basin (red). The lower plot shows the pressure reducing valve outlet temperature (blue).

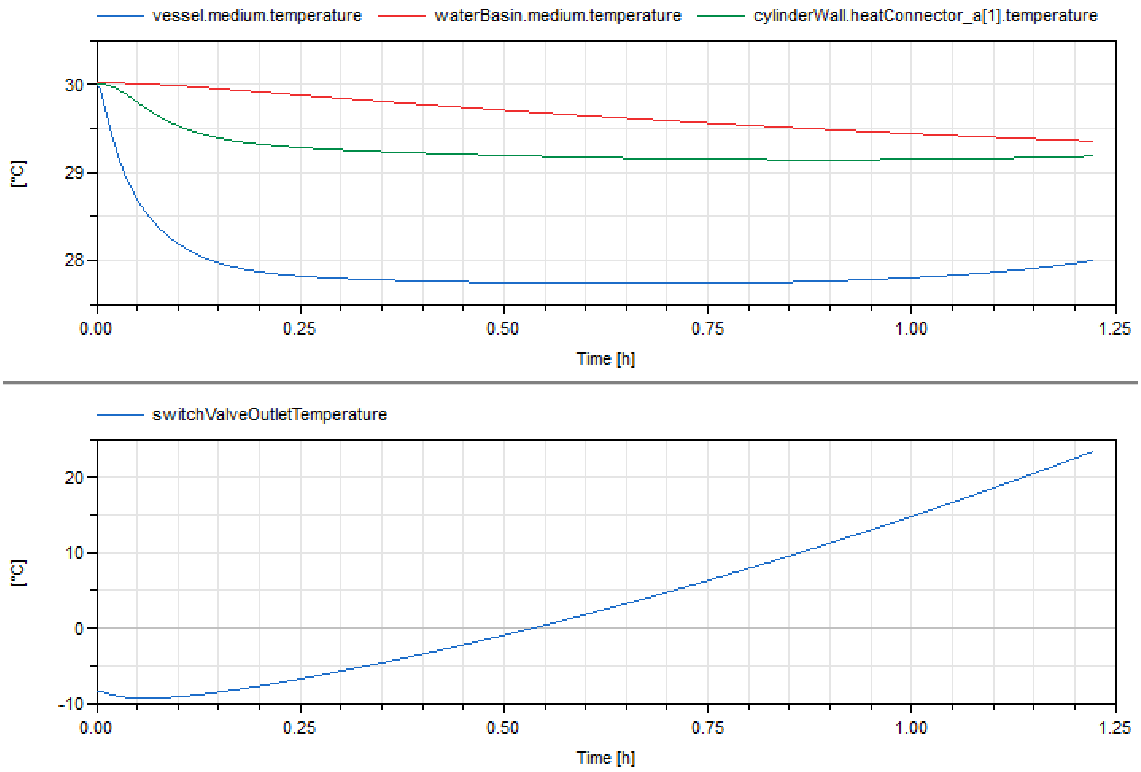


Figure 40: Simulated thermal behaviour of the CAES system (30°C start temperature). The upper plot shows the temperature of the compressed air (blue), the cylinder wall temperature (green) as well as the water temperature of the basin (red). The lower plot shows the pressure reducing valve outlet temperature (blue).

4.4.1 High pressure charging/discharging line DN25 Schedule 80

A DN25 high pressure piping is suggested to connect all tube bundles as outlined above. By selecting schedule 80 (OD 33.4 mm; wall thickness 4.55 mm) results in an internal diameter of about 24.3 mm. According to ASME boiler and pressure vessel code [5, 6], the piping material's maximum allowable stress shall be around 117 MPa or above. The high-pressure line will have a flange of type EN-1092-1 DN25 PN320 at each end. One flange will be a blind flange for the time being. In this way, the CAES system's capacity may be extended in the future by connecting another line with additional cylinder bundles. The bundle connections are foreseen by welding G ¼" (6000 Lbs) threadolets according to Figure 41.

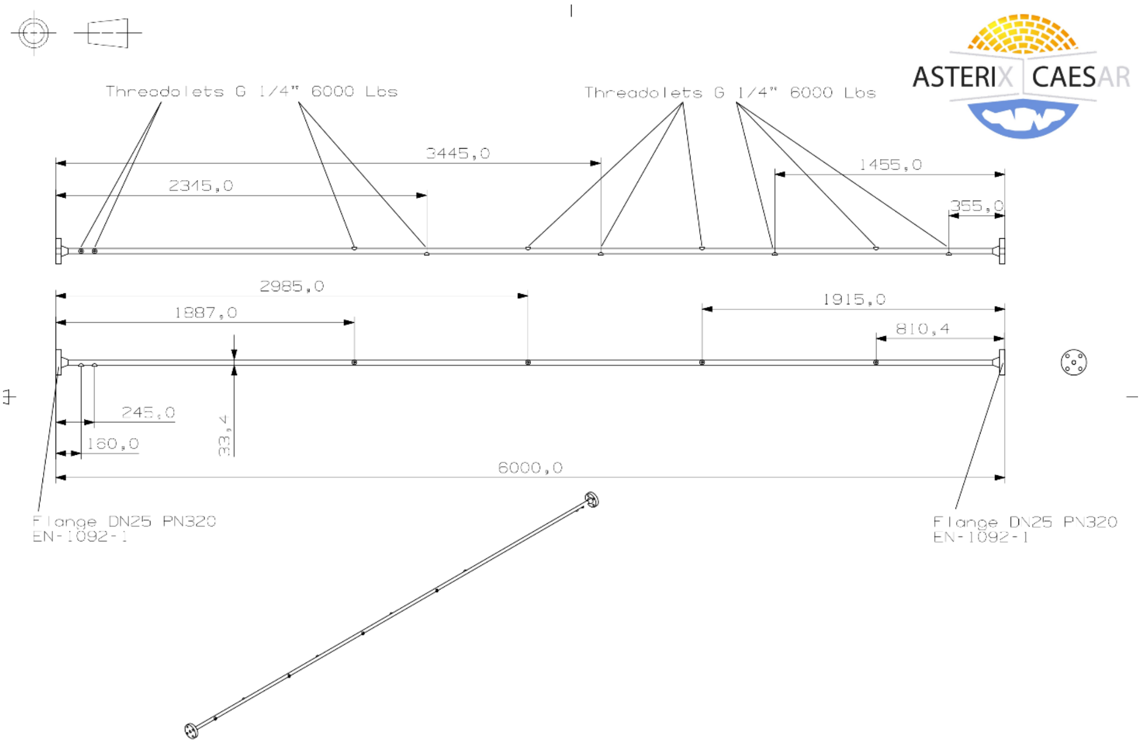


Figure 41: High-pressure DN25 PN320 line that connects all cylinder bundles

4.4.2 High-pressure shut-off valves

The discharging/charging header (29) is connected to automatic shut-off valves (item number 28 for charging, and item number 30 for discharging). Typical valve examples are shown in Figure 42. Valve 28 is optional since the air compressor has an internal check-valve which closes if compressor flow stops or if compressor is switched off. Instead of an automatic valve, a manual shut-off valve may be installed as valve 30 to reduce costs (see Figure 45 (d), (e)).

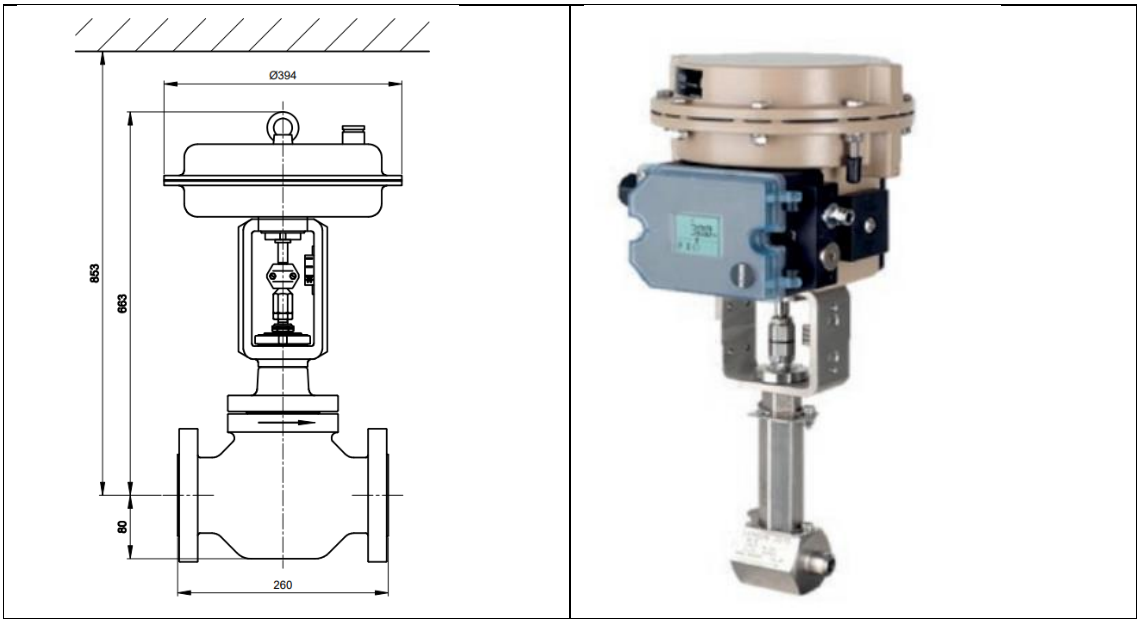


Figure 42: high-pressure on-off valve SAMSON Type 3251, DN 25 , PN 320 (a); high-pressure on-off valve SAMSON Type 3510, G ½", PN 320

4.4.3 Air compressor for CAES charging

A standard industrial piston-type air compressor (Bauer PE 120-7.5-VE) has been selected for the ASTERIx-CAESar prototype. It has a nominal electric consumption of approximately 7.5 kW and provides a volume flow of 260 liters per minute (15.6 m^3/h). The compressor will be equipped with a refrigeration dryer and an additional air filter to provide dry air for CAES charging (see Figure 43).

(a)

(b)

Figure 43: Bauer compressor model PE120-7,5-VE (a); Bauer refrigeration dryer B-KOOL 680 (b)

4.4.4 Primary pressure reducer

The pressure state of the cylinder bundles is reduced in an industrial pressure reducer to approximately 10 bar (Figure 44). Dome pressure regulators are characterised by an accurate regulation and a large throughput. The dome pressure regulator works according to the principle of the pressure balance between dome pressure and outlet pressure. A large independence from fluctuations is reached with a balanced poppet. The outlet pressure can be adjusted manually between 1 and 12 bar. The size of the pressure reducer must be correctly chosen such that the nominal turbine flow (0.3 kg/s) is guaranteed over a wide inlet pressure range (300 to 20 bar approximately). The chosen model has inlet and outlet connection of G 1 1/2“.

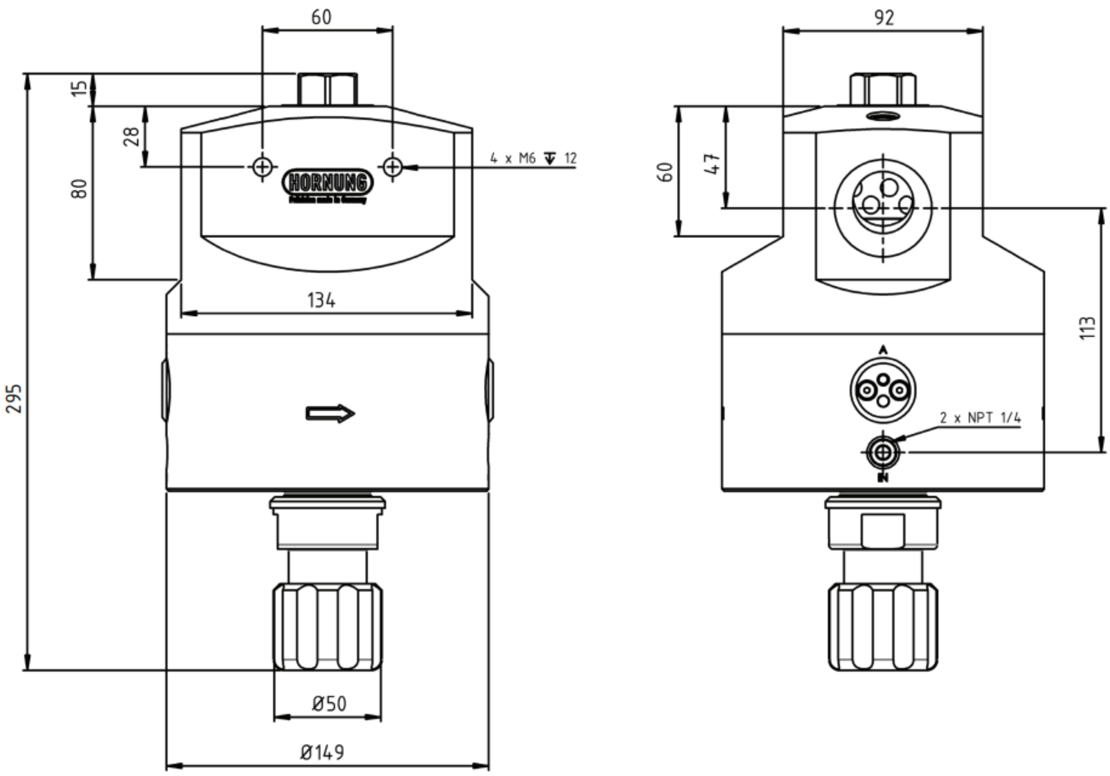
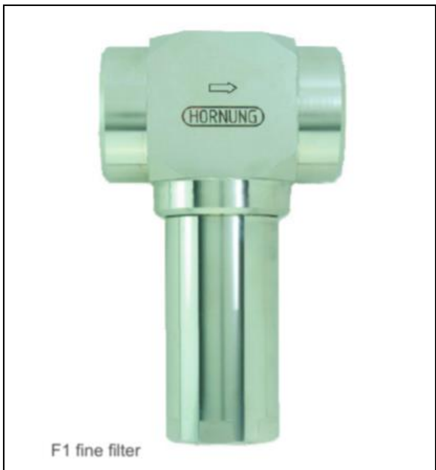


Figure 44: Hornung dome pressure reducer model PIDH 1 ½”

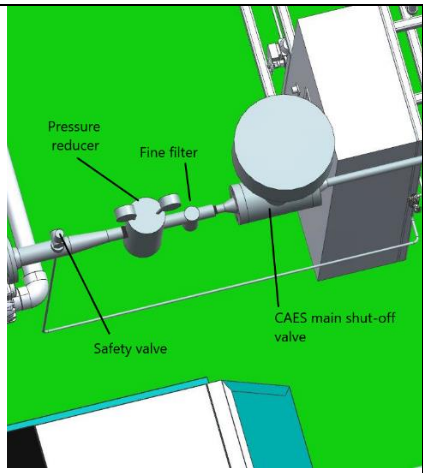
It is recommended to install a fine filter before the pressure reducer in order to avoid any contamination and blockage of the pressure reducer.



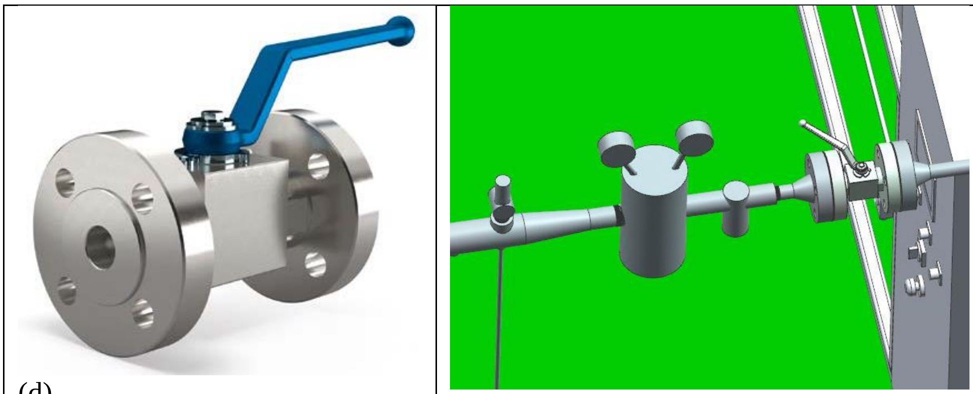
(a)

TECHNICAL DETAILS	
F1 fine filter:	
Material:	brass / stainless steel
Gaskets:	Viton
Max. pressure:	420 bar
Pore size:	20 or 40 µ (bronze) 20 or 35 µ (st. steel)
Operating temp:	-20°C to +70°C
Dimensons:	60 x 100 x 168 mm
Weight:	3400 g
Connections:	In-/ outlet G 1" f
Accessory coupling set:	
Material:	1.4571
Gaskets:	FKM
Connection to F1:	G1"
Connection to regulator:	G¾", G1" or G1½"

(b)



(c)



(d) (e)

Figure 45: Hornung F1 fine filter (a); Technical details of fine filter (b); 3D detailed view of pressure reducing section (detail of Figure 32) (c); Manual DN25 PN320 shut-off valve MHA Zentgraf BKH-DIN (d); Equivalent to Figure (c) with manual valve option (e).

4.4.5 Pressure relief valve

A pressure relief valve needs to be installed downstream the primary pressure reducer (see Figure 45 (c)) to protect the low-pressure air transport line that goes up to the tower (DN65, PN16) in case the pressure reducer has a failure. A suitable model is shown in Figure 46.

Seetru 15mm Nominal Bore Enclosed Discharge Safety Valve: 93615A1333

PED (CE) & UKCA approved safety relief valve for Air & Gases or Steam.

Technical Specification

Construction Materials:	Stainless Steel Body with Brass Seat
Seal Material:	Metal-to-Metal
Body O-ring:	Viton (FKM)
Inlet:	1" BSP Parallel
Outlet:	1 1/2" BSP Parallel
Easing Gear:	Sealed Cap
Bore Size:	15.00mm
Flow Area:	176.71mm²
Kdr:	0.850

Operating Conditions

Duty (Medium):	Air
Set Pressure:	**15.00 bar g.**
Temperature:	25°C

Flow Rates

litres/sec.:	502.57
SCFM:	1,066.36
Nm³/hour:	1,715.08
kg/hour:	2,216.73
lb/hour:	4,887.00

Flows are calculated to the applicable standard stated in the appropriate valve data sheet.

Figure 46: Pressure relief valve 15 bar for use after main pressure reducer

4.5 Prototype functional description (CAES + Solar receiver + Hot air turbine)

The following operating modes are planned for the prototype:

- Solar receiver only operation (M1)
- CAES charging (M2)
- Solar receiver and turbine preheating (start-up) (M3)
- Solar receiver and turbine operation & CAES discharging (M4)

Each operating mode should be selectable on the graphical operator interface.

By default, before selecting any operating mode, the main valves of the compressed air storage system are closed, the control valve (13) is closed, the on/off preheat circuit valve (15) is closed, blowers (4) and (17) are switched off, the bypass valve (3) is opened, and bypass valve (8) is closed.

Operating mode M1 and M2 can be active at the same time. The operating modes M3 and M4 can only be active alone, hence either only M3 (M1, M2 and M4 deactivated) or only M4 (M1, M2 and M3 deactivated). Furthermore, M4 can only be activated once M2 and M3 have previously been active.

4.5.1 Solar receiver only operation (M1)

In this operating mode, only the solar receiver is being operated, heating ambient air to high temperature. The hot air is cooled in the air/water heat exchanger (2). The receiver blower (4) forces ambient air through the receiver and the receiver loop.

Elements to be seen on the operator screen:

- Front view scheme of the receiver, indicating the temperature of each absorber module (TI01-TI16)
- Receiver outlet temperatures (TI21 and TI22)
- Receiver outlet pressure (PI01)
- Temperatures of outer receiver casing (TI17-TI20)
- Receiver air mass flow signal (FI01)
- Scheme of the air/water heat exchanger (2) with corresponding temperatures (TI23 – TI26) of air and water inlet/outlet flows.
- Cooling water mass flow (FI03)
- Temperature at blower inlet (TI31)

By activating operating mode M1, the air/water HEX valve (3) remains opened, and the air/air HEX valve (8) remains closed. Furthermore, the cooling water flow is switched on to nominal flow, and the receiver blower is switched on to minimum speed.

The **manual operating mode** is the default setting. In manual model, the operator can adjust blower speed manually.

The receiver start-up procedure is performed manually, by increasing manually blower speed to nominal speed and focusing the heliostats in sequential manner in specific groups (the heliostat or mirror control system is an existing system that is not subject of this document). The receiver temperature is increased step by step by increasing the number of heliostats and reducing blower speed until the receiver outlet temperature target is reached.

Once the receiver outlet temperature target is reached, the operator can switch to **automatic receiver mode**, where the receiver outlet temperature control loop is activated. In this mode, small variations in solar power should be compensated by adjusting blower speed via a conventional PI feedback loop.

At any time, the operator can switch back to manual operation to modify blower speed.

One **emergency stop button** is on the operator screen: By pushing the emergency stop button, the solar field is defocused, and later the blower is stopped (free cooldown of the receiver).

A **warning signal** shall appear if the temperature gradients in the receiver exceed 50ºC per minute.

A **warning signal** shall appear if the inlet temperature to the blower exceeds 200ºC.

A **warning signal** shall appear if the outlet temperature of the receiver (TI21/TI22) exceeds 950ºC.

4.5.2 CAES charging (M2)

Elements to be seen on the operator screen:

- Compressor discharge pipe pressure sensor signal (=storage volume pressure)

In this mode, the main **discharging** valve (30) of the CAES system is closed.

The main **charging** valve (28) is opened.

The compressor (Bauer Model PE 120-7.5-VE) has a pressure maintaining and non-return valve after the last compressor stage. Thus, by opening the bundles' main valve (28), the compressor's non-return valve maintains pressure in the system.

By pressing the **compressor start button**, the compressor is switched on (the compressor automatically switches off once the nominal pressure is reached).

The compressor operation can be stopped at any moment by pushing the **compressor stop button**.

Once the compressor switches off, the charging valve (28) of the CAES system is closed.

4.5.3 Solar receiver and turbine preheating (M3)

This mode is foreseen to be activated from full cold state (cold receiver, cold turbine). Direct switching from receiver operation (M1) to solar receiver and turbine preheating (M3) is not foreseen.

Before turbine operation, the air/air heat exchanger (7) as well as the turbine stages (11) need to be preheated to avoid too high temperature gradients during start-up.

An auxiliary blower is used to move ambient pressure air through the air/air heat exchanger and the turbine stages. The air is heated up in gradual manner until reaching about 400ºC (exact temperature level is to be defined).

By using the auxiliary blower, the system can be preheated without the use of compressed air. This is an advantage as we have limited compressed air storage volume.

Elements to be seen on the operator screen:

- all elements as in receiver only operation
- A scheme of the whole system loop with auxiliary blower and turbine system.
- Inlet and outlet temperatures (TI27 to TI30) of the air/air HEX (7).
- Air mass flow (FI02)
- Air intake temperature (TI32)
- Turbine stages inlet temperature (from turbine P&ID)
- Turbine stages outlet temperature (from turbine P&ID)
- Turbine stages outlet pressure (from turbine P&ID)
- Turbine stages speed (from turbine P&ID)

By activating mode M3, the air/water HEX valve (3) is closed, and the air/air HEX valve (8) is opened. The compressed air storage main discharge valve (30) is maintained closed. Compressed air mass flow control valve (13) is closed. Turbine system preheat valve (15) is opened. Furthermore, the cooling water flow (FI03) is switched on to nominal flow, the receiver blower (4) is switched on to minimum speed, and the turbine blower (17) is switched on to minimum speed.

Note: The operator should be able to manually open or close both heat exchanger valves, (3) and (8), at any moment. Both valves can be opened at the same time, **but cannot be closed at the same time**.

The **manual operating mode** is the default setting. In manual model, the operator can adjust **receiver blower (4) speed as well as turbine blower (17) speed manually**.

The receiver start-up procedure is performed manually, by increasing manually blower speed to nominal speed and focusing heliostats in sequential manner in specific groups. The receiver temperature is increased step by step by increasing the number of heliostats and lowering blower speed until the receiver outlet temperature target is reached.

At the same time, the turbine loop blower (17) speed is **manually increased step by step**, closely monitoring the turbine inlet temperature (TI30) as well as receiver blower inlet pipe temperatures (TI31 and TI28).

Once the receiver outlet temperature target is reached, the operator can switch to **automatic receiver mode**, where the receiver outlet temperature control loop is activated. In this mode, small variations in solar power should be compensated by adjusting blower speed via a conventional PI feedback loop.

At any time, the operator can switch back to manual operation to modify receiver blower speed.

One **emergency stop button** is on the operator screen: By pushing the emergency stop button, the solar field is defocused, and later **both** blowers are stopped (free cooldown of the receiver and turbine loop).

A **warning signal** shall appear if the temperature gradients in the receiver or air/air heat exchanger exceed 50ºC per minute.

A **warning signal** shall appear if the inlet temperature to the receiver blower exceeds 200ºC.

A **warning signal** shall appear if the outlet temperature of the receiver (TI21/TI22) exceeds 950ºC.

4.5.4 Solar receiver and turbine operation & CAES discharging (M4)

This mode is foreseen to be activated only after M3 mode (receiver and turbine preheating) and when M2 has previously charged the cylinder bundles.

After preheating is completed and the turbine system is preheated to approximately 400ºC, mode M4 will direct compressed air (3 to 4 bar) to the air/air heat exchanger (7) and the turbine set should start spinning at high speed and slowly generate power as temperature increases.

Elements to be seen on the operator screen:

- all elements as in receiver only operation
- A scheme of the whole system loop with turbine system.
- CAES pressure signal (PI04)
- Inlet and outlet temperatures (TI27 to TI30) of the air/air HEX (7).
- Air mass flow (FI02)
- Air intake temperature (TI32)
- Turbine stages inlet temperature (from turbine P&ID)
- Turbine stages outlet temperature (from turbine P&ID)
- Turbine stages inlet pressure (from turbine P&ID)
- Turbine stages speed (from turbine P&ID)
- Turbine output power (from turbine P&ID)

M4 can only be activated after M3. By activating mode M4, the receiver blower (4) remains at the same speed as in M3. Cooling water flow remains at nominal flow as in M3. The air/water HEX valve (3) is opened, and the air/air HEX valve (8) is closed. The turbine blower (17) is switched off. The turbine system preheat valve (15) is closed. Compressed air mass flow control valve (13) is closed. The compressed air storage discharge valve (30) is opened.

Note: The operator should be able to manually open or close both heat exchanger valves, (3) and (8), at any moment. Both valves can be opened at the same time, **but cannot be closed at the same time**.

The **manual operating mode** is the default setting. In manual model, the operator can adjust **receiver blower (4) speed as well as the opening of the compressed air mass flow control valve (13).**

If the receiver outlet temperature target is reached, the operator can switch to **automatic receiver mode**, where the receiver outlet temperature control loop is activated. In this mode, small variations in solar power should be compensated by adjusting blower speed via a conventional PI feedback loop.

At any time, the operator can switch back to manual operation to modify receiver blower speed.

Establishing compressed air turbine flow manually: To establish the compressed air flow across the air/air heat exchanger, the operator will slowly open valve (13), monitoring compressed air flow (FI02) as well as turbine inlet temperature (TI30). Once the turbine inlet temperature starts to decrease and compressed air flow is established, the operator directs the receiver air flow again across the air/air heat exchanger (7), by closing valve (3) and opening valve (8). Now, the air/air heat exchanger is again heated, and turbine inlet temperature shall re-establish again.

Note: The operator will have information of expected mass flows based on tables obtained from previous simulations as guidance.

Now, **receiver loop and turbine loop are thermally connected,** and the turbine inlet temperature can be raised gradually by increasing the receiver outlet temperature target. The operator will gradually add more heliostats and/or reduce receiver blower speed. Accordingly, the compressed air mass flow control valve (13) is opened, in order to adjust turbine inlet temperature and to reach nominal turbine air flow and power output.

The operator can activate the automatic turbine inlet temperature control mode, where the mass flow control valve (13) opening is automatically adjusted in order to reach or maintain a specific turbine inlet temperature setpoint via a conventional PI feedback loop. At any given moment, the operator can switch back to manual operation, adjusting the control valve (13) opening.

The shut-down process is performed manually. The simplest approach is the free cool-down. The solar field is defocused, the receiver blower speed is reduced and switched off, the compressed air control valve is closed.

One **emergency stop button** is on the operator screen: By pushing the emergency stop button, the solar field is defocused, the receiver blower is stopped, the compressed air main control valve (13) is closed as well as the compressed air storage system main valve (30) is closed. Free cooldown of the receiver and turbine loop is initiated.

A **warning signal** shall appear if the temperature gradients in the receiver or air/air heat exchanger exceed 50ºC per minute.

A **warning signal** shall appear if the inlet temperature to the receiver blower exceeds 200ºC.

4.6 ASTERIx-CAESar desalination unit specifications

This section of the document describes the specifications of the ASTERIx-CAESar desalination system that is going to be installed next to the CAES system at ground level (see Figure 32).

4.6.1 Simulation of the desalination system performance

The objective of the simulations is to evaluate the physicochemical performance of the reverse osmosis (RO) desalination system under the operation conditions of the feed water to be desalinated. The feed water is brackish water that will come from a supply point at the base of CRS tower at Plataforma Solar de Almería, close to the location of the RO+CAES prototype. The physicochemical characteristics of the water to be treated are shown in Table 4.

Table 4: Physicochemical characterization of the feed brackish water to be desalinated

Parameter	Units	Value
Conductivity	mS/cm	2.53
pH	-	7.22
IC	mg/L	235.2
TOC	mg/L	1.75
Ca^{2+}	mg/L	86.07
Mg^{2+}	mg/L	53.4
K^{+}	mg/L	1.3
NH^{+4}	mg/L	0
Na^{+}	mg/L	546.42
NO_2^{-}	mg/L	0
SO_4^{2-}	mg/L	154.64
Cl^{-}	mg/L	306.53
Br^{-}	mg/L	0
F^{-}	mg/L	0
NO_3^{-}	mg/L	8.05
PO_4^{3-}	mg/L	0

The desalination process was simulated using IMSdesign v.2.231.90, a software tool provided by Hydranautics, a Nitto Denko Corporation. As raw water, the input to the software was the feed water characteristics showed in Table 4, which calculated, after ions balancing, a total TDS of 2,139 mg/L and a conductivity of 3766 µS/cm. Feed water temperature was considered to be at standard testing conditions (25ºC).

For the design of the reverse osmosis train, we considered a single stage, 1 pass per stage, 2 pressure vessels and 2 membrane elements per vessel. As main design specification, the overall system **is required to be fed with 1 m^3/h of raw brackish water**. ESPA2-LD-4040, a RO membrane commercialized by Hydranautics, was used for the simulations, whose characteristics are suitable for brackish low salinity water desalination with high rejection rates working at low feed water pressure, which fits the requirements of the desalination plant to be built as part of the ASTERIx-CAESar project.

Table 5 shows the main design specifications used in the simulations.

Table 5: Main design specifications for the desalination simulations

Parameter	Units	Value
HP[1] pump flow	m^3/h	3.00
Feed pressure	Bar	9.0
Feed temperature	ºC	25.0
Concentrate recirculation	m^3/h	2.00
Feed water pH	7.22	
Chemical dose	mg/L	None
Specific energy	kWh/m^3	1.33
Pass NDP[2]	bar	6.0
Average permeate flux rate	l/m^2 h	23.5
Permeate flow	m^3/h	0.70
Raw water flow	m^3/h	1.00
Permeate recovery	%	23.33
Total system recovery	%	70
Element age	years	3.0
Flux decline	%, per year	5.0
Fouling factor	-	0.86
Salt passage increase, per year	%	7.0

[1]*High Pressure*
[2]*Net Driving Pressure*

Figure 47 shows the main scheme of the single-stage RO desalination system used in the simulation. As inputs for the simulations, a flow rate of 1 m^3/h of raw brackish water and a total recovery rate (or system recovery) of 70% have been taken, which results in the flows distribution showed in Table 7.

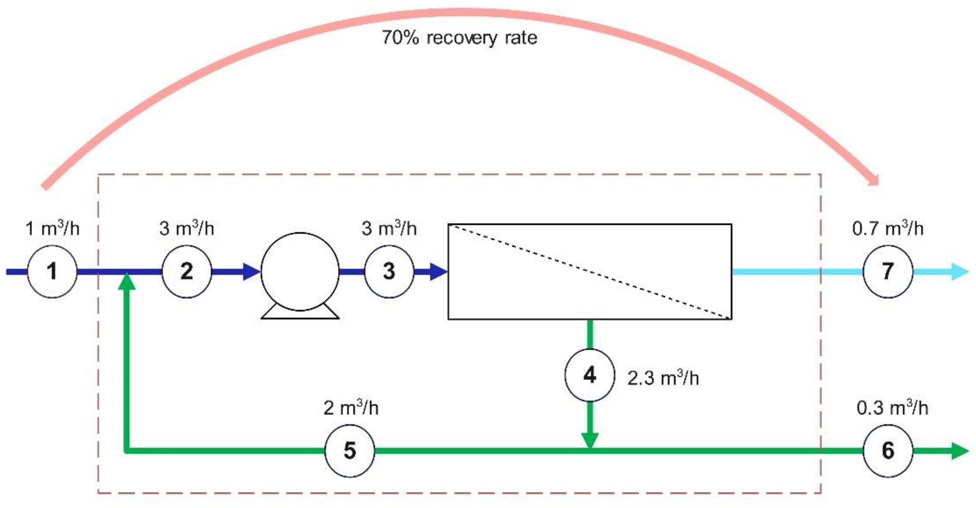


Figure 47: Main scheme of the single-stage RO desalination system.

Table 6: Main results from RO desalination simulation under ASTERIx-CAESar scenario

Stream (according to Figure 47)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Flow (m^3/h)	1.00	3.00	3.00	2.30	2.00	0.30	0.70
Pressure (bar)	0	0	8.98	8.74	0	0	0
TDS (mg/L)	2139	5356	5356	6964	6964	6464	70.0
pH	7.22	7.55	7.55	7.65	7.65	7.65	6.36
Conductivity (µS/cm)	3745	8614	6814	10965	10965	10965	138

Table 7 shows the main results from the simulation, in terms of physicochemical characteristics of the main flow streams entering and exiting the membrane train.

Table 7: Simulation of physicochemical characteristics of the main flow streams in the RO desalination under the ASTERIx-CAESar

Ion (mg/L)	Raw water	Feed water	Permeate water	Concentrate
Hardness, given by $CaCO_3$	434.03	1107.78	0.382	1444.7
Ca^{2+}	86.07	219.68	0.076	286.5
Mg^{2+}	53.40	136.29	0.047	177.7
Na^+	546.42	135.84	24.677	1760.8
K^+	1.30	3.21	0.0666	4.2
SO_4^{2-}	1137.93	2875.24	20.488	3743.1
Cl^-	306.03	749.58	21.320	971.1
NO_3^-	8.05	15.67	3.281	19.4
TDS	2139.30	5355.75	69.96	6963.72
pH	7.22	7.55	6.36	7.65

4.6.2 P&ID and design specifications of the RO desalination system

Based on the simulations, the Piping and Instrumentation Diagram (P&ID) of the RO plant was made to accordingly meet the main design specifications.

The system is designed to exclusively work under batch mode, to perform the corresponding validation actions. At this stage the prototype is designed to treat 1 m^3/h of brackish water.

The following main specifications and limitations were set:

1. The prototype must treat 1 m^3/h of brackish water.
2. Total recovery rate of the system is set to 70%, which means that 0.7 m^3/h must be recovered as permeate and 0.3 m^3/h goes to the concentrate tank. This means that a recirculation of 2 m^3/h is imposed to deal with such high Recovery Rate, having the GL-PX to pump 3 m^3/h of water entering the RO module.
3. The aim is to obtain high Recovery Rates, so to concentrate the brine as maximum as possible to reduce the brine discharge, which allows to reduce the environmental print of the RO desalination validation within the framework of the ASTERIx–CAESar project and to reduce the consumption of water resources, as water is a scarce resource in Almeria. For this purpose, at the end of every experimental run, both brine and permeate

storage volume must be remixed in the feed tank, allowing to recover both the initial feed volume and feed water physicochemical characteristics. This ultimately determines the sizes of the feed, brine and permeate storage tanks. The remix operation will be automatically carried out as fast as possible (high flowrates).

4. The pressure required to overcome the osmotic pressure of the feed water and therefore to drive the RO system will be provided by a Gas-Liquid-Pressure-Exchanger (GL-PX) device, which, at the same time, must be fed with pneumatic air at 10-12 bar from the CAES system. The selection of the GL-PX must allow to run the RO system the required experimental time and its pneumatic air consumption must be optimized to avoid total consumption of the CAES storage air before ending each experimental run.
5. The maintenance of the RO system, to ensure high water quality and system longevity, requires flushing and cleaning the system's prefilters and RO membrane module. This allows to prevent membrane fouling and scaling, ensuring optimal performance and an adequate lifespan of all elements. To flush the RO membrane and auxiliary elements in RO systems typically the permeate water is used. As in this pilot plant, permeate must be storage and remixed with brine because of system specification nº3, flushing operation must be done with external demineralized water supplied by a demineralized water tank and a water pump externally located in PSA facilities. Thus, these two elements are not considered in the P&ID.
6. The pneumatic air consumption for the GL-PX and the air consumption for the ASTERIx-CAESar turbine must be controlled separately. Thus, the RO PLC must control its own automatic valve that regulates the air inlet to the GL-PX.
7. Main system control parameters (flowrate, temperature, pH, conductivity, pressure, tank levels) must be registered in the PLC to allow data analysis. Thus, all sensors send the signal to the main PLC and no basic visual indicators are herein installed, except for a single one in the demi-water supply.
8. The maximum operating pressure will be determined by the characteristics and technological capabilities of the GL-PX device. This maximum operating pressure can never exceed the maximum allowed operating pressure for a brackish water RO membrane element (~40 bar).
9. No temperature control is here contemplated. Although solute diffusion mechanisms and water permeability in membrane processes may be affected by water temperature, upscaled desalination processes does not count with temperature control, because of high related OPEX. Thus, and considering the future scalability of the solution, temperature is not controlled.

Figure 48 shows the PI&D of the ASTERIx-CAESar RO desalination system. Five main lines are distinguished:

- A hydraulic line built in AISI 316 (diameter 32 mm). High pressure line (working pressure: 0 – 16 bar). This hydraulic line corresponds to the feed and concentrate streamlines (including the recirculation stream).
- A hydraulic line built in PVC (diameter 63 mm). Low pressure line (~atmospheric pressure), high flowrates. This hydraulic line corresponds to the water transfer line from the concentrate and permeate tanks to the feed tank.

- A hydraulic line built in PVC (diameter 32 mm). Low pressure line (~atmospheric pressure), low flowrates (~0.7 m^3/h). This hydraulic line corresponds to the permeate stream exiting the membrane module.
- A pneumatic line built in flexible tube. Pressure <20 bar. This line corresponds to the compressed air inlet to the GL-PX coming from CAES.
- An electric line. This represents the control logics between main controllers and drive elements.

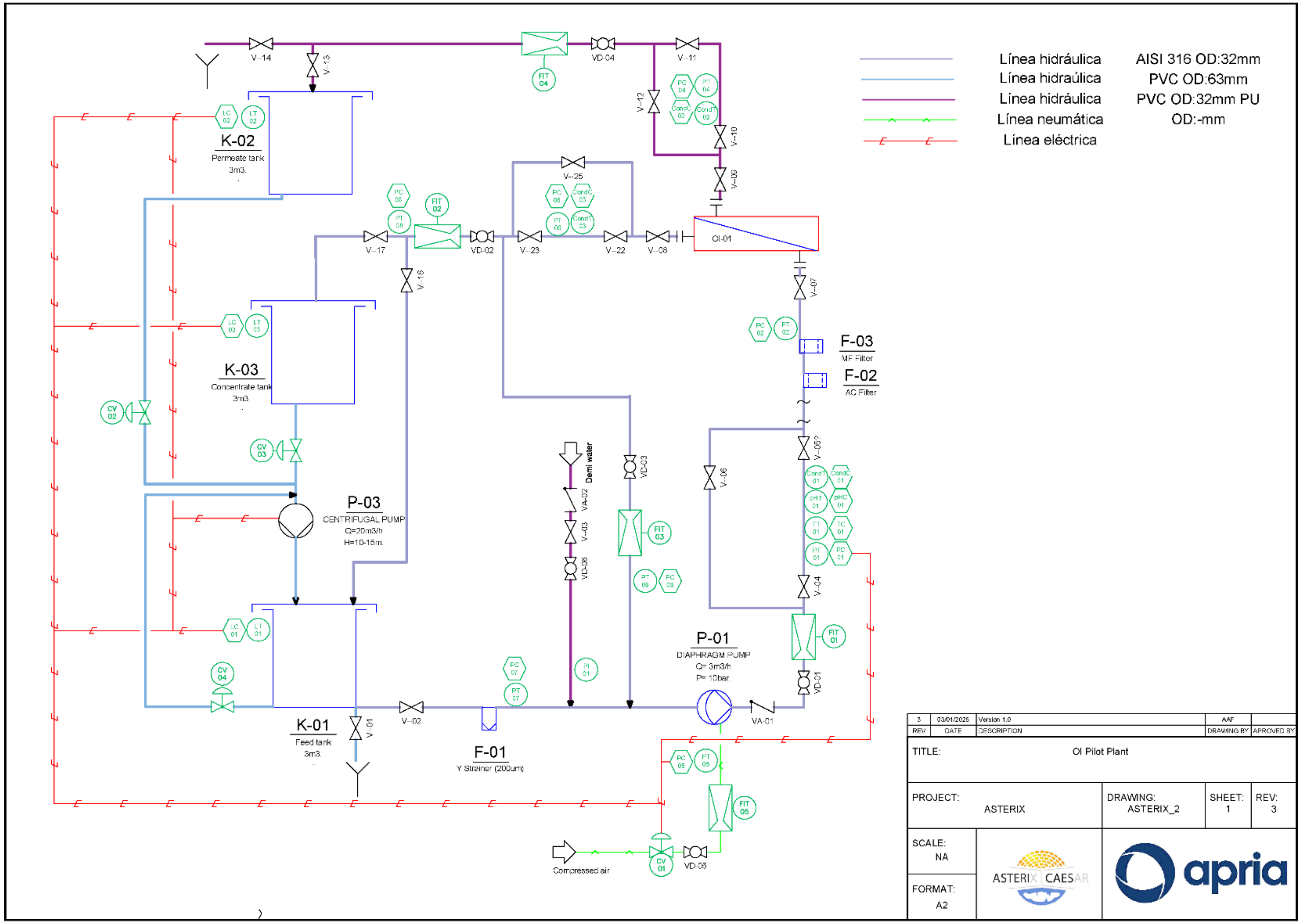


Figure 48: PI&D of the RO desalination system

4.6.3 Main elements of the RO desalination system

Table 8 shows the main elements that form part of the P&ID, as well as their corresponding TAG in the P&ID.

Table 8: Quick review of equipment showed in RO desalination system P&ID

Equipment	Units	TAG in P&ID	Brand	Model
3000 L Tank	3	K-01 a K-03	Aquablock	DE-8002-06
Horizontal centrifugal pump	1	P-03	Grundfos	CME 15-1
Ultrasonic level meter. 4-20 analog output.	3	LT-01 a LT-03	Endress Hauser	FMR10
Reverse osmosis membrane	4	OI-01	Hydranautics	ESPA2-LD-4040
Pressure vessel (2 elements)	2	OI-01	Auxicolor	Phoenix 40.300.2
Strainer	1	F-01	ARAG	335
Fabric type MF pre-filter. Design flow 12 m^3/h. Pitch size 25µm	1	F-03	Cintropur	NW400
AC pre-filter	1	F-02	Cintropur	NW 500 TE
Pneumatic pump Q=3m^3/h P=10 bar (working point of the simulation)	1	P-01	Almatec	AHD25-EEE
Flow meter with 4-20 analog output for recording. PN40.	5	FIT-01 a FIT-05	Tecfluid	SC-250
Pressure transmitter. Range 0-16bar. Material in contact AISI 316	8	PT-01 a PT-08	Endress Hauser	PMP21
Visual pressure gauge	1	PI-01	-	-
Conductivity sensor.	3	CondT-01 - CondT-03	Hach	D3725E2T.99
pH sensor.	1	pHT-01	Hach	DPD1R1.99
Sensing controller with analog outputs for logging	1	-	Hach	SC1000
Temperature probe pt-100	1	TI-01	Endress Hauser	TMR 31
Electrical panel	1	-	Apria	-

The main core elements of the RO desalination process are the RO membrane module and the GL-PX. The choice of these two core elements is discussed in more detail below.

As previously discussed in the simulation section, the Hydranautics ESPA2-LD-4040 has been chosen as RO membrane module. The characteristics of this module (suitable for brackish water desalination operations) makes it adequate for the validation actions (mild pressure conditions and brackish water as inlet water source) while the feed design flowrate (1 m^3/h raw water, 3 m^3/h inlet water) falls between this module specifications. Figure 49 shows the geometric characteristics of the RO module to be used in ASTERIx-CAESar while Table 9 shows the main restrictions, description and performance of the module.

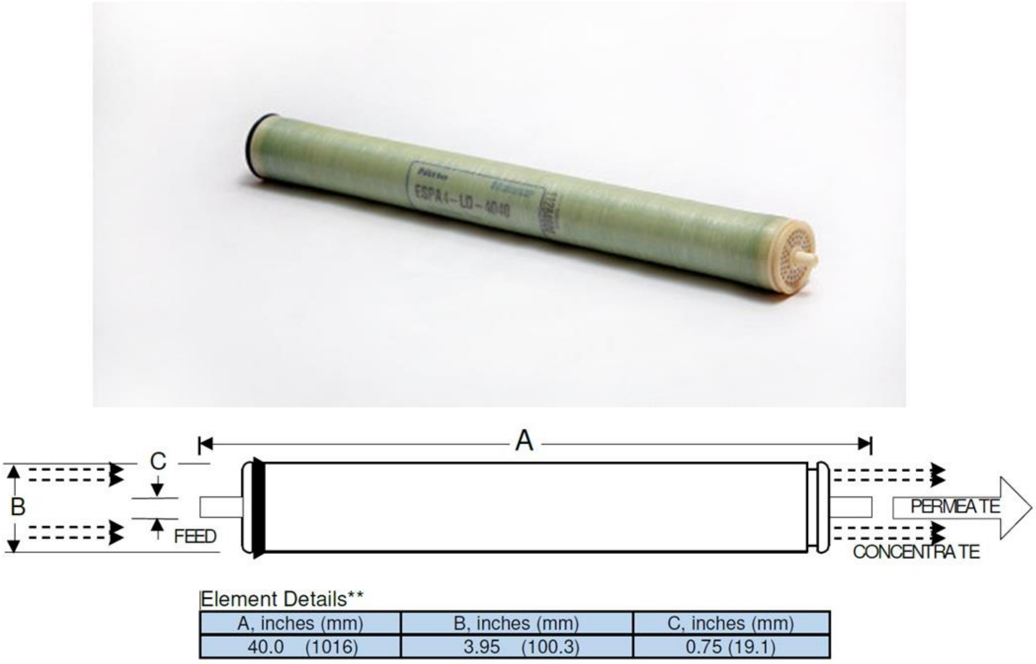


Figure 49: Hydranautics ESPA2-LED-4040 membrane module

Table 9: Main characteristics of the ESPA2-LED-4040 membrane module

Specified performance[1]	
Permeate flow	7.57 m^3/d
Salt rejection	99.6% (99.4% minimum)
General product description	
Configuration	Low fouling spiral wound
Membrane polymer	Composite Polyamide
Membrane Active Area	7.43 m^2
Feed spacer	0.86 mm
Main use and restrictions	
Maximum applied pressure	41 bar
Maximum chlorine concentration	0.1 ppm
Maximum operating temperature	45 ºC
Maximum feedwater turbidity	1.0 NTU
Maximum feedwater SDI (15 mins)	5
Maximum feed flow	3.6 m^3/h
Minimum brine flow	0.7 m^3/h
Maximum pressure drop for each elements	1.03 bar

1 – As specified by the manufacturer under specific test conditions (1500 ppm NaCl, 150 psig applied pressure, 25ºC operating temperature, 15% permeate recovery, 6.5 – 7.0 pH range. The Specified Performance is based on data taken after a minimum of 10 minutes of operation. Permeate flow for individual elements may vary + or -20 percent from the value specified.

As GL-PX it was decided to use a pneumatic pump. A pneumatic pump is an element that operate by using compressed air to drive a piston or diaphragm, which in turn pressurizes a liquid. This allows direct conversion of the pneumatic energy from an air supply into the necessary hydraulic pressure for reverse osmosis. Since pneumatic pumps do not require electricity, it is perfectly suitable for transforming CAES pneumatic air into hydraulic pressure without external electricity supply. Also, the output pressure and flow rate of a pneumatic pump can be easily controlled by adjusting the air supply pressure, which helps to optimize water pressure for different RO membrane requirements.

The chosen pneumatic pump was the Almatec AHD 25 EEE (Figure 50). It is a high-pressure plastic pump, with a maximum flow capacity of 10 m^3/h. Due to the integrated pressure transmission, it can achieve a discharge pressure of 15 bar (218 psig) with an air pressure of 7 bar (100 psig) (2:1 conversion ratio). Oscillating positive displacement pumps operate based on the principle of double diaphragm pumps. Their core structure includes two external side housings with a central block positioned between them. Each side housing contains a product chamber, separated from the central block by a diaphragm. These two diaphragms are connected by a piston rod, ensuring synchronized movement. An air control system regulates the operation by alternately applying compressed air to each diaphragm, causing them to move back and forth. Positioned between the diaphragms, a pressure booster increases the drive air pressure to more than twice its original value within the product chambers. In the first phase, compressed air pushes the left diaphragm towards the product chamber, displacing liquid through the open valve at the top and directing it to the discharge port (Figure 51). Simultaneously, the right diaphragm draws liquid into the second product chamber. Once the stroke completes, the system automatically reverses direction, repeating the cycle in the opposite manner. In the next phase, the left diaphragm draws in liquid while the right diaphragm displaces fluid from its chamber, ensuring continuous operation.

Figure 50: ALMATEC AHD 25 pneumatic pump used as GL-PX device

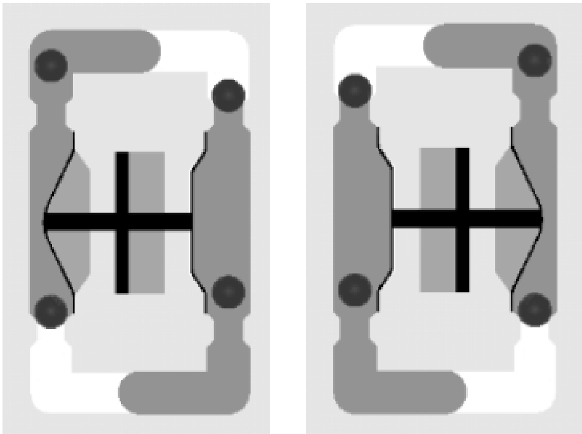


Figure 51: Working principle of the pneumatic pump used as GL-PX

Table 10 summarizes the main technical data of the GL-PX device.

Table 10: Pneumatic pump technical specifications

Specifications	AHD 25 EEE
Dimensions mm ("): width depth height	422 (16.6) 256 (10.1) 412 (16.2)
Flange connections, port DIN or ANSI Air connection BSP	25 (1") 1/2"
Weight kg (lbs)	24 (53)
Material of housing	PE UHMW
Material of diaphragms	EPDM
Material of ball valves	EPDM
Max. particle size of solids mm (")	5 (0.20)
Suction lift, dry mWC ('): Suction lift, wet mWC (')	3.5 (11.5) 9.5 (31.2)
Max. driving and operating pressure bar (psig)	7 (100)
Max. operating temperature °C (°F)	70 (158)
Sound pressure level acc. to DIN 45635, part 24, depending on the operating data [dB (A)]: driving pressure 3 bar driving pressure 5 bar driving pressure 7 bar	 76-86 78-88 79-88

Figure 52 shows the performance chart of the selected pneumatic pump, as stated by the manufacturer. Note that the blue lines state the air consumption in Nm^3/min.

The expected nominal air consumption of the pump is expected to be around 1 Nm^3/min. This would be equivalent to about 0.02 kg/s of air consumption during nominal operation.

The desalination system will be connected to the main compressed air line with a DN10 flexible hose. A threadolet of size G ¼" will be foreseen in the compressed air line after the pressure reducer to connect the flexible hose. 12 bar is foreseen as nominal feed pressure, which results in a nominal flow velocity of about 19 m/s in the connection hose.

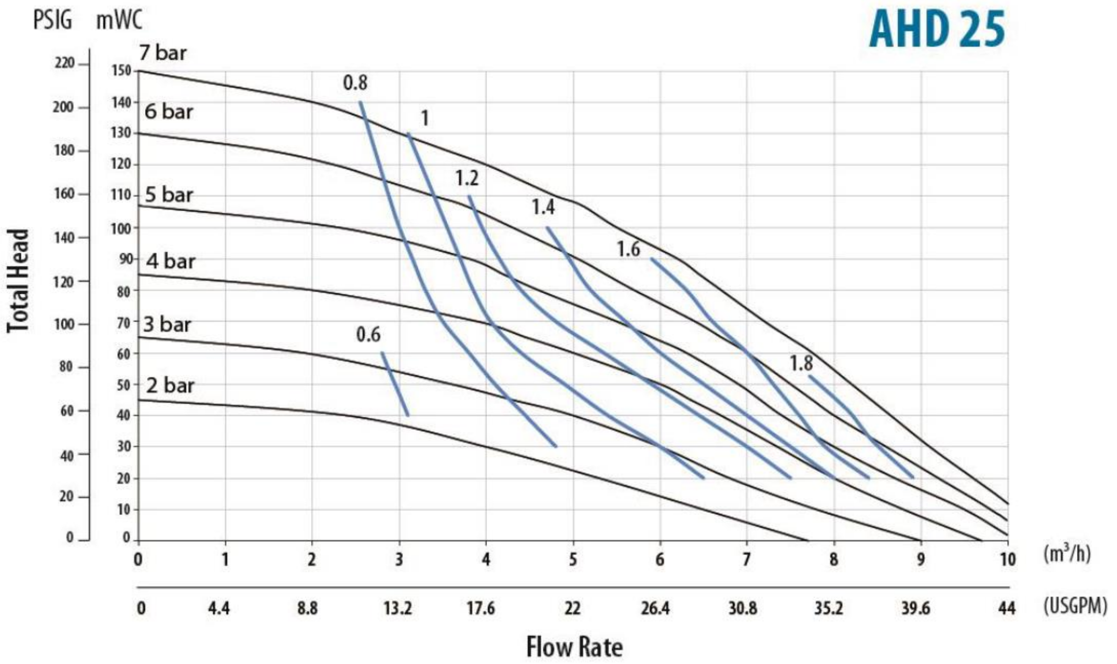


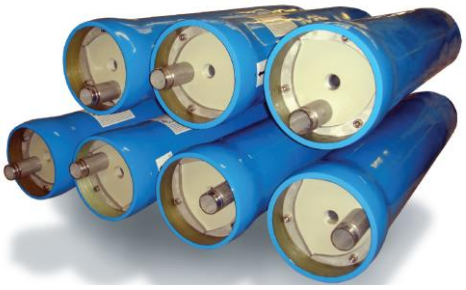
Figure 52: Pneumatic pump performance chart

Below, detailed information can be found related to the rest of the specified elements that forms part of the whole RO desalination system to be built in the project.

<table>
<tr><td><u>Feed, concentrate and permeate tanks</u>

Model: Aquablock DE-8002-06
Specifications:
Volume: 3000 L
Dimmensions (mm): 1725x1150x 1850
Weight (empty): 90 kg
Material: PEHD
Top cover DN250
Total units: 3
TAG in P&ID: K-01 a K-03</td><td></td></tr>
<tr><td><u>Horizontal centrifugal pump for fluid transfer from permeate and concentrate tanks to feed tank (specification nº3)</u>

Model: Grundfos CME 15-1
Specifications:
Preset Speed: 3480 rpm</td><td></td></tr>
</table>

• Nominal Flow Rate: 20.4 m³/h • Nominal Head: 21.19 m • Impellers: 1 • Primary Seal: AQQE • Pump Housing: Cast Iron (EN-GJL-200 / ASTM A48-25A) • Impeller: Stainless Steel (EN 1.4301 / AISI 304) • Maximum Operating Pressure: 10 bar • Max Pressure at Declared Temperature: 10 bar / 90 °C • Liquid Type: Water • Liquid Temperature Range: -20 to 90 °C • Operating Liquid Temperature: 20 °C • Density: 998.2 kg/m³ • Rated Power (P2): 2.2 kW • Mains Frequency: 50 / 60 Hz • Nominal Speed: 2900 - 4000 rpm **Total units**: 1 **TAG in P&ID:** P-03	
<u>**Ultrasonic level meter for tanks**</u> **Model**: Endress Hauser FMR10 **Specifications:** • Ingress Protection: IP66/68 / NEMA 4X/6P • Measurement Range: Up to 12 m (39.37 ft) • Process Temperature: –40 to 60 °C (–40 to 140 °F) • Process Pressure: –1 to 3 bar (–14 to 43 psi) • Measurement Accuracy: Up to ± 5 mm (0.2 in) **Total units**: 3 **TAG in P&ID:** LT-01 a LT-03	
<u>**Membrane pressure vessels**</u> **Model**: Auxicolor Phoenix 40.300.2 **Specifications:** • Material: reinforced fiberglass • End fittings designed for easy assembly and disassembly. **Total units**: 2 **TAG in P&ID:** OI-01	

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<u>Strainer</u>

Model: ARAG 335
Specifications:

3-inch BSP male threads
Filtering capacity 46 m^3/h (766 lpm)
Cartridge 145 x 320 mm
Polypropylene body, EPDM gaskets

Total units: 1
TAG in P&ID: F-01
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<td>
<u>Fabric type MF pre-filter</u>

Model: Cintropur NW400
Specifications:

Working mechanism: Cyclonic effect created by the centrifugal propeller.
Working pressure: 10 bar.
Working temperature: 0 – 50 ºC
Maximum working pressure: 16 bar.
Filter size: 25
Filter area: 1010 cm^2
Maximum flowrate: 12 m^3/h

Total units: 1
TAG in P&ID: F-03
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<tr>
<td>
<u>AC prefilter</u>

Model: Cintropur NW500 TE
Specifications:

Materials: PP ref. with glass fiber (head) SAN ref. with glass fiber (cup) NBR (gasket)
ΔP= 0.2 Bar
Maximum working pressure: 16 bar.
Working temperature: 0 – 50 ºC

Total units: 1
TAG in P&ID: F-02
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<u>**Flow meter with 4-20 analog output for recording. PN40.**</u>

Model: Tecfluid SC250
Specifications:

- Flowrate: 0 – 15 m^3/h
- Electronic transmitter with 4-20 mA analog output.
- Precission: 2.5% (q_G=50%)
- Materials: EN 1.4405 (AISI316L)

Total units: 5
TAG in P&ID: FIT-01 a FIT-05

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<u>**Pressure transmitter**</u>

Model: Endress Hauser Cerabar PMP21
Specifications:

- Feature: Cost-effective pressure transducer, piezoresistive sensor with metallic measuring diaphragm
- Voltage Supply: 10…30 VDC
Reference Accuracy: 0.3%
- Long-term Stability: 0.2% of URL / year
- Process Temperature: -40 °C…+100 °C (-40 °F…+212 °F)
- Ambient Temperature: -40 °C…+85 °C (-40 °F…+185 °F)
- Measuring Cell: +400 mbar…+400 bar (+6 psi...+6000 psi)
- Max. Overpressure Limit: 600 bar (9000 psi)
- Communication:4…20mA

Total units: 8
TAG in P&ID: PT-01 a PT-08

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<u>**Visual pressure gauge**</u>

Specifications: The system includes a visual pressure indicator to provide a quick visual reading of the pressure in the demi water stream.

Total units: 1
TAG in P&ID: PI-01

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<u>**Conductivity sensor.**</u> **Model:** Hach D3725E2T.99 **Specifications:** • Body Material: Polypropylene • Sample Flow Rate: Max. 3 m/s • Length: 127 mm • Cable Length: 6 m fixed cable + 1 m digital cable • Material: Polypropylene (PP) • Materials in Contact with the Sample: Polypropylene • Immersion Sensor Depth: 79.2 mm • Measurement Range: 200 µS/cm - 2000 mS/cm • Pressure Range: 6.9 bar at 100 °C • Operating Temperature Range: -10 - 100 °C (Sensor limited by body material) • Temperature Sensor: Pt1000 RTD • Sensor Type: Digital **Total units**: 3 **TAG in P&ID:** CondT-01 - CondT-03	

<u>**pH sensor**</u>
 	
Model: Hach D3725E2T.99
Specifications:
• Sensor Cable: 10 m polyurethane, 4-conductor shielded cable, rated for 105 °C (221 °F)
• Temperature Compensation: Automatic with 300 Ω NTC thermistor or manually set at a user-specified temperature. Additional selectable temperature correction factors available (ammonium, morpholine, or user-defined linear pH/°C slope) for automatic compensation of pure water from 0.0 to 50 °C.
• Communication: Modbus
• Storage Conditions: 4 - 70 °C, 0 - 95% relative humidity (non-condensing)
• Cable Connection: Digital
• Drift: 0.03 pH per 24 hours, non-cumulative
• Transmission Distance:
    o Maximum 1000 m (3280 ft) when used with a termination box
    o Maximum 100 m (328 ft)
• Accuracy: ± 0.02 pH
• Temperature Accuracy: ± 0.5 °C
	

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- Length: 271.3 mm
- Cable Length: 10 m PUR (polyurethane), 4-conductor shielded, rated for 105 °C
- Measurement Range: -2.0 to 14.0 pH
- pH Range: 0 - 14 pH
- Pressure Range:
  - Maximum 10.7 bar
  - 6.9 bar for digital sensor at 70 °C
  - 6.9 bar for analog sensor at 105 °C
- Operating Temperature Range:
  - Analog sensor with digital gateway: -5 to 105 °C
  - Digital sensor: -5 to 70 °C

Total units: 1
TAG in P&ID: pHT-01

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<u>Sensing controller with analog outputs for logging</u>

Model: Hach SC100
Specifications:

- Modular controller system. Can be used directly with up to 8 sensors or installed in a network to include many more sensors and parameters. The SC1000 controller consists of a display module and one or more probe modules. A single display module controls one or more probe modules connected through a digital network. The SC1000 display module is also available with GSM/GPRS, Ethernet, and TCP/IP functionality. Probe modules can be networked to install up to 32 expansion boards or digital sensors within the same network.

Total units: 1
TAG in P&ID: -

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<u>Temperature sensors</u>

Model: Endress Hauser TMR 31
Specifications:

- Feature / Application: Metric type, compact temperature probe, fast response time, threaded process connection, with or without neck.
- Insert / Probe: Pipe version, insulated cables, non-flexible
Protection Tube Outer Diameter / Insertion Element

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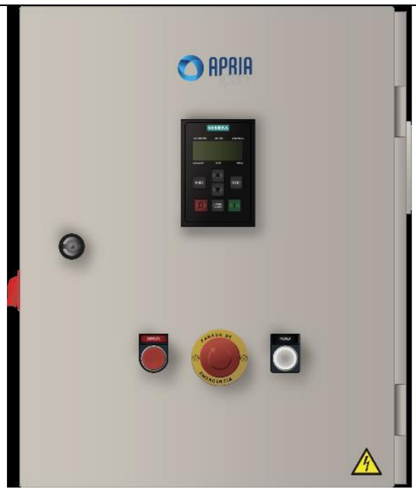
○ 4.0 m (0.16") ○ 4.00 mm (0.24") • Max. Immersion Length: up to 600.00 mm (23.62") • Protective Pipe / Thermowell Material: 1.4404 (316L) • • Process Connection • Operating Temperature Range: –50 °C … 200 °C (-58 °F … 392 °F) • Max. Process Pressure (Static): At 20 °C: 100 bar (1,450 psi) • Response Time: t50 = 1 s; t90 = 2 s **Total units**: 1 **TAG in P&ID:** TI-01	
<u>Electrical panel</u> **Model**: APRIA Systems **Specifications:** The system includes an electrical and control cabinet that allows starting or stopping the system operation. All equipment and instrumentation and control devices requiring power supply are connected to this electrical cabinet. **Total units**: 1 **TAG in P&ID:** -	

Lastly, Figure 53 and Figure 54 shows the 3D model representation of the RO pilot plant as well as the construction blueprints.

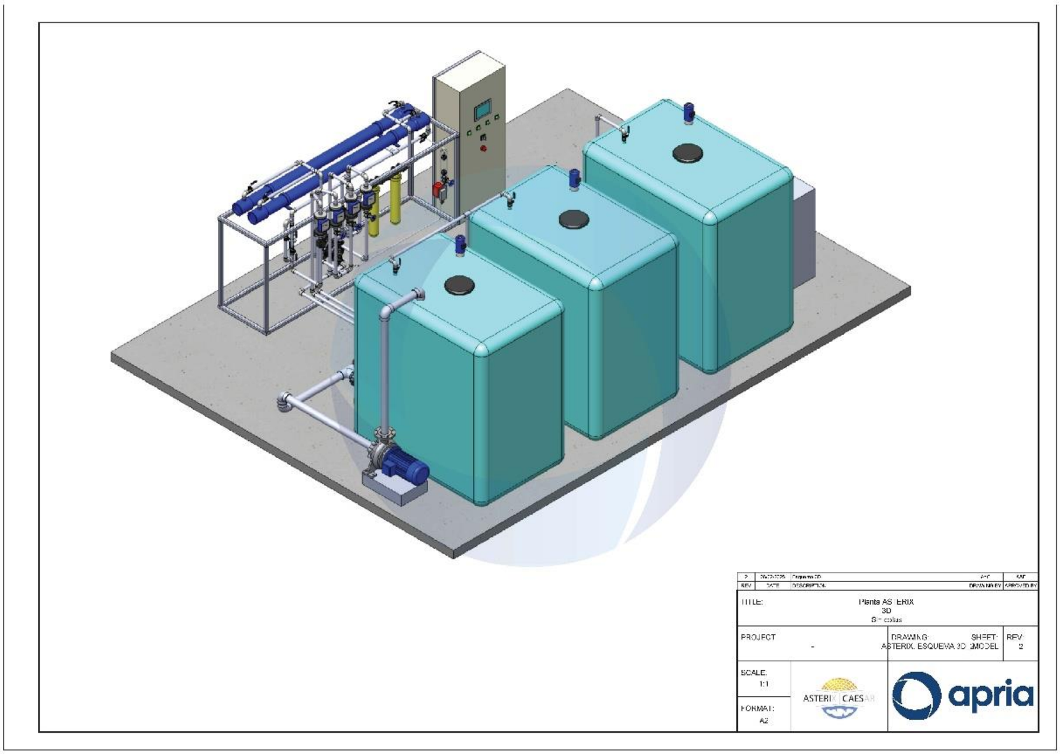


Figure 53. 3D model of the RO desalination plant

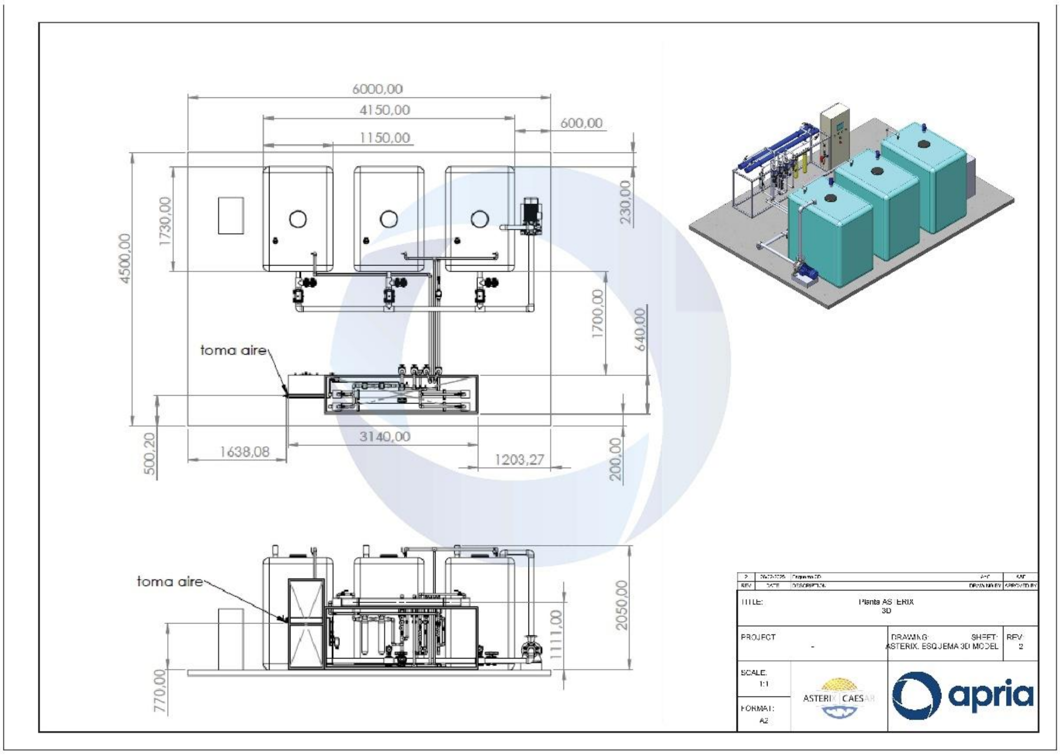


Figure 54. Construction blueprints of the RO desalination plant

5 Conclusions

This document describes the ASTERIx-CAESar prototypes that are going to be installed and operated during the project.

All required components are fully specified, and orders can now be placed to be able to start prototype installation as soon as possible. The installation of the solar turbine loop and CAES system is planned to be done during the year 2025. Wiring and control system modifications are foreseen to start at the beginning of 2026.

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ANNEX I – List of components (ASTERIx-CAESar solar turbine and CAES P&ID - Figure 14)

Components at tower testing level:
1 - Solar receiver (existing, installed)
2 - Air/water HEX (existing, installed)
3 - Bypass valve receiver only (existing, installed)
4 - Blower (existing, installed))
5 - DN200 (ambient pressure) piping to air/water HEX (existing, installed)
6 - DN200 (ambient pressure) piping from air/water HEX to blower (existing, installed)
7 - Air/Air HEX for heating compressed air for expansion (ordered, to be installed)
8 - Bypass valve turbine only operation DN200 (CERAVALVE KBRG500-HT, existing, installed)
9 - DN200 piping (ambient pressure) from receiver to Air/air HEX (to be ordered and installed)
10 - DN200 piping (ambient pressure) from air/air HEX to blower (to be ordered and installed)
11 - Hot air turbine (to be modified, to be installed again)
12 - DN150 PN40 piping from air/air HEX to turbine (to be ordered and installed)
13 - Flow control valve for turbine flow (DN50 CERAVALVE KBR500-HT FD150)
Note: Valve 13 can also be used to completely shut off the compressed air pipe in case of preheating
14 - DN100 PN16 piping from pressure reducer 20, over flow control valve to air/air HEX (to be ordered and installed)
Note: piping 16 should connect straight to piping 14 HEX inlet (DN100); T-joint with DN50 piping to valve 13
15 - On/off valve to activate/deactivate turbine preheat circuit (SAMSON 3335 DN 100 Wafer)
16 - Connection pipe between preheat blower, valve 15 and piping 14 (DN100)
17 - Auxiliary air blower for turbine system preheating
18 - Intake air filter (turbine compressor and auxiliary blower)
19 - Connection pipe between air filter 18, turbine compressor intake and auxiliary blower 17
20 - Pressure reducing valve to adjust to turbine inlet pressure (DN40, PN16, SAMSON Tipo 41-23)
32 - Pressure relief valve (6 bar max)
Connection Tower CAES:
21 - DN65 PN16 piping from tower top level to ground level (45 m height difference, about 60 m total length)
CEAS and compressor unit:
22 - Standard pressure reducer (300 to 10-12 bar)
23 - Bundle of standard high-pressure cylinders (12 pieces of 50 liter cylinders form one bundle) Each bundle comes with two manual shut-off valves (bundles to be ordered, to be installed)
24 - High pressure (300 bar) charging line (DN6 hose) connected to line 29 Connects compressor with bundles for charging operation
25 - Standard industrial compressor Bauer Model PE 120-7.5-VE (piston type, 3 stages with intercooling); Air drying system is included such that the outlet air is dry and no condensation water is accumulated in pressure cylinders
26 - Manual main shut-off valve, one per bundle (opened during operating period)

27 - Auxiliary shut-off valve (always closed) – each bundle comes by default with two manual valves
28 - Charging shut-off valve (on/off)
29 - High-pressure (300 bar) discharging / charging header DN25 line + DN6 hoses to connect bundle
30 - Discharging shut-off valve (on/off)
31 - Pressure relief valve (blow-off valve in case of failure of pressure reducer – 15 bar max)

ANNEX II – List of sensors (ASTERIx-CAESar solar turbine and CAES P&ID - Figure 14)

FI01 – Flow meter receiver loop (hot wire sensor)
FI02 – Flow meter turbine loop (vortex flow meter)
FI03 – Flow meter cooling water (electromagnetic sensor)
TI01 to T16 – Temperature sensors solar receiver (Thermocouple type k)
TI17 to TI20 – Temperature sensors receiver outer surface (Thermocouple)
TI21 – Solar receiver outlet temperature sensor tube centre (Thermocouple type k)
TI22 – Solar receiver outlet temperature sensor tube near wall (Thermocouple type k)
TI23 – Air/Water HEX air inlet temperature sensor (Thermocouple type k)
TI24 – Air/Water HEX air outlet temperature sensor (Thermocouple type k)
TI25 – Air/Water HEX water inlet temperature sensor (Pt 100)
TI26 – Air/Water HEX water outlet temperature sensor (Pt 100)
TI27 – Air/Air HEX hot side inlet temperature (Thermocouple type k)
TI28 – Air/Air HEX hot side outlet temperature (Thermocouple type k)
TI29 – Air/Air HEX cold side inlet temperature (Pt 100)
TI30 – Air/Air HEX cold side outlet temperature (Thermocouple type k)
TI31 – Blower inlet temperature (Thermocouple)
TI32 – Turbine preheat/compressor air inlet temperature sensor (Pt 100)
TI33 – Air temperature sensor after pressure reducer (Pt 100)
TI34 – Air temperature sensor in high pressure line (Pt 100)
PI01 – Solar receiver outlet pressure indicator
PI02 – Compressed air line 20 pressure indicator (before flow control valve 13)
PI03 – Compressed air line 14 pressure indicator (after flow control valve 13)
PI04 – CAES pressure indicator