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Finalization of a lab-scale ACAES demo

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TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO:	Finalization of a lab-scale ACAES demo
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RESUMEN

La creciente preocupación por el impacto ambiental de la utilización de combustibles fósiles lleva a la búsqueda de nuevas formas de obtener energía de fuentes renovables. Sin embargo, mediante estos métodos no se consigue una cantidad estable y controlable de energía. Por ello es necesario desarrollar sistemas capaces de almacenar la energía obtenida que no se necesite en el momento para después poder ser utilizada.

Este es el objetivo la tecnología de Almacenamiento Adiabático de Energía por Aire Comprimido. En este proyecto se continúa el trabajo de dos equipos anteriores, para terminar un modelo funcional a pequeña escala de uno de estos sistemas. Para ello se analiza, revisa y corrige el trabajo realizado hasta ahora, implementando mejoras en las distintas partes del sistema para incrementar la eficiencia de los diversos procesos termodinámicos.

PALABRAS CLAVE

Energías renovables, almacenamiento de energía, construcción, aire a alta presión, eficiencia

ABSTRACT

The increasing concern about the environmental impact of fossil fuels has caused the search of new ways of obtaining energy from renewable sources. However, these methods do not provide a stable and reliable amount of energy. Thus, it is necessary to develop new systems that can store the produced energy to use it when it is needed the most.

This is the goal of the Adiabatic Compressed Air Energy Storage technology. In this project, the work done by two preceding teams is continued, to finalize a functional lab-scale demo that can recreate these systems. To do so, all the previous work is checked, analyzed, and corrected and upgrades in the different subprocesses are implemented, to improve the efficiency of the various thermodynamical processes that take place.

KEYWORDS

Renewable energies, energy storage, building, high-pressure air, efficiency

ENERGY STORAGE
EPS SPRING 2021

Finalization of a lab-scale CAES demo

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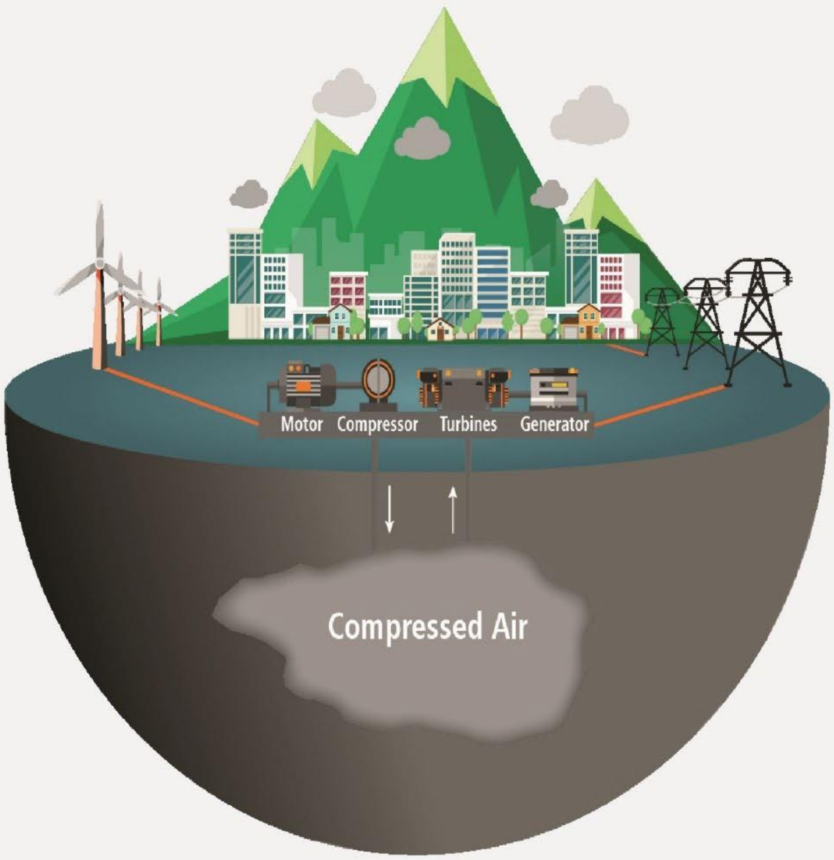

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Abstract

The aim of this project was to finalize a lab-scale A-CAES demo started by an EPS Autumn Semester 2019 team. The demo would be used for education, research personnel and demonstrations. Initially, the team's main focus was increasing the performance of the demo.

Firstly, The team worked hard on the calculations, test runs and troubleshooting. Management was essential for this project, as timing and organization are key components for a successful end result.

However, as the project proceeded, the team realized there were too many problems with the demo to solely do finalizing work. There was water found in the cycle, which caused corrosion and would do severe damage to the pipe system, the turbine and the overall efficiency of the demo. To solve this an air filter had to be made. Furthermore, there was a dent found in the TES, meaning it had to be completely redone. The main focus was then put on digitalizing the demo and obtaining a functioning demo by: building an air filter, rebuilding the TES and applying insulation.

The final outcome of this project is a functioning demo with improved efficiency, a user manual and a safety management plan.

Table of Contents

1 List of abbreviations

RES	Renewable Energy Sources
EPS	European Project Semester
WBS	Work Breakdown Structure
UAS	University of Applied Sciences
A-CAES	Adiabatic Compressed Air Energy Storage
TES	Thermal Energy Storage
CAT	Compressed Air Tank
VAMK	Vaasa University of Applied Sciences
WP	Water pillow
CPM	Critical path method
PHES	Pumped Hydro Energy Storage

2 List of figures

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4 Introduction

4.1 Background

Approximately 46% of the world's electricity is generated by the burning of fossil fuels. Traditional energy sources based on coal, oil and natural gas involve the combustion of fossil fuels.[1] But the world's ever-increasing demand for energy has caused stress on the fossil fuels reserves. Apart from these fossil fuel-based energy sources facing the challenge of limited reserves, their environmental impact is consequential.[2]

Affected by the increasing concern of the environmental impact of traditional energy sources, producing sustainable energy based on renewable energy sources (RES) has never been a more important debating topic than it is today. RES are limitless and pollution-free. In fact, RES could reduce the energy sector's emissions by approximately 81 percent.[3]

One of the largest concerns with RES is being able to concentrate the energy enough to economically convert it to electricity. Unlike traditional energy sources, renewables don't provide a dependable and predictable amount of electricity.[4] Thus making renewable energy a more unreliable source. Therefore new storage solutions are developed to defeat the RES's challenges of maintaining the stability of the power network. One way of storing renewable energy is via A-CAES (Adiabatic Compressed Air Energy Storage) technology.

4.2 Goal

European project semester

This project was a collaboration between five international students all participating in an EPS program offered by Novia University of Applied Sciences (UAS) for engineering students. The students that participated in the EPS program of spring 2021 met together to work on their dedicated project. EPS thrives to prepare future engineers to perceive, think and act globally.

Report

This report looks into finding a sustainable, low cost and efficient way to store and recover energy from compressed air. This was done by working on a lab scale Compressed Air Energy Storage demo, located in Technobotnia. The goal of this project was to finalize this CAES demo started by an EPS Autumn Semester 2019 team. This was done by reconstructing the existing demo whilst having a theoretical justification for all the changes made. The demo would be used for education and research. Therefore, a complete and accurate user manual with a safety management plan is a necessity.

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[1] (Hulisani. 2018)
[2] (Herzog, V. A. Timothy, E. Kammen, M. D. 2001)
[3] (Langeard, A. 2017)
[4] (Copadata. 2018)

In addition temperature and pressure sensors were put on the demo. To ensure that all students understand the demo in each part of its cycle, The data from the sensor is extracted in real-time.

4.3 System boundaries

This report is limited in time and budget. Therefore, this report focuses solely on CAES systems for storing energy and no other energy storage solutions.

5 Research

5.1 Technical analysis

5.1.1 Comparison energy storage systems

There are versatile energy-storage systems offering wide ranges of power and energy density.[5] In the following table characteristics from different energy storing technologies are summarized.

Characteristics	Large-scale CAES	Small-scale CAES	PHES	Li-ion battery	Hydrogen fuels
Power density (W/L)	0.5–2	> large-scale CAES	0.5–1.5	1500–10,000	> 500
Energy density (Wh/L)	2–6	> large-scale CAES	0.5–2	200–500	500–3000
Lifespan (years)	20–40	>23	40–60	5–16	5–20
Cycle efficiency (%)	40–70	-	70–85	75–97	20–66
Response time	Minutes	Seconds-minutes	Minutes	Milli-seconds	Seconds
Power capital cost ($/kWh)	400–1000	517–1550	2000–4000	900–4000	500–3000
Energy capital cost ($/kWh)	2–120	200–250	5–100	600–3800	2–15

Table 1 Comparison energy storage systems

Li-ion technologies are found in every household. They have a substantial power/energy density and a fast responding time. However, Li-ion batteries are difficult to scale, expensive and have a short lifespan. In addition, the production and removal process of these batteries is detrimental to the environment

[5] (Hall, J. P. Bain, J. E. 2008)

Hydrogen fuels have significant potential. They can be produced from multiple domestic resources with nearly zero greenhouse gas emissions. Furthermore, hydrogen fuels provide quality properties on scale with other storing solutions. For example, they have a high power/energy density, fast responding time, a relatively long lifespan and low capital costs. On the contrary, storing hydrogen is a challenge as it requires high pressures and chemical additives to be stored compactly.

Compressed Air Energy Storage and Pumped Hydro Energy Storage systems are comparable systems. PHES systems contrary to CAES systems, have a longer lifetime and higher cycle efficiency. For instance: the Huntorf system in Germany has been running since 1978 and is still in satisfactory condition. The efficiency of the Huntorf system is 48% which is a moderate result. Nevertheless its efficiency could rise up to 86 % by using a Thermal Energy Storage (TES) in connection with a distinct heat network.

In general CAES systems are slightly cheaper than PHES systems and with a value of 400–1000 $/kWh they have the lowest power capital cost of all energy storing systems to date.

A disadvantage of CAES and PHES is their low power and energy density. Extensive air or water tanks could compensate this disadvantage. Therefore, both systems are dependent on geologic formation. The installation of standing or dammed-up water reservoirs has become a major obstacle since the 90s, due to the absence of suitable locations. Furthermore concerns about massively modifying the earth's geological structure, are rising. For example: if the Three Gorges Dam in China would break, there would be a noticeable buckling of the axis of the earth with extensive consequences.

The air tanks for CAES systems are less dangerous. For these, old mines or salt caverns can be used and they are globally found more frequently. However, these caverns are not necessarily near an appropriate location for renewable energy sources, and this possible distance results in electricity transport losses.

5.1.2 Mode of Operation "Compressed Air Energy Storage" CAES

Overall a Compressed Air Energy Storage system or CAES describes a process of converting electricity into compressed air. Later when needed this thermodynamic potential is reconverted to electric energy. Therefore the system is working in two different cycles.

Charging Cycle (transfers electric energy into compressed air)

Step	Name	Function	Device
1	Compression	air compression	compressor
2	Heat transfer	cool down the air for less volume	heat sink
3	Storing	store the compressed air for reuse	cavity/pressure tank

Table 2 Charging cycle CAES

Discharging Cycle (transfers compressed air into electric energy)

Step	Name	Function	Device
3	Storaging	reuse of the storaged air	cavity/pressure tank
4	Heat transfer	heating up the air for more volume	heat sources
5.1	Expansion	air pressure into mechanic work	expander
5.2	Expansion	torque/revolution speed adjustment	transmission
5.3	Expansion	mechanic work into electricity	generator

Table 3 Discharging cycle CAES

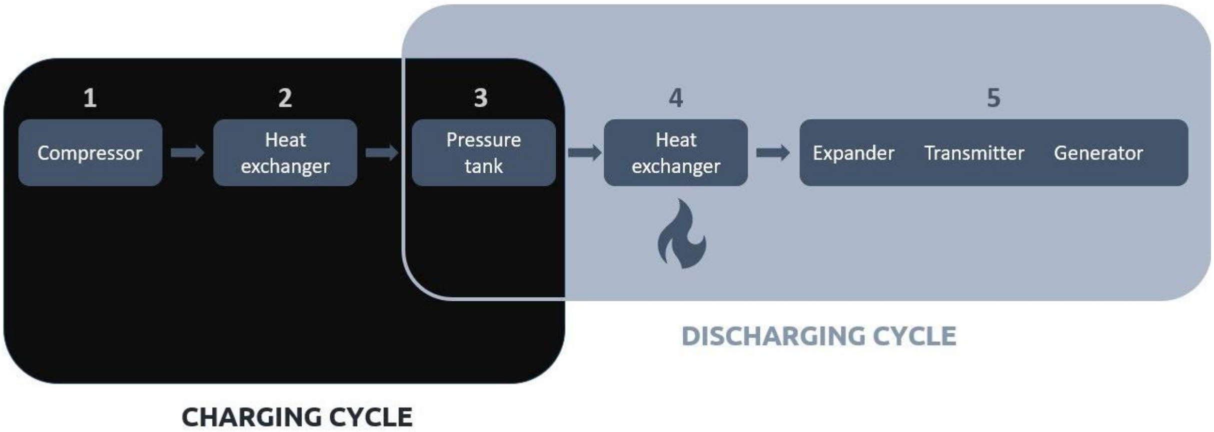

Figure 1 Own illustration cycles A-CAES

For both cycles the heat transfer is very important. The general mathematic correlation, known as the ideal gas law, is:

$$mRT = PV \qquad (1)$$

R is the gas constant of air and the volume V is specific of the chosen location which means they are consistent values. For the charging cycle, a low temperature T of the stored medium air is very important. It enables to store a greater amount of mass while keeping the stress due to pressure, in the tank, on an inevitable minimum. Therefore, the air flows through interconnected heat exchangers to decrease its temperature.[6] Relevant for the discharging is a high temperature of the air, to create as much volume as possible, which then feeds the turbine.

[6] (Wei He. 2018, p.78)

PV-diagram of CAES cycle

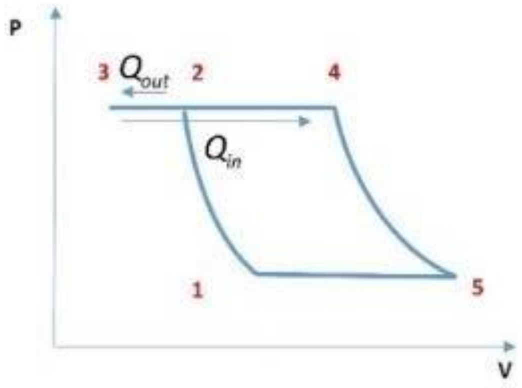

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Figure 2 PV-diagram of CAES cycle

With:

Q_{out} =heat energy taken away from the heat sinkers
Q_{in} =heat energy provided by burning fossil fuels

While compressing the fluid, heat is generated. During the expansion cold is produced. These are, as mentioned, the opposed values the team is aiming for. In a normal CAES system the heat from the compression is, with heat sinkers, released to the surrounding. Later, before the expander, the heat is produced by burning fossil fuels. This is not an efficient solution since it requires additional resources.

5.1.3 Mode of Operation "Adiabatic-Compressed Air Energy Storage" A-CAES

Adiabatic means, that there is no heat exchange with the surrounding.[8] This is just an idealized assumption, but following this idea, there is still a lot of potential to improve on the efficiency of CAES.

As mentioned, in CAES heat is first flushed out of the system and then produced again. To keep the whole process adiabatic, it must be possible to store the produced heat form the compression step and reuse it before the expansion. Therefore, a Thermal Energy Storage (TES) can be used. With a TES the dependence on fossil fuels can be eliminated, without suffering great efficiency losses.

[7] (Wei He. 2018)
[8] (Tripathi, S. 2019)

Charging Cycle (transfers electric energy into compressed air)

Step	Name	Function	Device
1	Compression	air compression	compressor
2	Heat transfer	cool down the air for less volume	TES
3	Storing	store the compressed air for reuse	cavity/pressure tank

Table 4 Charging cycle A-CAES

Discharging Cycle (transfers compressed air into electric energy)

Step	Name	Function	Device
3	Storing	reuse of the stored compressed air	cavity/pressure tank
4	Heat transfer	heating up the air for more volume	TES
5.1	Expansion	air pressure into mechanic work	expander
5.2	Expansion	torque/revolution speed adjustment	transmission
5.3	Expansion	mechanic work into electricity	generator

Table 5 Discharging cycle A-CAES

In the charging cycle the air is getting compressed in the compressor. In that process, a lot of heat is generated. This heat is saved in the TES, before the air is getting stored in the pressure tank.

After a while, when energy is needed again, the air will run through the TES. That is the discharging cycle. In the TES the air is heated up again to provide more volume for the expander. After that the air is powering the expander. The turbine from the expander and a gear from the transmission are fitted to the same shaft. Equivalently the generator is connected to a gear too. Like that the ideal gear transmission ratio for the generator is created.

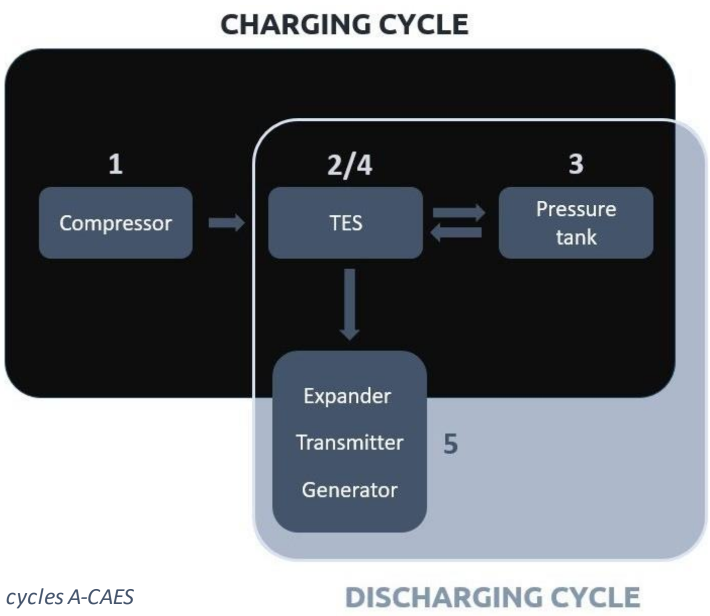
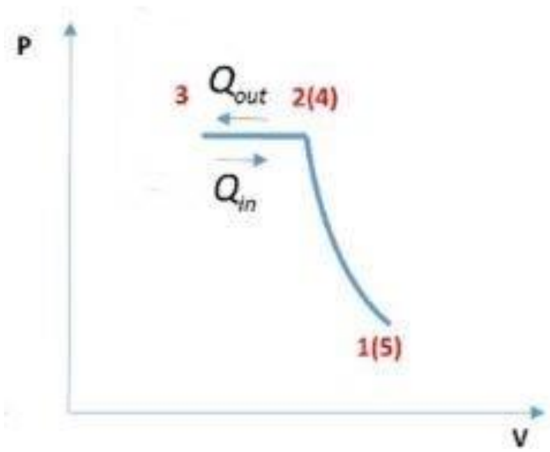


Figure 3 Own illustration cycles A-CAES

PV-diagram of A-CAES cycle



[9]

Figure 4 PV-diagram of A-CAES

With:

Q_{out} =heat energy reduction saved in TES
Q_{in} =heat energy added by the TES

For an ideal adiabatic working process Q_{out} equals the value of Q_{in}. In reality is Q_{in} smaller than Q_{out}. The reason for that are unavoidable heat losses.

[9] (Wei He. 2018, p.78)

5.2 Demo - Examination of current demo

At the start of the project the team found an uncompleted demo. In this chapter, the different components will be described.

5.2.1 Pipe system

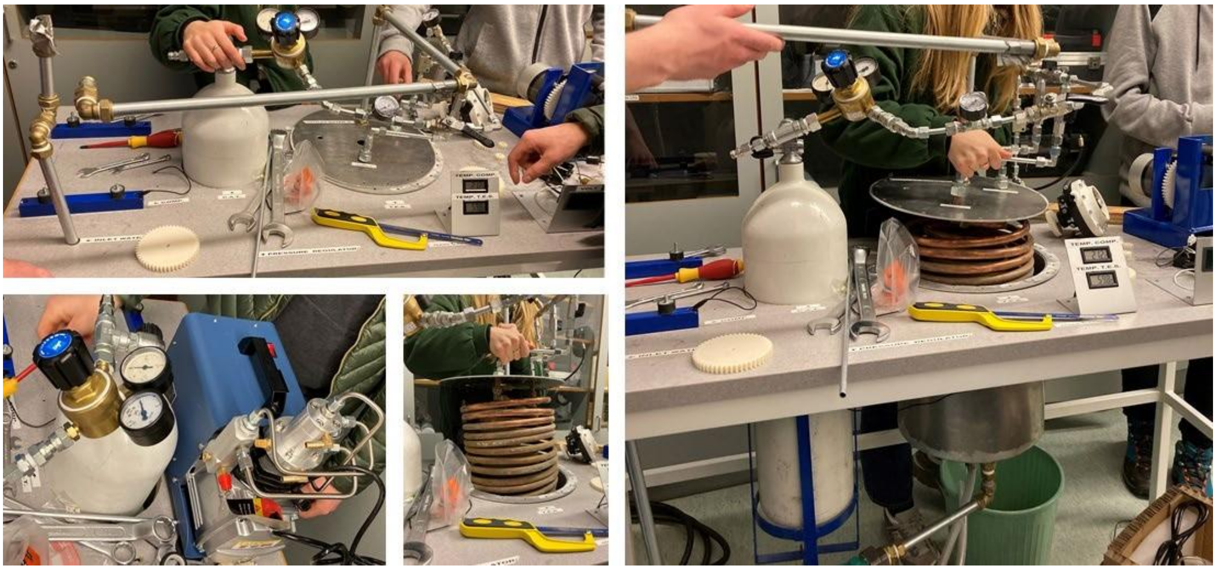


Figure 5 General overview demo

In the system there are two separate cycles, one for water and one for air. Each of them has different pipes and characteristics.

For the water cycle, 18mm diamater steel pipes and standard plumbing couplings were used. The stiffness of the steel allowed the system to be build over and under the table, without the need of extra restraints.

For the air cycle, high pressure components were needed. The valves could work up to 30 bar and the steel pipes, that had an outside dimension of 8mm and a thickness of 1mm, could withstand up to 700 bar.

Figure 6 Pipe system

5.2.2 Compressor

The team received a new compressor from the supervisor Cynthia Söderbacka, since the one used by the previous team was damaged. The model was a Yong Heng YH-QB01, capable of compressing the air up to 300 bar. The charging rate of this compressor is 40-50 l/min. The compressor is water cooled and has several valves to relief the pressure in case of emergency. Furthermore, the compressor has a pressure gauge where the team can check the correct development of the process.

Figure 7 Yong Heng Air pump

5.2.3 CAT

The selected air tank is a professionally tested scuba tank, that could work until 300 bar, with a volume of 12 liters. It is made out of steel.

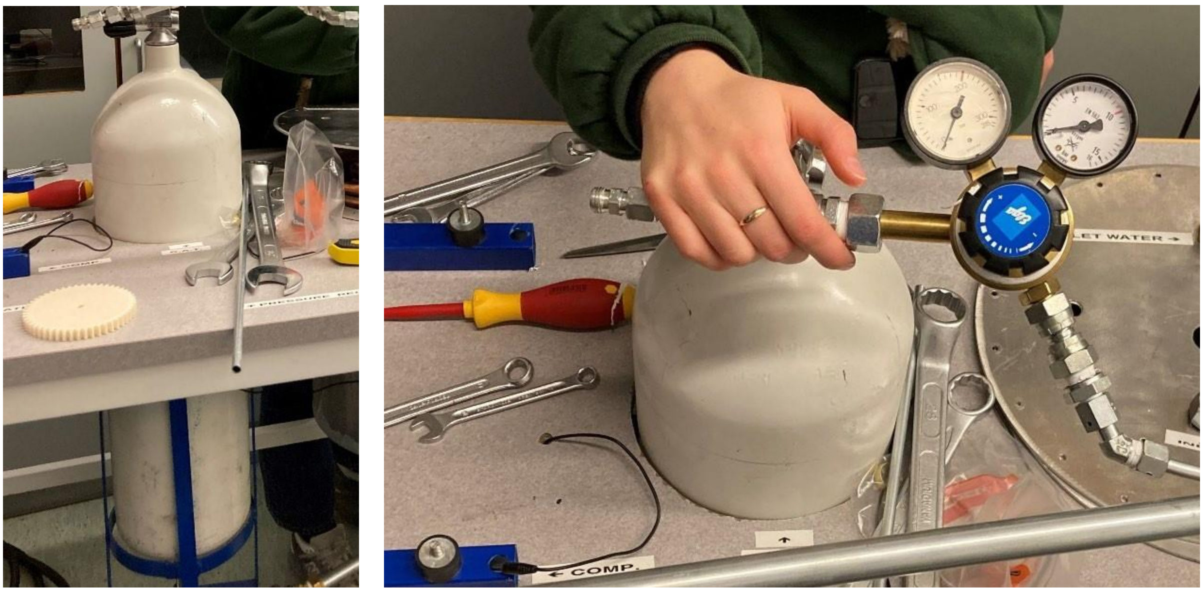


Figure 8 CAT

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5.2.4 TES

The TES is composed of a tank and a heat exchanger.

The tank for the TES was made out of aluminium, and it is a 300mm diameter cylinder with a height of 340mm. It will need to be insulated to maintain the heat in the water.

The heat exchanger was built with copper pipes that had an outside dimension of 15mm and a thickness of 1mm. These copper pipes were bent into two spirals, that had diameters of 15 and 22cm.

Figure 10 TES

Figure 9 TES tank

5.2.5 Turbine and gears

The 2019 EPS group designed and manufactured the turbine with a 3D printer. The rotor design was clutched from the open source platform Grab CAD. The following parts were designed in SolidWorks.

- Housing rotor back top (pink)
- Housing rotor back bottom (blue)
- Housing rotor front (yellow)
- Axial connected to rotor with thread and bolts (white)
- Adjustment mechanism generator to rotor axial (green)
- Exchangeable gears (blue)

The bearings are connected between the two back rotor housings. They ensure the axial spins without friction. Figure 11. gives an exploded view of the turbine with the bearings colored orange.

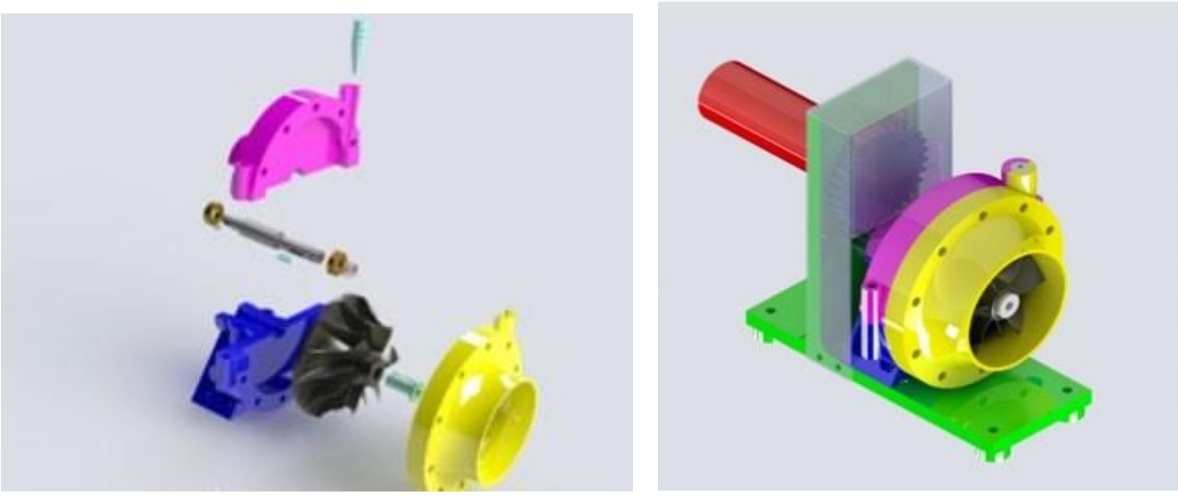

Figure 11 Turbine design 2019

The team was given two options to carry out the final expansion from 6 bar to ambient pressure: an air motor (Bibus Easy Drive PMO 0450) and a turbine designed and 3D printed by the 2019 team. [10] The gear system and the gear train bracket were constructed by the 2020 team. The gears were 3D printed in plastic, while the bracket was made using metal working processes.

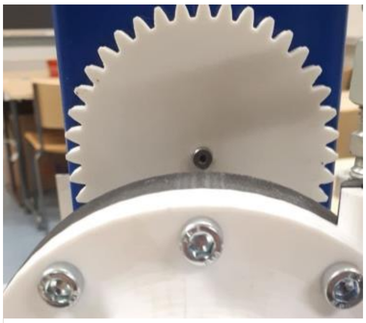

Figure 14 Gears

Figure 12 Turbine

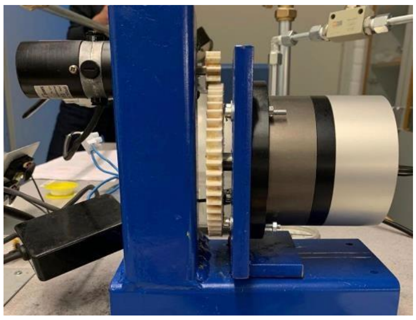

Figure 13 Air motor

[10] (Verberne, L. Pogats, F. Looijen, R. De Jong, E. Perez, C. 2019, p.49)

6 Revision previous demo

In an early stage of the project, the A-CAES demo was thoroughly examined. In this chapter, the problems with the A-CAES demo were defined.

6.1 Old demo lay-out

Multiple issues as corrosion and leakages were discovered in the 2019/2020 demo construction. In the figure below, the original state of the demo is shown.

Figure 15 State of Demo 23/02/2021

The following lay-out was used for the construction. The air flew in one line while the water followed a circle.

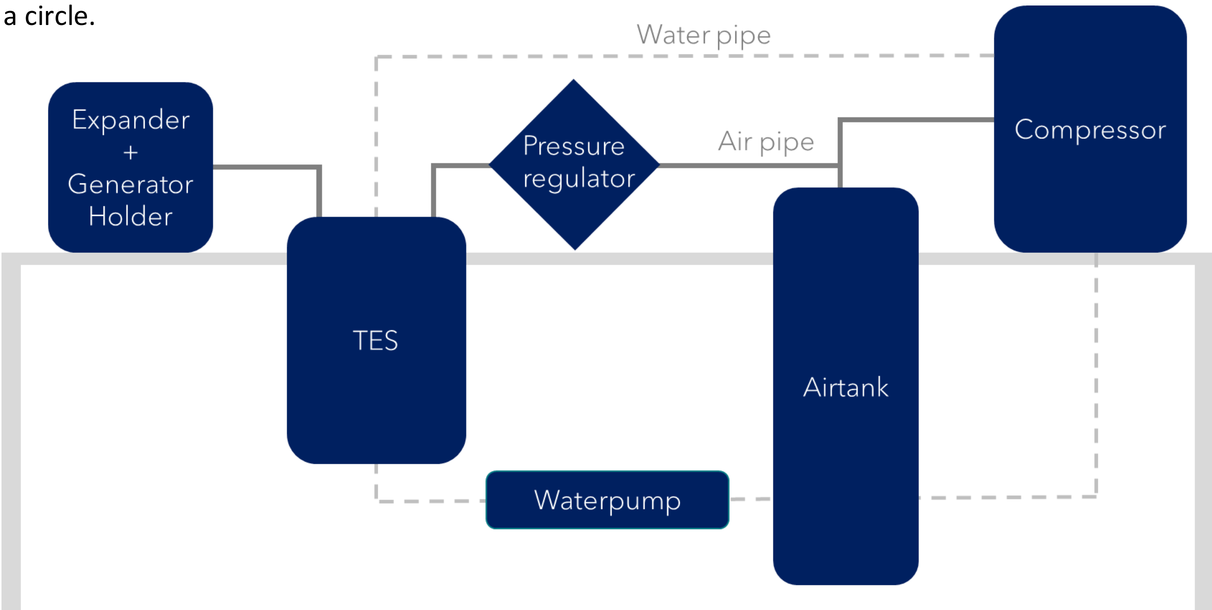

Figure 16 Front view lay-out old Demo

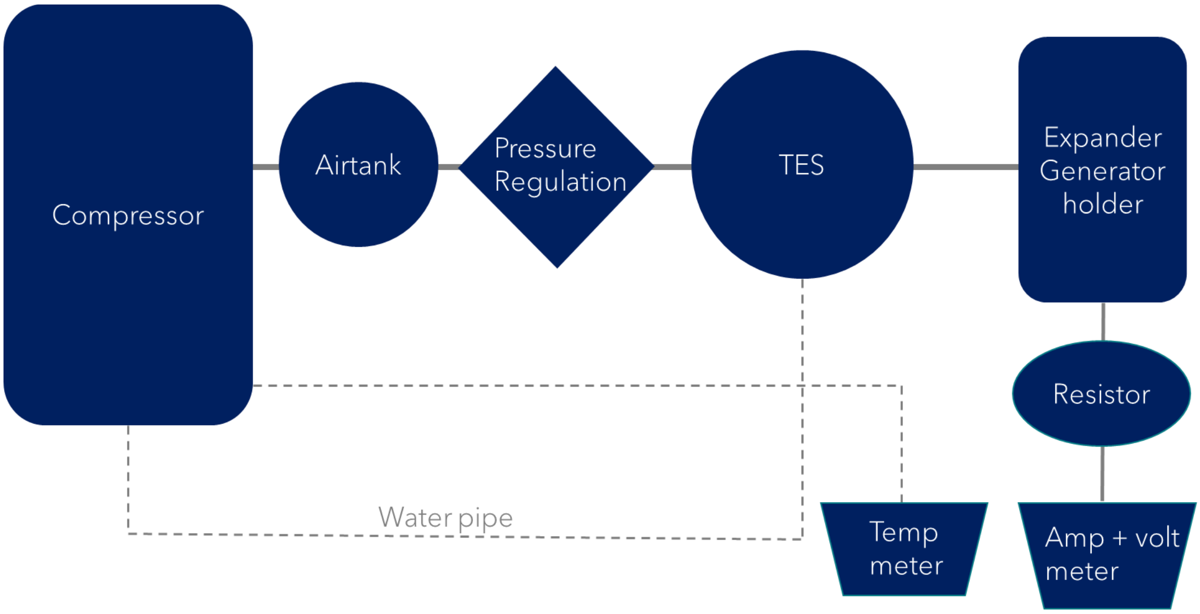

Figure 17 Top view lay-out old demo

6.2 Pipe system

The pipe system was constructed above the table as can be seen in figure 15. Due to the weight of the pipes, the lay-out choice was inefficient and caused bended pipes. Furthermore, the pipe system was constructed with ample parts including couplings which caused diverse leakages. For instance: there was a hefty leak between the CAT and the compressor. Besides, the valves could not hold the amount of pressure.

6.3 Corrosion

6.3.1 Corrosion TES

The outer layer of the copper pipes of the TES underwent a chemical reaction, a thin layer of corrosion formed: tarnish. Tarnish is caused by oxidation, but it is not the same as rust. Metals that contain iron are prone to rust, their oxidation process leads to a degradation of the metal surface.[11]

Contrary to rust, the compounds caused by copper oxidation do not degrade the metal. The tarnish limits itself to only the surface of the metal and prevents the metal underneath from further oxidation. The formation of this protective outer layer on the pipes is a result of the chemical process passivation. In conclusion the rough-looking surface of the copper pipes are solely unpleasant to the eye. No action will be taken to clean the copper as the tarnish serves a protective role to the copper.

[11] (Deziel, C. 2020)

6.3.2 Corrosion pipes

With previous setup of the demo, a determination had been made that a lot of rust in the steel pipes was located. This was caused by a long standstill time in combination with the water that was present in the pipes.

6.4 TES

Settled minerals on the surface

In a first visual inspection of the TES - designed by a previous team, settled minerals from water were seen on the surface of the copper pipes. The settled minerals caused the copper pipes to have a whitish layer on them. This does not degenerate the copper pipes in any way.

Dent in the copper pipe

Upon closer scrutiny, the team found a dent in the heat exchanger. This would be dangerous in the future as the dent would disturb the airflow, while also modifying the mechanical properties of the material. The demo is operating at a high pressure, a disruption of the airflow should therefore be avoided at all costs. Thus the TES and its dent had to be assessed and possibly rebuild before running the demo.

This dent was a decisive turning point. Initially, rebuilding a TES was not included in the scope of delivery. But after the discovery of the dent it became one of the main focal points for this team. The preliminary time schedule and planning had to be revised.

Figure 18 Surface of TES

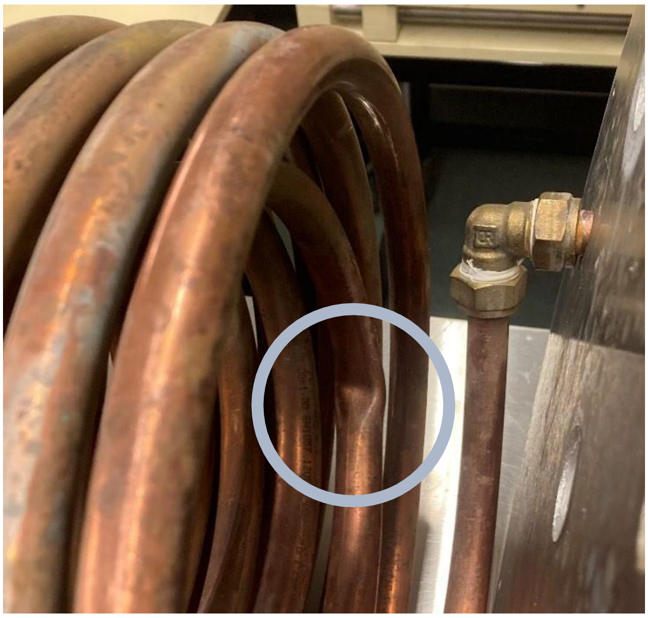

Figure 19 Dent in TES

Low efficiency

The heat exchanger is a key part of the system because it determines the amount of energy that can be transferred between the air and the water, or in other words: the energy that will be recovered by the cycle. [12] The TES defines the efficiency of the system, so any improvement on its low efficiency, could substantially increment the performance of the process.

The heat flow exchanged (Q) depends directly on the surface area of the exchanger (A) and the thickness of the pipes used (s). Other parameters involved (heat transfer coefficient and thermal conductivity) depend on the air, the water and the material used so they cannot be changed. The objective of the team is to increase this heat flow as much as possible by modifying the dimensions of the heat exchanger.

$$QQ = U * A * \Delta T \tag{2}$$

$$U = \frac{1}{\frac{1}{h_c} + \frac{s}{k} + \frac{1}{h_{ff}}} \tag{3}$$

With:
Q = heat flow exchanged
U = Thermal transmittance
A = surface area exchanger
S = thickness of pipes
h = heat transfer
k = thermal conductivity

Different inner pipe diameter

The copper pipes of the original TES had a different diameter than the rest of the pipes in the demo. The inner diameter of the copper pipes was 13mm whilst the diameter of the pipes in the rest of the air cycle was 6mm. Pressure loss in the heat exchanger depends on the cross section of the pipes, different pipe diameters could result in unexpected compressions or expansions. This could endanger the system and surrounding people, while also modifying the desired working conditions for the process.

Casing of TES

The EPS-team of 2019 built a casing for the TES out of aluminum with a thickness of 2,5 mm. This team drilled two holes in the bottom of the casing. A draining valve serving as an outlet for the water in the TES-casing, and a hole to connect the water pump to the TES.

However there were some faults in the way the casing was constructed. After the cycle still water stays present at the bottom of the tank. Despite the release valve, it is not possible to evacuate all the water.

[12] (Lumencandela)

The inlet of the valve is higher than the bottom of the tank, so some water will accumulate. This still water causes the copper pipes of the TES to oxidate and to deteriorate in quality.

Figure 20 Still water in casing of TES

6.5 Turbine and gears

To increase the structural integrity, the turbine rotor was printed - by a previous EPS team, with the Markforge MarkTwo 3D printer that uses EXOO ONX as base material with Carbon. Fiber CF-BA 50 inlays are used for increasing the tear strength of the material. [13] A disadvantage is the roughness of the materials. The jaggy surfaces of the blades disturb the air flow. As a result, the propeller does not work effectively and causes a lower efficiency rate. On the other hand, the rough gears have a shorter lifespan and less transmission of power due to vibration and not gearing correctly and smoothly.

Lastly, while using a turbine, the air must be dry. The turbine could be damaged as a consequence to water exposure.

6.6 Safety

Work on the demo is not only about the operational part but also about its potential impact on the surroundings.

The air pipes operate under extremely high pressure which creates an dangerous area. The risk for an explosion is more realistic, besides that, the high pressure also creates very high temperatures which can cause burning wounds.

Another potential safety issue is the noise the compressor can generate. The compressor generates sound of 78 dB, which can be annoying and damage the hearing after 2+ hours of functionating.

[13] (Verberne, L. Pogats, F. Looijen, R. De Jong, E. Perez, C. 2019, p.49)

6.7 Heat loss

To increase the efficiency rate, one of the main problems must first be addressed: heat loss. Heat loss is a consequence of the high pressure created by the compressor. This is the greatest efficiency loss when it comes to the productivity of the working process.

The quantity of the heat loss depends on the conductivity of the material. In the previous setup this material was stainless steel. The thermal conductivity of steel is 17 W/mK, this is considered as a high value when it comes to temperatures approximately up to 100°C.

7 Thermodynamical basis

To get a better understanding of the state of the project, the reports of the past years had to be reviewed and analyzed. In this process, the team found some assumptions that did not match the reality of the system nor the results obtained.

The most important correction was about the expansion from 100 to 6 bar after the CAT. It was assumed that it was isentropic, but this would be the case if this expansion was performed in a turbine. In this situation the difference of specific enthalpy between the inlet (h_{ii}) and the outlet (h_o) would be the work generated (WW), as shown in equation 4.

$$h_{ii} = WW + h_o \qquad (4)$$

where $h_o < h_{ii}$. This illustrates the fact that after one of these expansions the fluid will have a low temperature, because of the exchange of energy with the turbine that generates work.

In the A-CAES demo, this expansion is performed in a valve. This means that there will be no energy exchange with other components and no work will be generated. Following equation (0), now an isenthalpic expansion will take place, where $h_{ii} = h_0$. This has important consequences because in this case the temperature after the expansion will be much higher than in an isentropic process. Now the drop in the temperature will only occur because the pressure difference, and not because the exchange of energy with the turbine.

Another important aspect that was not taken into consideration by other teams, is the condensation of water in the air cycle. Ambient air is mainly composed by nytrogen (78%) and oxygen (21%), but also contains a variable amount of water vapor. This depends on the conditions of the air and the location, and it can emerge as a problem in thermodynamic systems.

This is the case when working with compressed air, when condensation of this water vapor can happen. In air systems, liquid water can endanger different components like turbines or motors, in addition to partially obstructing the correct air flow through the pipes and to lowering the average lifespan of the system.

To verify if this situation could happen, the team proceeded to calculate how much water vapor was in the air and if it would condensate at any stage of the process. To do that, several properties of the air had to be analyzed.

Vapor pressure

It is the pressure of a vapor in equilibrium with its non-vapor phases. It describes the tendency of a liquid to evaporate or, in this case of study, its tendency to condensate. The bordeline case is represented by the vapor pressure of saturation, which is the maximum partial pressure that the water vapor can have in the mixture before the water starts condensating. This pressure solely depends on the temperature, and can be obtained by the Antoine equation:

$$\log_{10} p_v^{sat} = A - \frac{B}{C + T} \qquad (5)$$

where p_v^{sat} is the vapor pressure, T is the temperature and A, B and C are component specific constants. For water between 1 and 100 ºC, they have the following values: A=8.07131, B=1730.63, C=233.426.

In this formula T and p_v^{sat} are directly proportional, so the warmer the air is, the more water it will be able to hold.

Relative humidity

Is the ratio of the amount of water vapor in the air to the maximum amount of water which the air can hold at a given temperature, expressed as a percentage. In general, RH is defined as the ratio of the actual water vapor pressure to the saturation vapor pressure.

$$RH = \frac{p_v}{p_v^{sat}} * 100 \qquad (6)$$

When RH =100%, the air is saturated with water vapor and it is at its dew point. However, this is not a representative property of the amount of water vapor in the air, since the maximum amount of water, represented by p_v^{sat}, heavily varies with the temperature.

To measure the actual quantity of water in the air, there are other properties that can be used: absolut and specific humidity.

Absolut humidity

It is the weight of water vapor in a given volume of air, expressed in grams per cubic meter (g/m^3). However, the measurement of AH by itself is not useful to determine how close the air is to saturation.

Specific humidity

It is the weight of water vapor per kilogram of dry air (g/kg). Assuming the air behaves as an ideal gas, it is related to the vapor pressure by the following formula:

$$XX = 0{,}622 * \frac{p_v}{p_T - p_v} \qquad (7)$$

where p_T is the total pressure of the air at a certain stage. When p_v is substituted by the vapor pressure at saturation p_v^{sat}, the result is the maximum humidity that air at a certain pressure can have, measured in g/kg. This is now an appropriate way of quantifying the amount of water vapor in the air.

After this analysis, the properties of the air through the cycle had to be determined to design the demo correctly and to determine how much water would condesate.

To start, some initial assumptions had to be made. The team did this with the help of some preliminary tests, and always knowing the desired pressure at every stage of the process.

Moreover, an isentropic expansion from 6 bar to ambient pressure is also assumed. The real value of the temperature at the outlet of the expander will be much higher than the one calculated, but there is no other way to aproximate the result. The greater the gap between the real value and the one calculated, the less efficient the process in the expander is.

Furthermore, an initial relative humidity of the air is also assumed to be 40%, which is an average value for a closed room. This will be need to estimate the initial amount of water in the air, before the compression process starts.

Every value for the temperature and pressure of the air are represented on table 1, where the stages can be summarized as follows:

- 1-2' → Compression from 1 to 100 bar and cooling in the compressor
- 2'-2 → Cooling of the air in the TES
- 2-3 → Isenthalpic expansion from 100 to 6 bar
- 3-4 → Heating up the air in the TES
- 4-5 → Isentropic expansion from 6 to 1 bar in the turbine

In the compression process, there are two different processes happening simultaneously: the air is getting compressed and cooled at the same time. This complicates all the estimations, since the process will not approach any ideal evolution, such as isentropic or isenthalpic. However, a difference between the cooling happening in the compressor and in the TES can and should be made. The properties before the TES (2') are needed to evaluate the efficiency of the heat exchanger.

Stages of the air	Pressure (bar)	Temperature (ºC)
1	1	20
2'	100	100
2	100	50
3	6	35
4	6	45
5	1	-82

Table 6 Initial estimations of air properties

To start with, the vapor pressure of saturation of every point can be calculated, since it only depends on the temperature and can be obtained equation 1 or using the database CoolProp in Microsoft Excel. The team decided to use the second one because of its versatility. The results are shown in table 2.

Stages	1	2'	2	3	4
$p_v^{sat}\ (bar)$	0,02339	1,014	0,1235	0,0548	0,0956

Table 7 Vapor pressure of saturation

Then, knowing that $HR_1 = 40$ and with equation 2, the vapor pressure for the ambient air can be calculated, obtaining a value of $p_{v1} = 0{,}009356\ bar$. Using this value in equation 3, a specific humidity before the compressor of 5,874 g/kg is obtained. This is the amount of water in the air before any compression, so it will be the maximum quantity of water that could condensate.

Next, with the values in tables 6 and 7 and using equation 7, the specific humidity at saturation for every stage can be determined.

Stages	1	2'	2	3	4
$\omega_{sat}\ (g/kg)$	14,897	6,372	0,769	5,574	10,112

Table 8 Specific humidity at saturation

The values in table 6 represent the maximum amount of water the air can have at each stage. By noticing the difference with the initial value of $\omega_1 = 5{,}874$ g/kg, stage 3 is identified as the critical point, where up to $5{,}105$ g/kg would condensate.

After this, the relative humidity can also be calculated. With all this properties the specific enthalpy is also determined, and all this results are shown in table 8. This numbers are approximations, but they are useful to understand the critical points in the system. The real values could vary because the initial assumptions of temperatures and pressures determine the rest of the results.

Furthermore, the implementation of a component to remove the water from the air will be assumed, because this is necessary for a correct functioning of the process. Consequently, the specific humidity will stay constant after stage 3.

The humidity has a very slight effect in the enthalpy, following equation:

$$h = c_{p_{da}} * T + (c_{p_v} * T + L_{ff})\omega \qquad (8)$$

where $c_{p_{da}}$ and c_{p_v} are the specific heat capacities of dry air and vapor, respectively, and L_{ff} is the latent heat of water. These properties slighly vary depending on temperature and pressure. The different values are shown in table 9:

Stages of air	$c_{p_{da}}\ (KJ/(kg * K)$	$c_{p_v}\ (KJ(kg * K)$	$L_f\ (KJ/kg)$
1	1,017	1,864	2453,5
2'	1,103	1,89	2256,4
2	1,130	1,871	2381,9
3	1,018	1,866	2420,3
4	1,022	1,869	2396,4
5	1,007	1,851	-

Table 9 Heat properties of air at different temperatures and pressures

Substituting these values in equation 8, the values for the specific enthalpy are obtained.

Stages of the air	Pressure (bar)	Temperature (ºC)	Relative humidity	Specific humidity (g/kg)	Maximum specific humidity	Specific enthalpy (KJ/kg)
1	1	20	40	5,874	14,897	315,86
2'	100	100	92	5,874	6,372	428,91
2	100	50	100	0,769	0,769	382,83
3	6	35	14	0,769	5,574	330,52
4	6	45	8	0,769	10,112	342,75
5	1	-82	-	-	-	194,05

Table 10 Thermodynamical properties of the air

After this, a first diagram can be made to help understand the air cycle figure 21. It is a PH diagram, so the enthalpy difference between two consecutive stage is visually represented in the x-axis. These differences ultimately represent the various energy flows energy flows throughout the cycle, needed

to analyze the efficiency of the cycle. This analysis will be done with experimental data extracted from sensors in chapter 9.3.

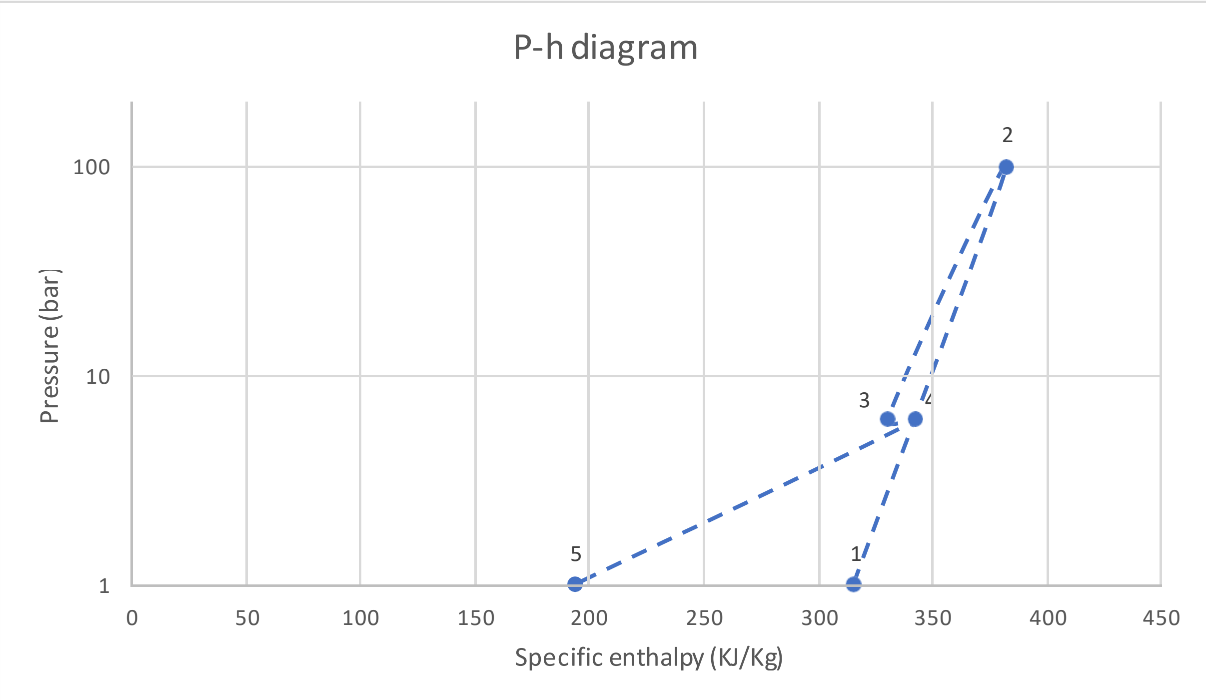

Figure 21 P-h diagram for the A-CAES cycle

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8 Solutions (general)

Via troubleshooting the team came up with several solutions to improve the efficiency of the demo and to reduce problems. All these ideas are bundled together in this chapter. In a next phase the final and desired solution will be determined and applied on the demo.

8.1 Lay out cycle

The process involves two cycles, one for water and one for air.

The first cannot be drastically changed from the original one, because the water pump must be under the table to direct the water upwards from the TES to the compressor.

The main idea to improve the layout of the system was to fix the pipes of the air system to the table in an efficient and organized way. This would mean that the pipes would not be subjected to extra stress due to gravity and other forces related to the air and water flow. The course of action would act as a prophylactic measure, assuring a long lifespan of the system. Another effect of this change is the general simplification of the layout, making it more intuitive for the students.

On a first approach, the team redesign the original cycle with the same stages but rearranging the distribution of the pipes. The result can be seen in figure 15, where the main challenges for the team were the following:

Bypass for TES

It is needed to check the difference in efficiency between having a heat exchanger to recover energy and not having it. This entails the use of more valves in the system which can produce small pressure losses, so its distribution must be optimized.

Efficient sensor layout

The aim of the team was to obtain as much data as possible with few sensors. This data is needed to monitor the process, and to later analyze its efficiency. In the following diagrams the pressure and the temperature sensors will be represented with a letter P and a letter T, respectively.

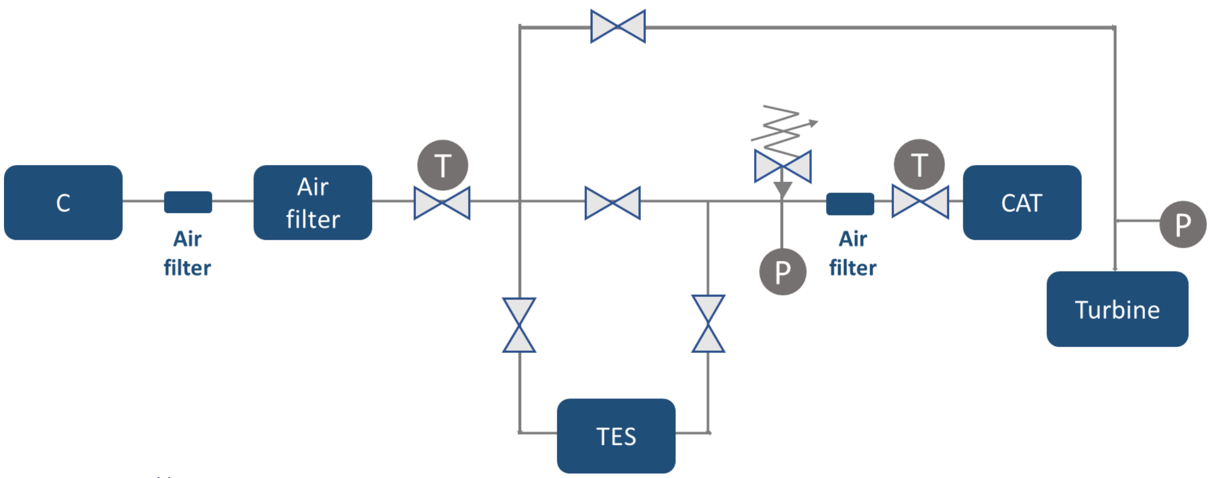

Figure 22 Initial layout

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However, in order to further improve the efficiency, the team decided to redesign the process and the layout. This would allow the air to go through the TES twice, one at high pressure (100 bar) first and then at low pressure (6 bar). The extra step at high pressure would help the air to cool down more after the compression. This also had an impact on the design of the TES, as will be explained in chapter 9.2.

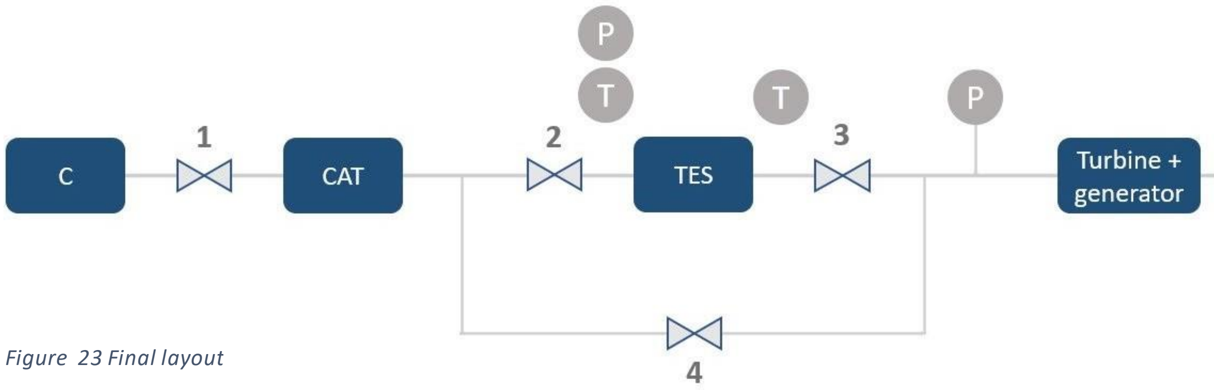

Figure 23 Final layout

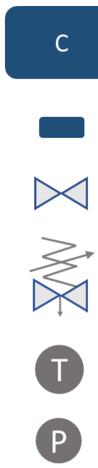

Figure 24 Legend demo lay-out

Lastly, to improve the safety of the system, the team also included an extra release valve. With this and the security valves in the compressor there would always be a possibility of releasing the pressurized air at any stage of the process safely.

8.2 TES

8.2.1 Casing of TES

In order to achieve a proper water outlet for the TES, the TES casing had to be revised. The most efficient way to ensure all water will flood out is to make the flat surface of the bottom conic.

However, the bottom of the casing is not perfectly circular: from one point the diameter is 29mm and from another its 30mm. In addition, the team of 2019 welded the separate parts of the casing together which caused the connection of the cloak of the circle and the bottom plate to be bumpy and uneven. These circumstances made building a conic shape more challenging, as 3D printing a new shape was written of due to the casings unsure form. Therefore different solutions were proposed.

Clay

One way to create a conic shape would be to model clay around the bottom. Any sort of self-hardening clay won't resist the water and the heat that will be generated in the TES tank. The clay would start to crumble or even soften.

Fire clay would need to be baked in an oven at approximately 1200C-1300C. These ovens are not only difficult to find, the aluminum casing would not hold the heat.

Fimo-clay could be an option: the clay needs to be baked for 30 minutes in an oven for 110C. However the entire TES and the clay would need to fit in an oven. The dimension of the TES might not fit in any available oven.

Negative mold

<u>Silicone</u>

Another solution to build a conic shape would be to make a solid funnel in Solidworks that would be 2,5cm's high with a diameter of 29cm as biggest circle. This funnel would be 3D printed. Then the smaller part of the funnel could be placed in the center hole on the bottom of the TES. With the funnel in its place, a self-hardening mixture could be poured from the space between the outer diameter and the TES casing. The could be a silicone mixture: it is heat and water-resistant but would need to be ordered and unforeseen delayed delivery times could occur.

<u>Polyurethane resin</u>

Another alternative for a pouring liquid could be polyurethane resin. Polyurethane resin is heat and water resistant. However in order to loosen the mold out of the hardened polyurethane, a release agent would need to be used. In addition, polyurethane is a highly toxic product that would require extra safety measurements to pour.

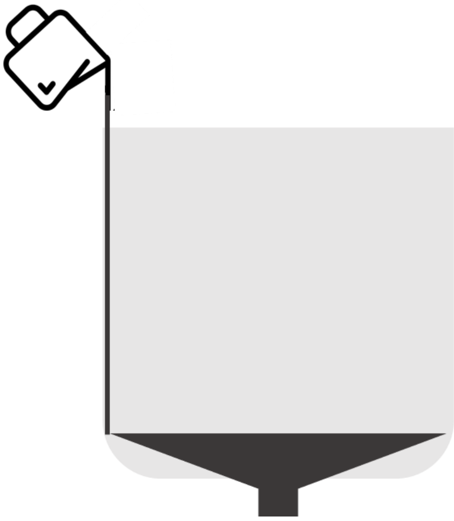

Figure 25 Own illustration of mold

Water pump

The last solution could be to order a manual hydro pump to get the water out of the TES tank. This wouldn't improve the design of the TES casing, but would solve the problem of having water resting on the bottom.

8.3 Pipe system

Firstly, to ensure that the demo meets the safety requirements, the maximum work conditions must be determined. As seen in table 10, the maximum pressure and temperature would be 100 bar and 100 ºC, respectively. Even though some parts of the system will work at less demanding conditions, they will also be designed to resist high pressures and temperatures.

The team had two options to construct the water and air cycles:

- Metal pipes. These were used by the other groups. By using normal steel pipes, oxidation problems could appear. This could be solved by using stainless steel. Other interesting properties of metal pipes are their rigidity, that could be beneficial or detrimental, depending on the design; and their thermal conductivity, which in this case is a disadvantage since it means higher heat losses.
- Plastic pipes. There is a wide variety of plastic materials available, so this allows a more adaptable design. In this case, the material would be more flexible than steel, so this would also condition the layout. Lastly, plastic is a better insulator than steel.

The next big objective of the team was to avoid leaks in the air cycle. Due to high pressure, the air will tend to escape from the cycle, and this was a problem for past teams working in the demo.

To fix together the different pipes and components of the system, the couplings used are determinant to ensure that there are no leaks.

Therefore, standard threaded joints with thread seal tape should not be used. This is the general solution for plumbing and water systems, but it will not work with pressurized air. Special hydraulic or pneumatic couplings are needed, along with O-rings or toric joints to seal the connection between two parts when necessary.

Figure 26 Rubber seal

For the valves, there are two main options: flow control valves, that allow to regulate the air flow in in accurate way; and ball valves, that always should be fully open or closed to not damage the mechanism.

[14]

Figure 27 Flow control and ball valves

8.4 Corrosion

Every steel pipe has been replaced by rubber hydraulic pipes. These are resistant against high pressure and can withstand a relatively long standstill time.

For short term corrosion, vinegar could be added to the surface. The chemical reaction between vinegar and the metal will cause dissolution between the layer of corrosion and the metal layer.

[14] (Flomatics. 2021)

When the layers are separated from each other, the part where the corrosion took place should be painted to protect and prevent it from this event.

Corrosion on long term is more complicated to erase from that same layer. The cohesion in between molecules is much stronger then corrosion on short term. When this event appears, the part with corrosion must be replaced into a new part.

8.5 Air filter

As stated before, five grams of water condensates per kilogram of dry air that is compressed. To solve this, the team evaluated every option to eliminate the water from the air cycle. Several factors affected this decision:

- Location. The water would mainly damage the expander in the system, but could also cause other problems such as oxidation in the CAT or obstructing the airflow. Therefore the objective was to remove the water from the air as soon as possible, so every component of the air cycle is water-free.
- Price. The team had a limited budget that should not be surpassed.
- Size. Due to the limited dimensions of the demo, the team had to find a solution that would fit in the space available.
- Working conditions. Depending on the location, the condition of the air could heavily vary in temperature (from 20 to 100ºC) and in pressure (from 1 to 100 bar).
- Efficiency. The water should be removed as efficiently as possible, ensuring a flow of dry air and using as little energy as possible, while also minimizing pressure losses.
- Availability. Because of the previously mentioned factors of the demo, this problem had very specific conditions that had to be met. The goal of the team was to find a solution in the market that could be delivered on time.

Next, the different options evaluated by the team are listed, with an explanation on why they were dismissed.

1. Dehumidifying the air before it was compressed. This would eliminate the water as soon as possible, as desired. However, to do that an industrial dryer would be needed. These machines are large and expensive, so it is not a feasible solution for the demo. Furthermore it would consume electrical energy, which would decrease the total efficiency of the demo. Lastly, the charging time for the demo would increase due to a lower starting pressure.
2. Filtering the air after the compressor. In this case, the challenging conditions of the air (100ºC, 100 bar) made it impossible to find a suitable commercial filter. It should be able to absorb not only liquid water but also water vapor, because due to the high temperature of the air, most of the water has not condensated yet. Despite this being an efficient solution and having a viable size, a standard high pressure filter for moisture can work at 16 bar, which is too low for the demo at that stage.

An alternative would be to build and air vessel resistant to high pressure and fill it with desiccant material that can work at high temperatures.

3. Filtering the air before the expander. Now the working pressure would be 6 bar, so one of the commercial filters mentioned above could be used. Even though this would protect the expander, water would still be found in the pipes and in the CAT, so the problem would only be partially solved.

	Solution 1	Solution 2	Solution 3
Location	Before compressor	After compressor	Before turbine
Drying equipment	Air dryer	Absorption filter	Absorption filter
Price	2500 €	300 €	1500 €
Availability	Available	Not available	Available
Size	Large	Small	Medium
Working conditions	1 bar 20ºC	100 bar 100ºC	6 bar 50ºC
Cycle efficiency losses	High impact	Low impact	Low impact
Water removal effectiveness	High	Medium	Medium

Table 11 Comparison of solutions

As a final observation, other alternatives would arise if the expansion from 100 to 6 bar would happen in a turbine. Ideally, this would be an isentropic expansion, and not an isenthalpic one. In the first case, the temperature would drop drastically, to below 0 ºC. Consequently, the vapor pressure of saturation would also decrease and most of the water vapor in the air would condensate. As a result, a mechanical filter for the liquid water could be used after that expansion.

8.6 Turbine and gears

The turbine and the gear are the ultimate elements that transmit the power that will produce electrical energy in the system. Therefore, it is important to also optimize these components, where the main problem is the energy loss due to friction.

For the turbine, the only possible improvement would be to print again the blades to achieve a better air flow. A complete redesign of the turbine was discarded because it would deviate the team from the main objectives of the project.

However, there were numerous possibilities to change de design of the gear system.

Firstly, the target of the team was to increase the velocity of the generator up to 3000 rpm, knowing that the air motor generates up to 300 rpm. This was discussed in the EPS report from 2020, when two options were given: to only use two gears to transmit the power or to build a gear train composed by four gears and one shaft.

Two gear system

In this case, the necessary gear ratio "i" between the two gears can be calculated, as the two velocities are known:

$$i = \frac{\omega_1}{\omega_2} = \frac{300\,rpm}{3000\,rpm} = 0{,}1 \qquad (9)$$

Now, equation 10 dictates the number of teeth required in the system, and equation 11 the relative size between those gears:

$$i = \frac{Z_2}{Z_1} = \frac{r_2}{r_1} = 0{,}1 \rightarrow Z_1 = 10 Z_2 \qquad (10)$$

$$r_1 = 10 r_2 \qquad (11)$$

Therefore, the gear fixed to the expanders shaft must have ten times more teeth than the one in the generator's shaft, and it also must be ten times bigger. This is the most limiting factor, and the final relation needed between number of teeth and size is the module m (12). They must have the same module for them to gear correctly.

$$m = \frac{2r}{Z} \qquad (12)$$

Gear train (a shaft and four gears)

This system is not as restricted as the previous one because many different combinations of four gears can transmit the power from 300 to 3000 rpm. However, more gears will also mean more friction and more probability of failure due to more components involved in the transmission. For the same reason, it is much harder to build a system like this than one with just two gears, because more elements to hold the shaft and gears in place are needed.

In table 12, a comparison between these two options is established.

	Two gears	Gear train
Assembly	Easy	Hard
Efficiency	Minimum friction	More friction
Restraints	Size and teeth ratio are determined	Flexibility to choose between different sizes
Gear ratio	Big difference between the two gears	More equally distributed power transmission

Table 12 Comparison between gear systems

Secondly, the friction and therefore the efficiency of the power transmission highly depend on the material of the gears. It will also affect the resistance and the durability, and thus the lifespan of the system. There are two basic possibilities: metal or plastic.

Plastic

The easiest solution would be to 3D print in plastic the gears needed. This would be fast and cheap but has several disadvantages.

Firstly, the resistance of 3D printed plastic is not proven for high-speed systems, nor for long processes. Considering that one gear would spin at 3000 rpm for about 20 minutes in a single discharge process, this would mean that it would complete up to 180000 revolutions in three complete cycles of the system. Even though the forces transmitted are relatively low, this high number of revolutions in a short period of time could easily initiate diverse fatigue failure mechanisms, such as propagation of micro cracks and thermal fatigue. These phenomena could provoke the complete failure of the system, and due to the highly variable properties of 3D-printed plastic it is complicated to perform a theoretical resistance analysis.

Secondly, due to the rough finish of 3D printed gears, the friction would cause more energy losses. This has no easy solution other than reprint the gears with different parameters or materials, but the result will always be worse than a manufactured gear.

Lastly, the design of the shaft must be taken into consideration in the solution with four gears. As explained before, there is a high uncertainty regarding the resistant properties of 3D printed plastic. This could be solved using other manufacturing processes such as industrial molding, but this is not available for the team.

Metal

Mainly steel and cast iron are used in the construction of gears and shafts, with different surface treatments depending on the resistance requirements. In this project, the maximum power that can be transmitted to the generator is 60 W, which is a low power output that any metal gear can withstand. Furthermore, metal gears provide high durability and low friction.

To obtain metal gears, the only possibilities for the team were to mill them in the university's metal workshop or to order them from an external source. The metal 3D printer was not available at the time of the project, but it would have been an easy and fast solution, despite it also being expensive.

	Plastic	Metal
Time	1-2 days	One week
Friction (energy losses)	High	Low
Mechanical properties	Poor-medium (High uncertainty)	Very good

Table 13 Comparison of materials

8.7 Insulation

When running the compressor in several test rounds until 110 bars, the surrounding pipes heated up to a point they became dangerously warm to touch with bare hands. This occurrence proves that not all the heat of the compressor is captured and stored in the TES. Therefore, insulation needs to be applied to the pipes to reduce heat loss and also to protect the users of the A-CAES demo. For further testing and minimization of heat losses, the aluminum TES tank will need to be insulated as well.

Calculations on the TES tank

The objective is to calculate how much energy can be saved insulating the TES tank, by comparing the heat losses with and without the insulation. As shown in equation 13, these values depend on the surface area of the aluminum tank, on the difference of temperatures between the inner (water) and the outer (air) substances and on the thermal transmittance of the tank. This last term is the one that will be affected by the application of insulation, so it will have to be calculated twice.

Calculating heat losses TES

$$P = U * A * \Delta T \qquad (13)$$

with:
P = total heat loss
U = Thermal transmittance
A = surface in total
ΔT = $T1 - T2 =$ difference between temperature
$T1$ $= 50ºC$ = temperature of water inside the TES
$T2$ $= 20ºC$ = temperature of ambient air
$T1$ is assumed to be 5 0ºC since it is the expected temperature of the water after one charging cycle.

Calculate 'U' without insulation

$$U = \frac{1}{R} => R = \frac{d}{\lambda} + R_{ii} + R_e \qquad (14)$$

With:
U = Thermal transmittance
R = Thermal resistance
d = Thickness material
λ = Thermal conductivity (aluminum)
R_{ii} = Thermal resistance (water)
R_e = Thermal resistance (air)
dPE = Thickness isolation
λPE = Thickness isolation

$$R = \frac{0{,}0025\,m}{160\frac{WW}{mK}} + 0{,}13\,\frac{m^2K}{W} + 0{,}0008\,\frac{m^2K}{W} = 0{,}130815625\,\frac{m^2K}{W} \qquad (15)$$

$$U = \frac{1}{0{,}130815625\,\frac{m^2K}{WW}} = 7{,}644346767\frac{WW}{m^2K} \quad (16)$$

Calculate 'U' with insulation

The only difference from the previous calculation is the addition of another term, representing the insulation

dPE = Thickness mineral wool
λPE = thermal conductivity (mineral wool)

$$U = \frac{1}{R} => R = \frac{d}{\lambda} + \frac{dPE}{\lambda \mathrm{PE}} + R_{ii} + R_e \quad (17)$$

$$R = \frac{0{,}0025\,m}{160\,\frac{WW}{mK}} + \frac{0{,}020\,m}{0{,}039\,\frac{WW}{mK}} + 0{,}13\frac{m^2K}{WW} + 0{,}0008\frac{m^2K}{WW} = 0{,}6436361378\frac{m^2K}{\mathrm{W}} \quad (18)$$

$$U_{iins} = \frac{1}{0{,}6436361378\,\frac{m^2K}{WW}} = 1{,}553672861\frac{WW}{m^2K} \quad (19)$$

Calculating surface of the tank

$$\mathrm{A} = 2 * \pi * r^2 + 2 * \pi * \mathrm{r} * \mathrm{h} \ (20)$$

$$\mathrm{A} = 2 * 3{,}1415 * 0{,}15^2\mathrm{m} + 2 * 3{,}1415 * 0{,}15\mathrm{m} * 0{,}34\mathrm{m} = 0{,}4618005\,m^2 \ (21)$$

with:
r = radius of tank
h = height of tank
Now, with the values of U and U_{iins} the heat loss can be calculated in both cases with equation (13):

without insulation

$$P = U * A * \Delta T = 7{,}644346767\,\frac{WW}{m^2K} * 0{,}4618005\,m^2 * (323{,}15\,K - 293{,}15\,K) = 105{,}905\,\mathrm{W} \quad (22)$$

With insulation

$$P = U_{iins} * A * \Delta T = 1{,}553672861\frac{WW}{m^2K} * 0{,}4618005\,m^2 * (323{,}15\,K - 293{,}15\,K) = 21{,}5246\,\mathrm{W} \quad (23)$$

As shown in the calculations above, the heat loss with insulation around the TES tank is 21,5246 W whilst without insulation it would be 105,9 W. This difference was significant to improve the efficiency of the system.

Calculations on the pipes

In this case, the pipes used are not made of stainless steel, but from composite materials.[15] The team was not able to obtain the thermal conductivity (λ) of these materials to perform similar calculations and to evaluate the heat losses.

However, since the pipes are mainly made of rubber, they have a much lower thermal conductivity than the steel. For example, the average λ of steel is 17 W/mK, while for standard rubber is 0,5 W/mK. This also decreases heat losses substantially, but insulation is still needed to maximize the efficiency and for safety reasons.

8.8 Safety

In terms of safety, a lot of precautions are required to let the demo operate at its full potential. The first problem is the high pressure which creates an dangerous area around the demo and the people who are working on it.

This can be resolved by applying a pipe system that can hold the working pressure. When the pressure is still present in the system and it needs to find a way to escape, a pressure relieve valve needs to be integrated in the working cycle of the demo. The valve will release the pressure at a certain flow until it reaches the level of the atmospheric pressure.

A second problem was the high temperatures, generated by the high pressure, the temperature will rise to a high level. This can be solved by applying isolation which prevents a person getting burning wounds caused by touching the surface.

8.9 Heat loss

A cylindrical foam is applied to the pipes to reduce heat loss to a minimum. For the tank, a layer of glass fiber insulation is used in combination with the layer of plastic, to reflect the heat rays that will penetrate the glass fiber.

The tank is the biggest area where heat loss can take place, the pipe system in general has in total the most area surface where this energy loss can appear. This will be solved by putting on isolation around the pipes and close it off very well to avoid any escape of heat flow.

In terms of safety measures, the pipes must be connected to the work table with clamping points.

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[15] (Dextraft. 2016)

9 Construction

In this chapter it is explained which specific solutions were used for solving the previously stated problems. Furthermore, the way the solution is constructed is shown.

9.1 Lay out cycle

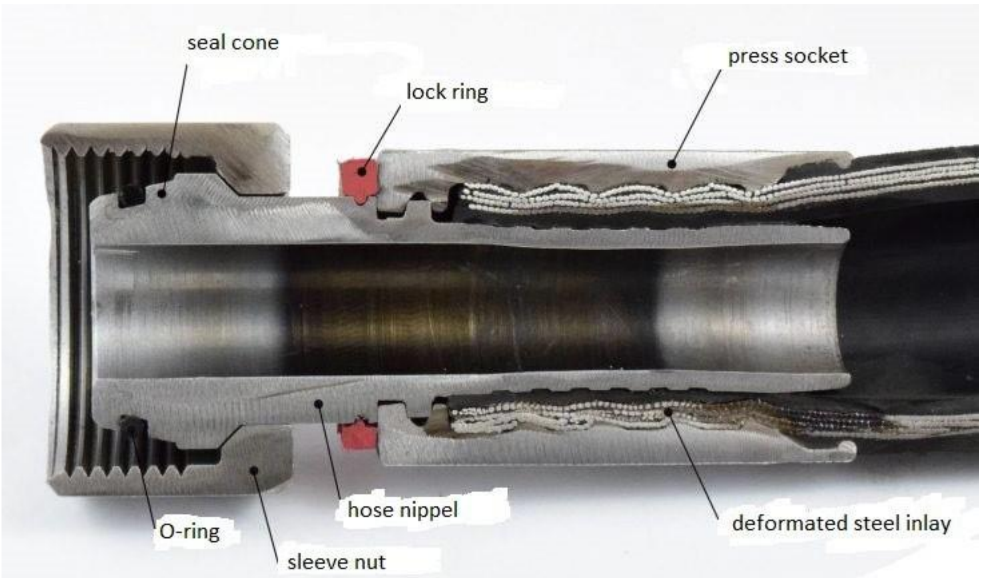
9.1.1 Air cycle

Since the previous groups had to deal with massive oxidation and leakage issues, the team changed the way of approach. Firstly, flexible hydraulic hoses were implemented. They can hold up to 450 bars, making a clean cycle lay-out possible, and also enable different coupling solutions. These couplings were selected according to SO 8434-1 / DIN 2353. The light series were chosen, since there was no need of going higher than 150 bar.

All coupling parts were bought at Hydroscand *Oy* in Vaasa as same as the hoses. The chosen size for most couplings, if possible, were quarter of an inch. This was done to unitize the air cycle.

Structure hose

The hose itself consists out of rubber with an insertion of woven stainless steel layers. The O-ring is enabling a mechanical connection to a positive part.



[16]

Figure 28 Structure hose

[16] (Hydraulikschlauch. 202)

Couplings

All parts were made of stainless steel. Two different possibilities of mechanical connections were used. One of them was sealing rings, which were mainly required for the connection between valves and positive coupling parts as shown in the figure below. They were also used for the pressure sensors.

Figure 29 Sealing rings

The other solution was form closure. Thereby the cone-shaped couplings were tightened to each other, so they could hold the pressure.

Figure 30 Form closure

This also enables preferred tightening torque for a certain turning position. Consequently additional adapters were useful for just this turning positions, which were for example required for the valves.

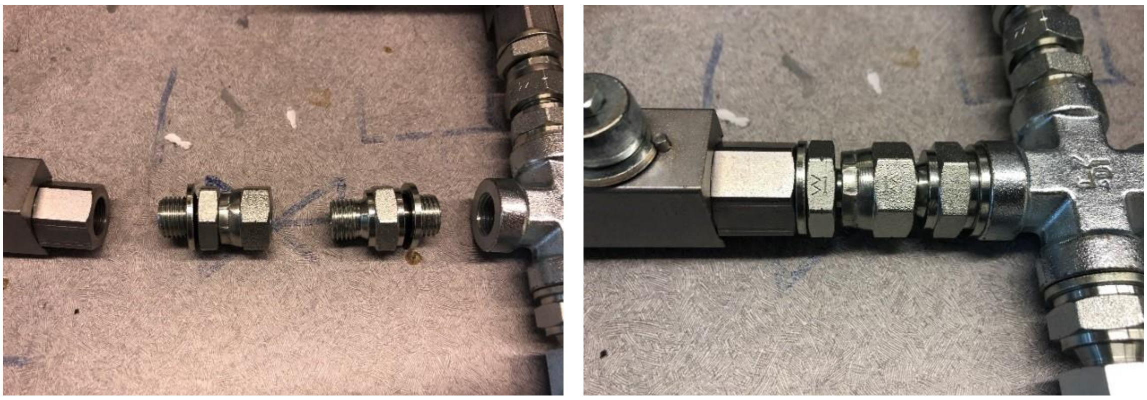


Figure 31 Example of a coupling between a four times splitter and a valve.

For comfortable usage all pipes got mounted on the table to prevent rotation while turning. That applies for the pipes too.

9.1.2 Water cycle

Due to the enormous corrosion problems with the steel pipes of the water cycle, that the first group used, the team chose to replace them with flexible rubber pipes.

The pump was replaced for the same reason.

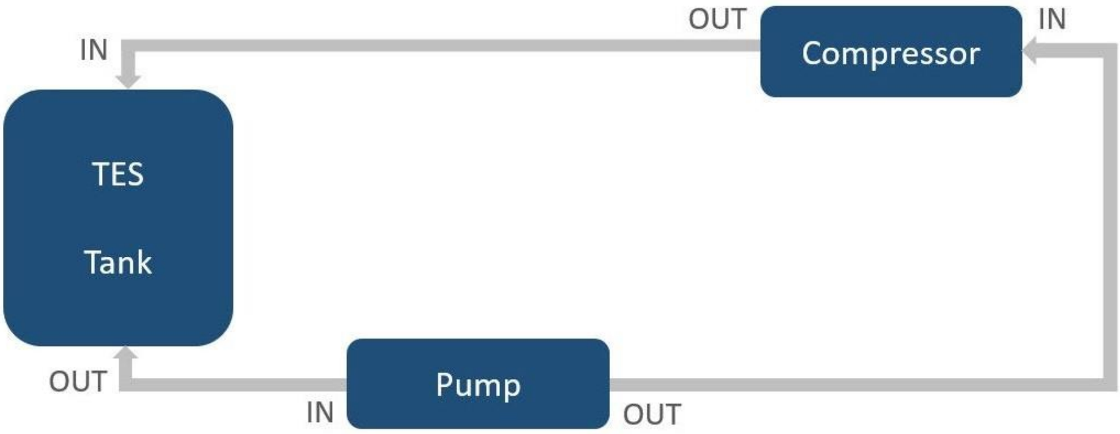


Figure 32 Own illustration water cycle

With:

D =14 (outer diameter)
d =10 (inner diameter)

This change lead to new challenges, because the pump was not mounted in any way and only held in place by the structural integration of previous pipes. Therefore this solution was no longer appropriate and it was dismissed.

Consequently, the pump needed to be installed with a bracket under the table. This bracket was already built by the metal workshop. To establish a comfortable working position the table was turned around. Firstly, the marking was done, followed by drilling four eight millimeter holes to fit M8 screws. For providing an even table the screw head was sinked five millimeter in the surface with a diameter of fourteen millimeter.

Figure 33 Reconstructing table

To lessen the vibrations caused by the pump, the pump was pinched in the bracket with layers of synthetic material in between. To assure this position, cable tie was used.

The pump itself was replaced, due to high corrosion damage too. Despite testing the new one only once, the massive oxidation reoccurred.

Figure 34 Corrosion on new pump

Assuming that these issues were caused by water, which establishes an electric contact between brass and iron that are both used for the couplings, it was necessary to replace the connection parts. The choice was made for stainless steel couplings. For additional protection, the pump was painted form the inside, with three layers of metal paint. This paint had been used for the TES-tank before.

Figure 35 Inside of pump painted

As a consequence of water, there were leaks between the hose and the positive coupling part. Therefore, clamps were added. They can be removed easily to empty the water cycle after usage and constitute therefore as the desired solution in contrast with glue, tape or cable tie.

Figure 36 Final assembly of the pump

9.2 TES

9.2.1 New TES

For building the TES the same idea was used that the previous group came up with, which is bending copper pipes in a cylindrical shape. To reach a high efficiency it is crucial to maximize the surface area that is in contact with the cooling/heating fluid. This area is the outer surface of the pipes and is calculated:

$$A = \sum_{ii=1}^{n} 2\pi \times r_{ii} \times l \qquad (24)$$

With:

r_{ii} = radius of 'i' layers
L = length of bent copper pipe

Furthermore, of major importance is the volume flow of the cold/heat, providing fluid on the outer surface. Due to the heating/cooling of the water, circulation occurs, which is caused by the temperature difference within the water.

To enhance the exchange further, the water pump of the compressors cooling system is used. The warm water flow is therefore tangentially engaged on the inner wall of the TES-tank. Running the water pump results thereby in circulation.

Bending

The bending of the copper was done around different pipe diameters, available at the university. After checking the available sizes, four different diameter layers were chosen: d_1 110 mm, d_2 160 mm, d_3 210 mm and d_4 260 mm. Initially there was not an available pipe for d_4. Therefore, an aluminum sheet that was already bend by a previous group, that should have originally become the TES-tank, was used. First the desired diameter was measured and marked. After that the metal sheet was bended further until it fitted the required regulations. To assure its position, four holes were drilled and fitted with M6 screws.

Figure 37 Result of pipe with d4

Since the copper was bend around these diameters, each layer has an actual diameter of:

D_{pipe} = +8 mm each.

Furthermore, some of the bended material untwisted, as it was still in the elastic but not yet in the plastic deformation area.

The dimensions of the tank are: a height of 340 mm with a diameter of 300 mm. Therefore the maximum diameter was chosen as 260 mm, to make the TES fit in the tank and still leave space to the outer wall for water to flush around.

The minimum diameter was set on 110 mm. A lesser diameter would cause higher stress on the deformed copper. In addition, it would not increase the total outer area considerably, since the additional diameter is marginal. For example:

$$\Delta d_1 = d_1 + d_2 + d_3 + d_4 = 0{,}11 + 0{,}16 + 0{,}21 + 0{,}26 = 0{,}74\,m \quad (25)$$

$$l_{pipe1} = \Delta d \times \pi \times a = 62{,}8\,m \quad (26)$$

$$A_1 = \pi \times D_{pipe} \times l_{pipe} = 1{,}58\,m^2 \quad (27)$$

$$\Delta d_1 = d_1 + d_2 + d_3 + d_4 = 0{,}11 + 0{,}16 + 0{,}21 + 0{,}06 = 0{,}80\,m \quad (28)$$

$$l_{pipe2} = \Delta d \times \pi \times a = 67{,}9\,m \quad (29)$$

$$A_2 = \pi \times D_{pipe} \times l_{pipe} = 1{,}71\,m^2 \quad (30)$$

With:

a = number of spirals = 27
A = surface area TES
D_{pipe} = 0,008 m

To improve the previously mentioned water circulation and mainly the heat exchange in general, there is a 5 mm gap between the copper pipes in each coil.

The bending itself was done by hand. Therefore the copper pipe and the support form got jammed in the bench vice. One person bent the copper with the 5 mm spacing around the support profile. Another person was required to turn the copper pipes, to prevent unintentional deformation. The smaller the diameter, the fastest is to turn the coil. Starting with the smallest diameter, the first coil was bent until all 27 layers were finished.

To start the second coil, it was required to thread the next support profile through the unbent end. Thereby fitting it over the already finished first coil. This leaved over some space between the coil and the support profile, which did not negatively affect the further bending.

The transition to this second layer was a critical stage in the building process. Since it was not possible to fix the beginning of the second coil properly to the support pipe without damaging it.

This could lead to inadvertent deformation and could ruin the part. Therefore, it was crucial to bend the first layers with caution.

Figure 38 Bending process TES 1

After the first layers, the bending process eased due to friction, and the coil stayed in place itself. Contrary to the first spool of copper pipe, which lasted barely for finishing the second coil with the crossing to the third.

Figure 39 Bending process TES 2

For the third coil, the process started again in the bench vice with the 210 mm support form. Likewise, the third and fourth coil were built until all 65 meters of copper pipe were done. This resulted in three spoils with flattened pipe ends, as these were used to mount in the bench vice. These flattened endings were cut off with a rasp and thereafter prepared for a coupling.

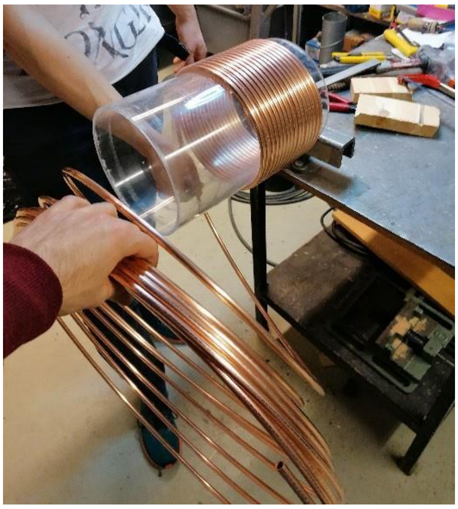


Figure 40 Bending process TES 3

Due to the lack of proper high pressure couplings for copper pipes, adaptions from steel solutions were made. The following trade-off of the different couplings was required to find the best suiting option for fitting the three TES parts together.

Coupling Solutions

The 8 millimeter copper pipe were only in a length of twenty-five meters or shorter available. Since a total of 65 meters was needed, two full and a fifteen meter coil were bought. To connect the different pieces to each other, high pressure couplings were needed.

Since copper pipes are usually not used at a pressure of 100 bar, finding couplings that can deal with these values was a challenge.

The form-closure solution was again the way of approach, which has previously been explained in the air cycle chapter. Therefore two coupling types could be used, a JIC coupling or a cutting ring fitting. Both are made for steel pipes, which can take more force.

Cutting Ring Fitting (Ermeto-Verschraubung)

According to DIN 2353, these are usually used for hydraulics. They can be distinguished in three different types. LL means very light, L is light and S stands for heavy. The light version was used, because it can hold up to 350 bars.

The cutting ring fitting consists of four parts including the pipe (4), a cap nut (2), a clamp taper socket (1) and a cutting ring ().

For assembling the coupling, the cap nut needs to be put on the pipe first, followed by the cutting ring, as shown in figure 41.

Figure 41 Cutting Ring Fitting

The connection forms when the pipe is put against the inner notch of the clamp taper socket. If the cap nut is getting tightened, it then pushes the cutting ring forward. Due to the clamp tamper sockets shape, the cutting ring is pushing in the pipes surface, which leads to a form closure.

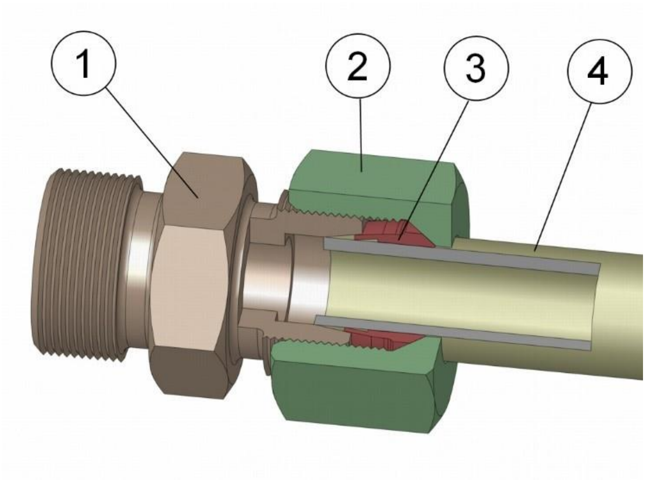


Figure 42 Cutting Ring Fitting (Ermeto-Verschraubung) [17]

To establish a proper connection, a certain amount of force is needed to cut in the pipe. As mentioned, these copper pipes are very soft compared to the steel pipes, therefore, an inappropriate force could easily lead to a critical material failure. Cutting in the pipe is a weakening procedure too. This is important to keep in mind, since the copper pipe has a working pressure of only 168 bar and it is difficult to tell how much it will actually weaken. However, there is a security value of 4 on the pipes, so the maximum pressure is 672 bar. This should allow a save use of the connection. With these insecurities, testing was a necessity.

Joint Industrial Council Fitting (JIC)

JIC fittings as well are meant for high pressure and steel pipes. They are defined by SAE J515. In addition they work similar as the cutting ring fitting, but instead of cutting in, a seat is used to verify the form closure. Both the positive and the negative seat have a 37° cone shape. Applying force on them is creating the form closure.

It consists out of four different parts including: the pipe, a fitting, a flare nut and a sleeve.

To establish a fitting, the flare nut and then the sleeve is put on the pipe. After that a 37° cone is created on the pipe as shown in the figure below.

Figure 43 Joint Industrial Council Fitting (JIC)

[17] (Schneidringverschraubung. 2021)

At last the fitting can be put on and screwed together. Creating this cone shape was a challenge, since there was no access to the required tools.

Testing Couplings

For testing the coupling, a sample was requiered. Therefore the JIC and the cutting ring fitting where created. Creating the 37° cone shape for the JIC fitting in the pipe was challenging, since the approriate tool for it was lacking.

Instead a huge nail was used, whose forefront got grinded to 37°. Putting the test pipe in the bench vice with two soft wood pieces between the brackets, for not damaging it, allowed to hammer the nail and successfully creating the cone.

The following figure shows the sample.

Figure 44 Testing couplings

The sample got screwed to the compressor on one end and on the other to a valve. To ensure a save testing, cable tie was used to mount every part, which could come lose, to a steel grid.

Figure 45 Testing couplings 2

Putting leakage spray on every connection assured recognizing potential leaks. Running the compressor to 120 bars took a few seconds, because the volume in the pipes was little. 120 bars were chosen to provide some additional safety values. It turned out that both connections could deal with the pressure.

Conclusion TES Building

The first decision was to use the JIC fitting, since it would not cut in the pipe and therefore keep the stress on the material lower. But shortly after, this idea got dismissed, because it was not possible to create the cone shape on the already bend coils.

As a result, the cutting ring fitting was chosen and successfully tested to 120 bars again.

Figure 46 End result TES

9.2.2 Casing TES

The water outlet was due to the design of the tank of the TES not draining all the water out of the tank. Many solutions were suggested (see chapter 8.2.1). the desired solution would have been to create a conic shape on the bottom of the tank. The negative mold for the shape was 3D printed as can be seen in figure 47.

However, the unforeseen availability of any releasing agents in local stores - to loosen the mold from the pouring liquid – resulted in a change of final solution. Therefore, the team decided to use polyurethane resin to flatten out the previous increasement around the draining valve. The polyurethane resin is mainly used in boat maintenance and is therefore waterproof, making it an optimal resin for the TES tank.

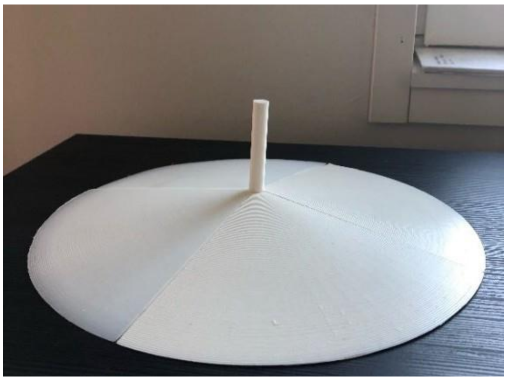


Figure 47 negative TES mold and resin

After the drying period of the liquid, the team saw that the hardened polyurethane had shrank and there were gaps between the edges of the tank and the liquid. These gaps were then filled with polyester sealing.

Figure 48 Gap between edges

As a result, an evenly flattened surface on the bottom of the tank was achieved, this reduced the amount of water resting in the tank after drainage. Lastly the resin and the tank were painted over with waterproof metal paint.

Figure 50 Gaps filled up with polyester

Figure 49 Bottom covered with paint

9.2.3 Lid TES

The original lid of the TES tank was a 3mm thick aluminum circle, that was perfectly fitted for the tank. However, since the team rebuilt the heat exchanger and the water cycle, the holes drilled in its surface did not match the new design, they were either too big or too small. Other holes could be drilled, but the team judged that it would not be aesthetically nor practically correct and decided to build a new lid.

The new lid followed the same design as the original one, so first a 35x35 cm square was cut from a bigger aluminum piece with a sheet cutting machine. Then, with a big manual cutter the square was transformed into a circular shape, by turning the sheet while cutting it. Lastly, the outer surface was manually sanded down to give the lid the final circular form.

After that, only the necessary holes had to be made. This included two connections for the heat exchanger, the inlet for the water coming from the compressor, another one to initially fill the tank with water, and multiple small holes to fix the lid to the tank.

Figure 51 Comparison between original and new TES lid

9.3 Digitalization of demo

The digitalization of the demo via sensors plays a significant role in improving the efficiency of the demo. The data collected by sensors will be processed and provide precise and reliable information about the operating environment of the A-CAES demo.

Buying the correct sensors and equipment is important. This team aimed for real time data extraction from the sensors. Future users of the A-CAES demo get a better general understanding of the working temperature and the pressure rate of the demo in several charging and discharging phases.

The live data extraction required some steps to be taken. These were:

- Write a code in Arduino that: reads every value of each sensor and sends this values to the serial monitor.
- Have the code on a laptop form NOVIA, so it is always available to access the sensors data.

The only experience with programming some group members had was working with an Arduino Uno microcontroller board. Arduino is an open-source electronics platform based on easy-to-use hardware and software.[18] Additionally LabVIEW and Arduino are easily connectable with each other. Therefore the microcontroller of choice for the team was an Arduino Uno board:

Figure 52 Arduino Uno

9.3.1 Temperature sensors

The previous EPS group of 2020 had already bought a temperature sensor. A waterproof DS18B20 digital temperature sensor for Arduino. The temperature sensor has the following specifications:

- A usable temperature range between -55°C to 125°C
- A ± 0.5°C Accuracy from -10°C to +85°C.
- Usable with 3.0V to 5.5V power/data

[18] (Mahamudul, K. 2018)

Figure 54 Robooma temperature sensor

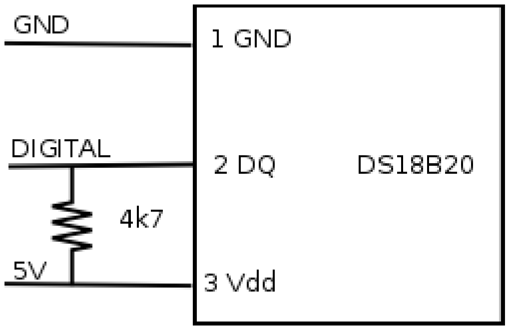


Figure 53 Circuit Temperature sensor

The Robomaa temperature sensor meets all the necessary criteria and will be continued to serve purpose in the demo. This saved delivery time and budget.

The team chose to place three temperature sensors. When the Dallas Temperature library – a standard library for the Robooma sensors - is included, all sensor sharing the same row are detected. Each sensor gets assigned an index to make reading the temperature possible.

9.3.2 Pressure sensor

Barometer

The regulated power supply used to power the Arduino microcontroller is 5V. Thus meaning that pressure sensors with a maximum range of 100-150 bars can't be used. Those are not only out of budget, they require higher power supply.

However, catching on the changes of the compressed air coming out of the TES is important to fully understand the working cycle. The pressure after the TES could be up to 100 bars. Therefore the team installed a barometer on the pipe after the TES. This allowed the team to read the pressure rate manually.

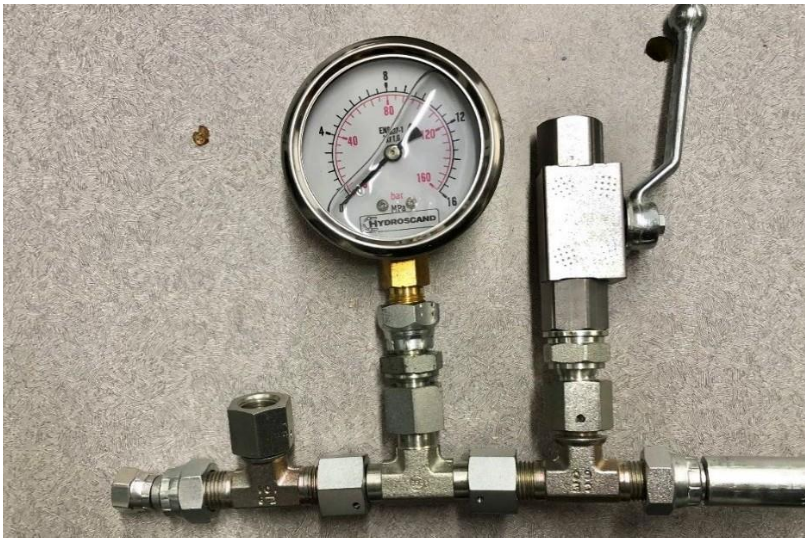


Figure 55 Barometer

Pressure sensor

The most important position in the demo to measure the pressure is right before the air goes through the turbine. The compressed air going through the turbine should be no more than 6-8 bars. If the pressure would be higher the turbine would break down. Therefore positioning a pressure sensor before the turbine is a necessity.

A pressure sensor had not yet been bought by the previous EPS teams working on the demo. The pressure sensor of this teams choice is the 96770 10 900 pressure sensor.

Figure 57 96770 10 900 pressure sensor

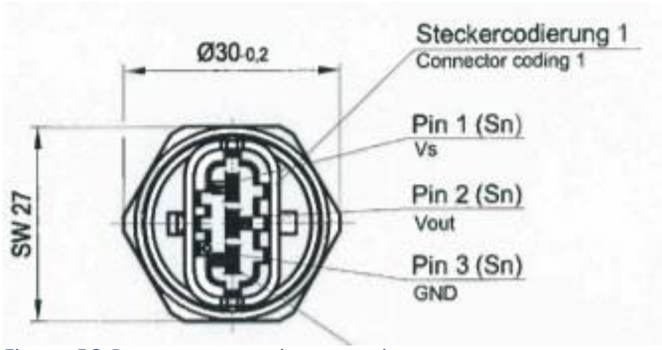
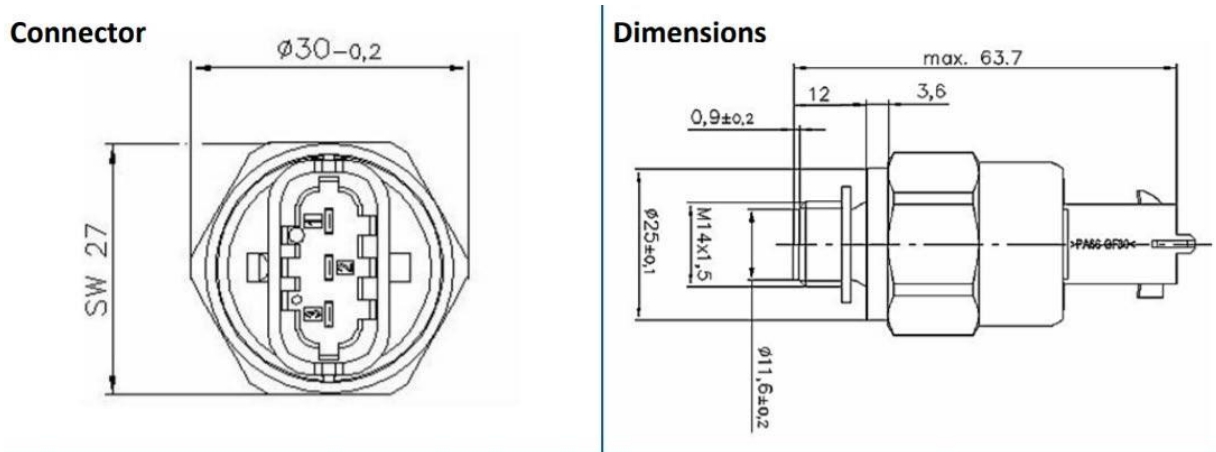


Figure 56 Pressure sensor pin connections



Media	Liquid media e.g. fuel, engine oil air and exhaust	**Pressure range**	E.g. 0 ... 10 bar, relative *
Temperature range	- 40 °C to + 125 °C	**Output signal**	0.5 ... 4.5 V ratiometric
Thread	M14 x 1.5 or M18 x 1.5	**Connector**	Bosch Compact
Protection range	IP 6K9K		

Figure 58 Pressure sensor data sheet

This pressure sensor meets the brief: it's usable pressure range (1-10) allows it to be placed in front of the turbine. Furthermore the sensor costs 63,63 euros, which is relatively low in the price range of pressure sensors.

The 96770 10 900 pressure sensor is one that is not commonly used for Arduino boards. Pressure sensors as such are more often used in car-applications. Thus meaning that the wires, to connect the sensors to the Arduino uno, had to be soldered.

Figure 59 Pressure sensor on demo

Lastly, the Arduino software and codes were installed on a laptop that the team received from the university. Thereby, students don't have to install any additional applications on their own personal laptops. As result, all sensor analysis can be done with the foreseen material at the demo. Further instructions on how to operate the sensors will be given in the operation manual.

Figure 62 shows how the sensor values are written out by the serial monitor of the Arduino Software. Every half a second new values are measured.

Final Arduino board lay-out

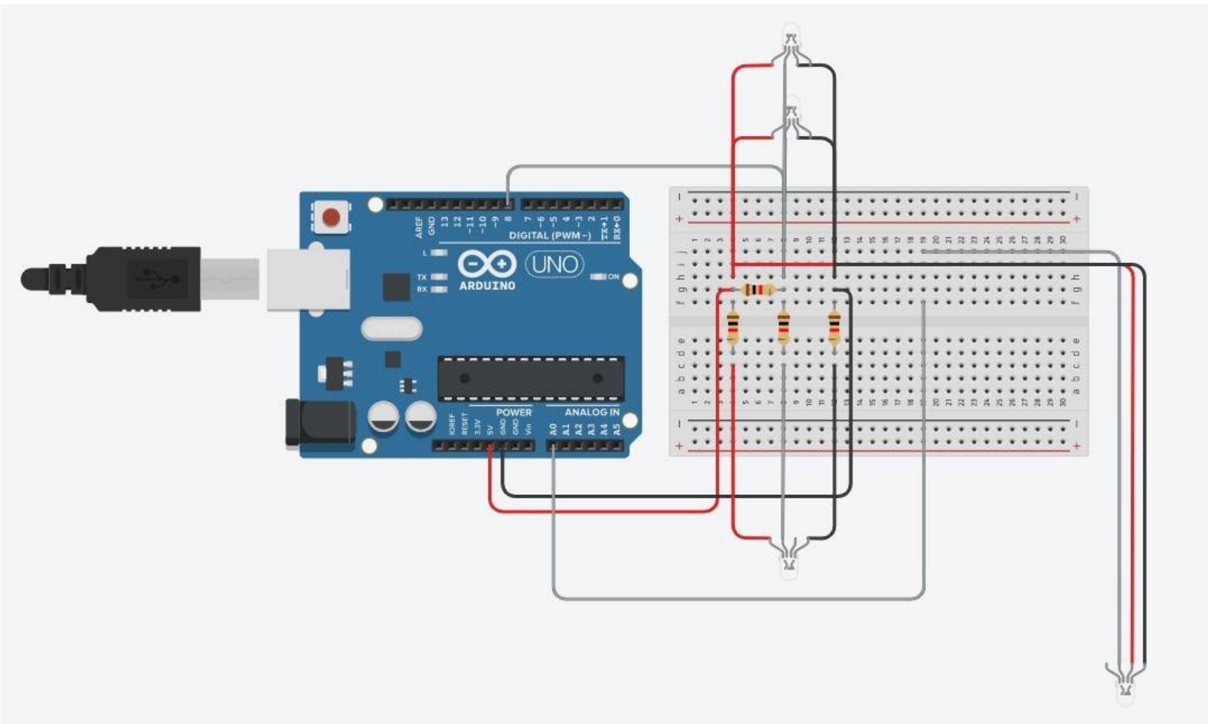


Figure 60 graphic sensor setup

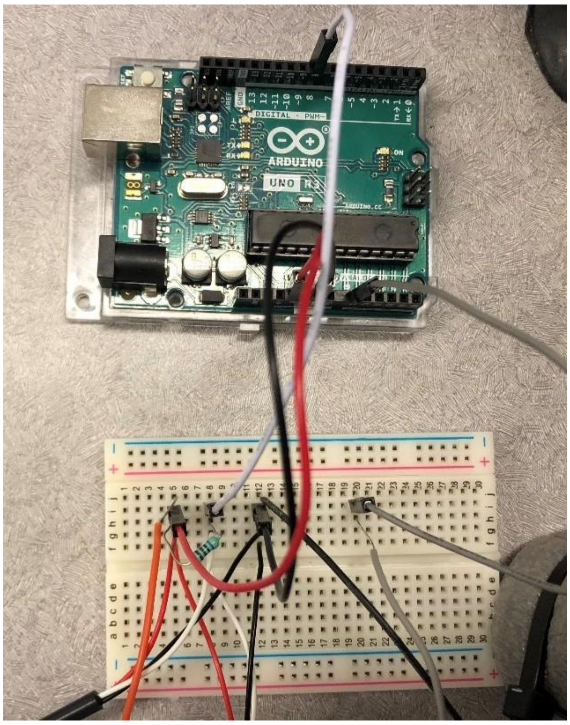


Figure 62 Sensors set up

```
sensorvalue: 99 // pressure: 0.99 Ba
Sensor 1 : 21.25C°  |  70.25F°
Sensor 2 : 21.37C°  |  70.47F°

sensorvalue: 100 // pressure: 1.00 Ba
Sensor 1 : 21.25C°  |  70.25F°
Sensor 2 : 21.37C°  |  70.47F°

sensorvalue: 100 // pressure: 1.00 Ba
Sensor 1 : 21.25C°  |  70.25F°
Sensor 2 : 21.37C°  |  70.47F°

sensorvalue: 100 // pressure: 1.00 Ba
Sensor 1 : 21.31C°  |  70.36F°
Sensor 2 : 21.44C°  |  70.59F°

sensorvalue: 100 // pressure: 1.00 Ba
Sensor 1 : 21.31C°  |  70.36F°
Sensor 2 : 21.37C°  |  70.47F°
```

Figure 61 Sensor values on serial monitor

9.3.3 Volt and Ampère measurements

At the end of our demo cycle, the voltage and amperage need to be measured at the location where the servo motor is placed. The servo motor has a maximum of rotations per minute of 3000 rpm. Depending on the rotations, a certain current and voltage is given.

With the given measurements, a graph could be shown via Excel. At every rotation a different quantity of voltage and current is given.

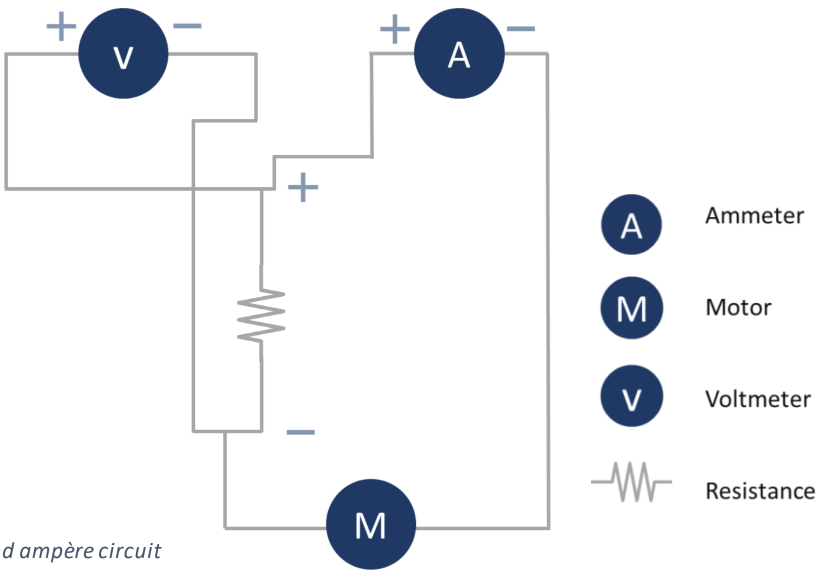


Figure 63 Volt and ampère circuit

9.4 Efficient Sensor lay-out

The temperature sensors will be taped on the outside of . The figure bellow shows where the pressure sensors (P) and the temperature sensors (T) are placed on the demo.

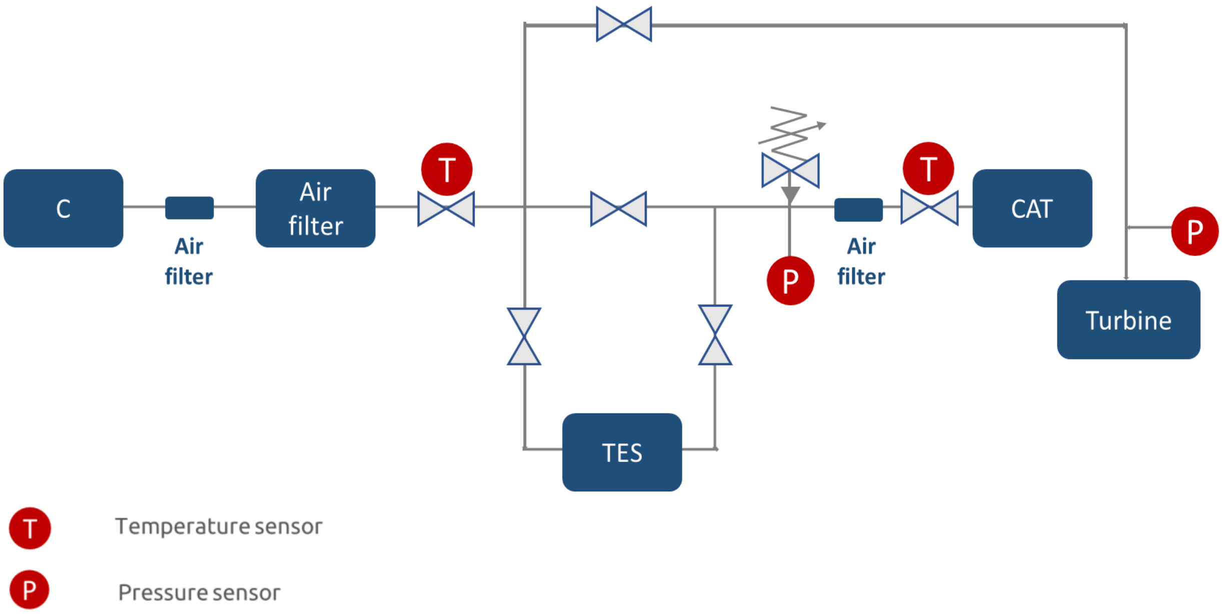


Figure 64 sensor placement

9.5 Filter

After the evaluation of the different possibilities to deal with the problem of the water in the air, the decision of constructing an absorption filter for high pressure was made.

This was the cheapest solution and would allow to eliminate the water from the air cycle. The main challenges designing this filter were the following:

- High pressure. Because the filter would stand after the compressor, it would have to withstand up to 100 bar. Furthermore, the team had to find a way of preventing any leaks.
- Desiccant material. The conditions of high temperature limit the materials that can be used, because most desiccants start releasing water at a certain temperature.

The main idea was to build a stainless steel vessel that could easily be filled and emptied with the desiccant. To do so, the team first had to find the appropriate material. Knowing its properties, the amount of desiccant needed to remove the water could be determined. This quantity would impose the size of the air filter.

To start with, the only type of desiccant material that can work at high temperature are molecular sieves. As shown in figure 65, other common desiccants as silica gel have a poor performance at high temperatures (212ºF = 100ºC).

They would absorb almost no water, while the molecular sieves remain having a high absorption capacity. One of the most popular molecular sieves is zeolite, which is a microporous mineral used in plenty of industrial applications. This was the material chosen by the team.

With this kind of material and taking into consideration that about 15 grams of water must be removed every three complete cycles of the demo, the size of the filter can be established. According to figure 65 [19], at a temperature of 200ºF (93ºC), with 100 grams of material, 15 grams of water can be absorbed before reaching the equilibrium point, when the material would start releasing the water.

Then, to know the volume of the vessel the density of the material is needed. This density varies between 550 and 800 g/l. Taking the lower value for the density, the minimum needed of 100 grams would occupy about 0,19 liters. Being this volume the minimum, the team aimed to build a filter about 2 to 3 times bigger to ensure a sufficient water absorption.

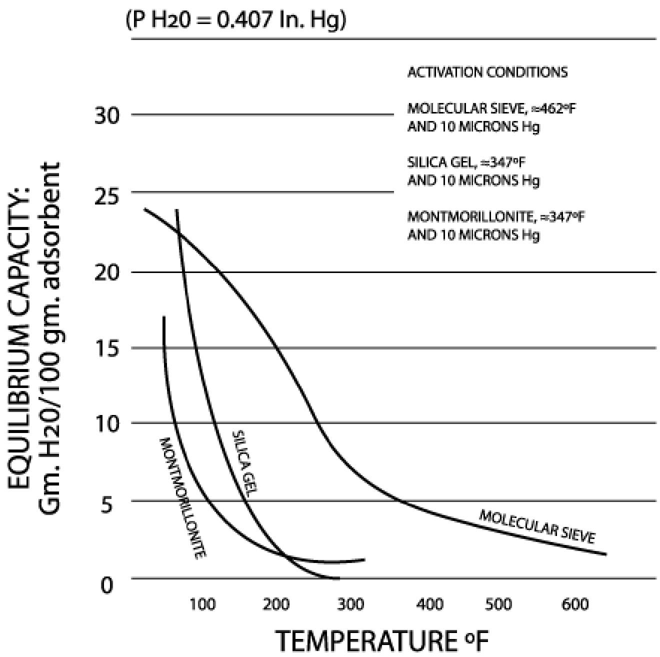


Figure 65 Relation temperature and absorption capacity

After this research, the team focused on the design of the air vessel. Different possibilities were evaluated to build it, but the easiest way was to use a stainless steel pipe and connect it to the air cycle. The selected pipe was manufactured and delivered by the company ASCHL. It was made of V2A stainless steel, was 40 cm long, had an outer diameter of 42,4mm and a thickness of 3,25mm. It also had both threaded ends of G1-1/2". This would result in a volume of 0,41 liters, which is 2,16 times bigger than the minimum previously mentioned. The working pressure was 158 bar and the maximum pressure was 501 bar, so it was safe to use it in the system.

Afterwards, there were various forms to perform the connection from G1-1/2" to 1/4" (the diameter of the rest of the cycle). Some of them included multiple couplings that would progressively decrease the diameter, but this would involve several expensive components and a bigger size of the filter, which is restrained by the table in which the demo is built. Therefore, the team decided to use threaded steel

[19] (SorbentSystems. 2006)

caps to close the vessel, and then drill the necessary hole in the cap to insert a direct connection of 1/4".

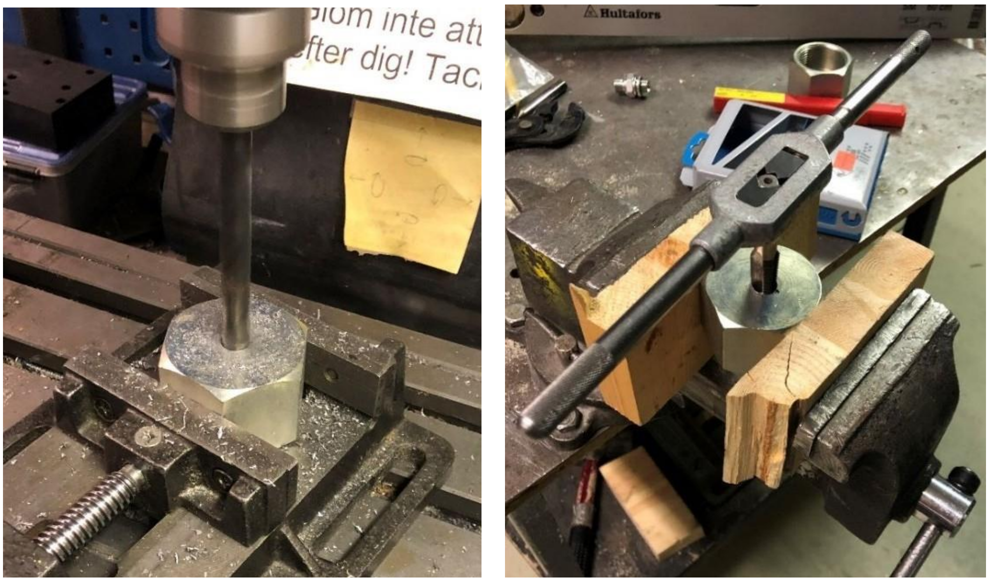


Figure 66 Process of drilling the hole in the iron caps

Then, the main idea to correctly seal the air vessel was to install rubber O-rings in both ends of the pipe. The rings would come into contact with the steel cap and applying the appropriate force, they seal the container. This is a standard procedure in many applications, and a similar principle was used in the connection of other pipes in the demo.

However, the threaded length of the caps was longer than the one of the pipe. With this initial dimensions, much rubber would be needed, and the sealing would be more difficult to perform. Therefore, the team had to cut 1,15 centimeters from the threaded caps using the lathe from the metal workshop at university.

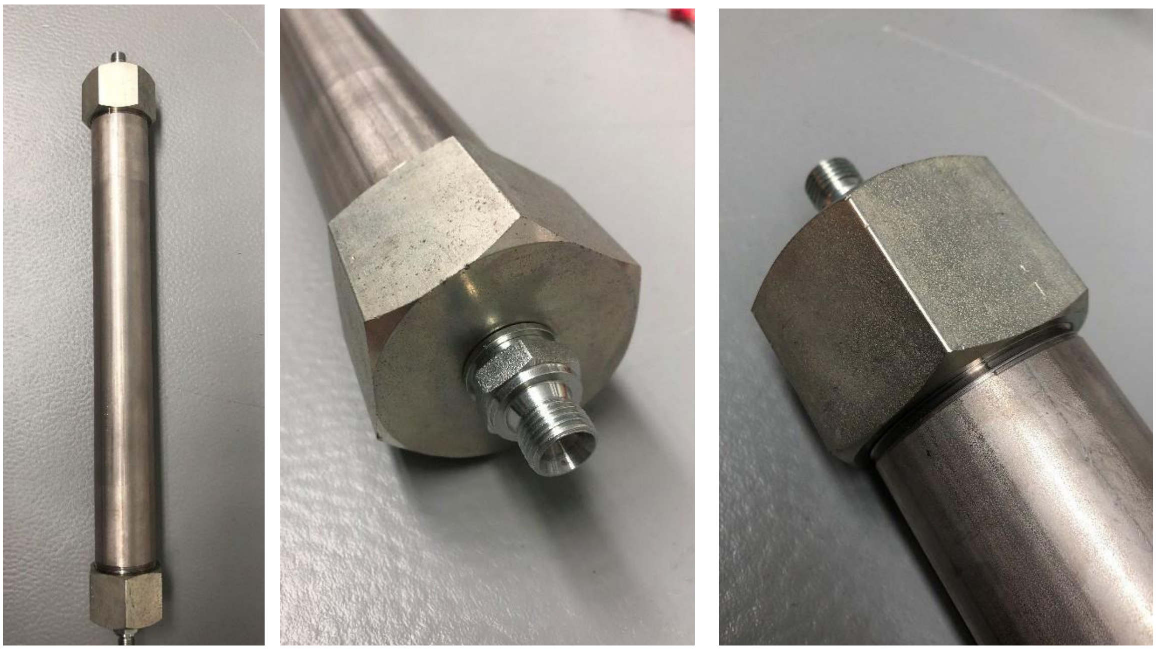


Figure 67 Final result of the air vessel and the connectors

Lastly, to prevent the desiccant material to go throw the system, the team had to install a grid or a web at the ends of the vessel. This would allow the air to flow but would block the solid particles of the desiccant. To do so, first the size of the material should be known.

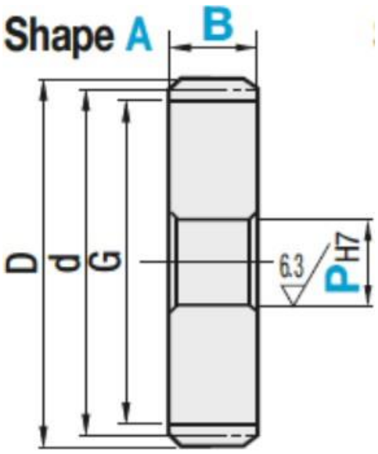
The chosen material was zeolite Z4-01 from the company Zeochem. This material forms spheres of between 2,5 and 5mm of diameter, so the holes in the grid had to be smaller than that. The team manually cut two circles from a steel sheet, so that it could fit in the cap. After that, multiple holes of 1,5 mm diameter were drilled and then it was sticked to the cap with special glue. (figure 68)

Figure 68 Drilled holes in filter

This way, the desiccant is easy to remove while also ensuring that it could not flow through the air cycle.

9.6 Bracket and gears

To start with, the team had to decide which material and gear system to use. The objective was to achieve an optimal transmission of power with a simple design. Therefore, the team concluded that using only two metal gears was the best solution. The gears were ordered to the company Misumi-vona, and they had the following dimensions:



[20]

Figure 69 Drawing of the spur gear

[20] (Misumi. 2021)

	Gear 1 (air motor)	Gear 2 (generator)
Z (number of teeth)	120	12
D (tip diameter) [mm]	183	21
d (reference diameter) [mm]	180	18
B (width) [mm]	15	15
P (shaft bore diameter) [mm]	14	6

Table 14 Dimensions gears

The shaft bore diameters P were imposed by the shafts of the air motor and the generator.

With the new gear system, the bracket gear also had to be redesigned. Also, since the team decided to only use the air motor and not the turbine, the idea of the 2020 group could not be used. However, the metal pieces built by past groups could be adapted.

To start with, the defining dimensions were the diameters of the gears. The references taken by the team were the shafts of the motor and the generator. The distance between the shafts was:

$$\frac{d_1}{2} + \frac{d_2}{2} = 90 + 9 = 99\ mm$$

This distance must be accurate to ensure an efficient gearing, the bracket of the generator was built so that the shaft could be adjusted, while the air motor would always stay fixed to minimize vibrations.

The team was able to reuse the metal bracket for the generator built by past teams, since it already had the necessary holes to allow the movement needed to adjust the generator. The idea was to have the generator below the air motor, so the original bracket was too high. The team proceeded to cut the part that could be reused at the appropriate high and solder it to an additional metal plate to form a 90º bracket.

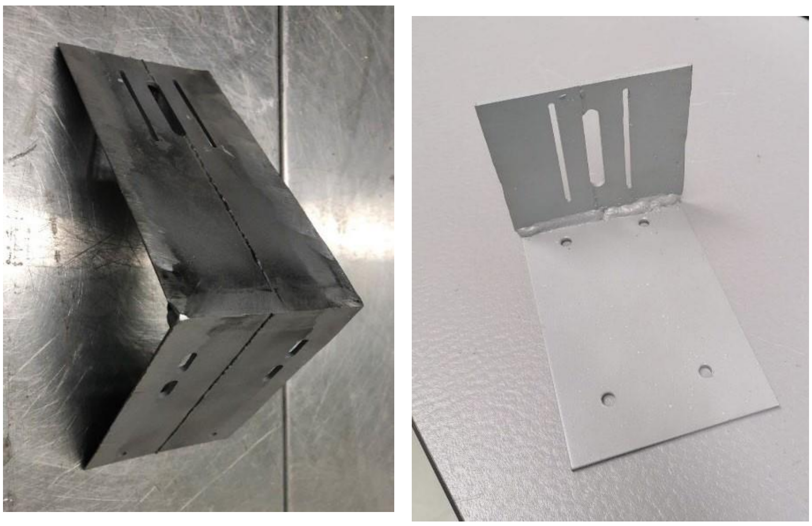


Figure 70 Comparison between original and new generator bracket

For the air motor, a completely new support had to be built. Due to time constraints, the team could only work with the materials available in Technobothnia and limited design options. The final solution was to use a 22 mm thick wood plate to hold the air motor and attach the wood plate to the table with L-shaped steel bars.

First, a 10 cm diameter hole was drilled in the wood plate, where the motor would stand. Its center, where the shaft of the motor would stand, was 15 cm high to ensure that the gears would not come close to the table. After that, the necessary holes to then hold the motor and the steel supports were also drilled. For the steel bars, they were first cleaned with a sandblasting machine and then the appropriate holes were drilled.

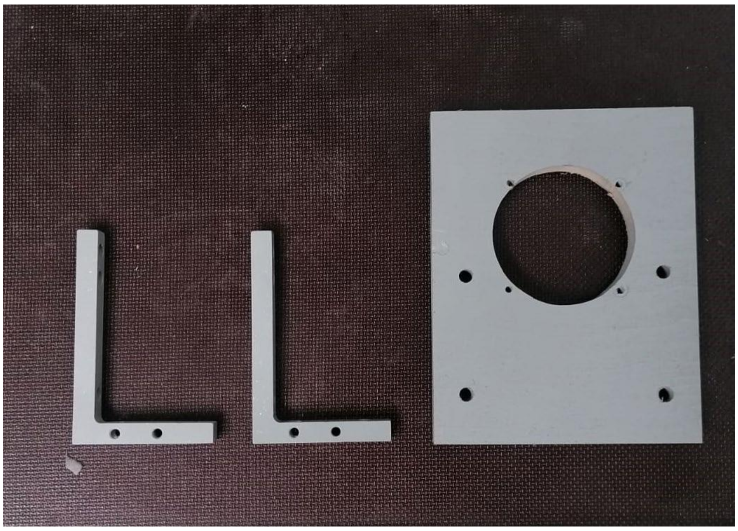


Figure 71 New bracket for the air motor.

Lastly, every part was painted to prolong their lifespan and prevent problems as oxidation in the steel components.

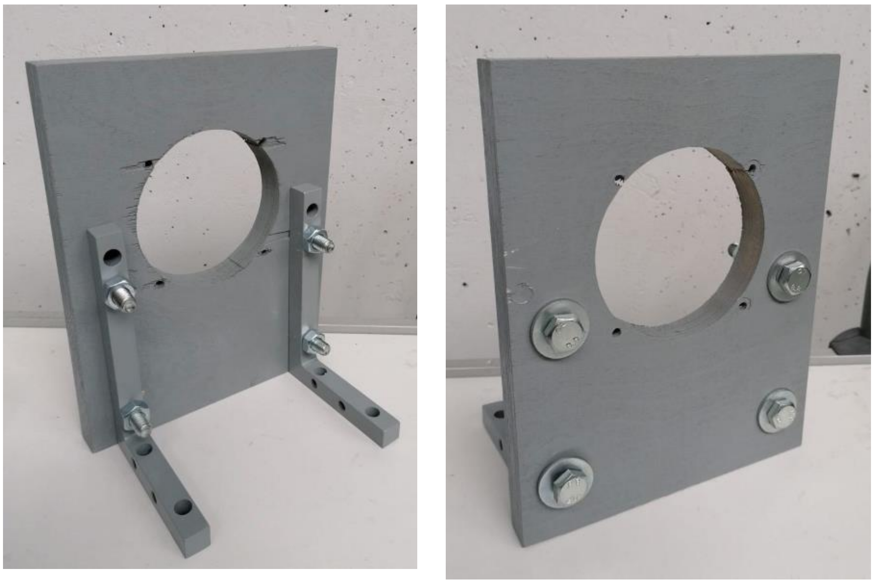


Figure 72 Final assembly of the air motor bracket

9.7 Insulation

Insulating pipes

For the insulation the team decided to follow the recommendations of the EPS group of 2020. Therefore their recommended polyethylene insulation pipes were bought in the store Biltema. This insulation has a thickness of 13mm and their overall diameter is 40mm.

Furthermore the team put insulating tape on the pipes to close them and applied zip ties to ensure the insulation and its tape to stay put.

Figure 73 Insulation for pipes

Figure 74 Construction of insulation

Insulating TES

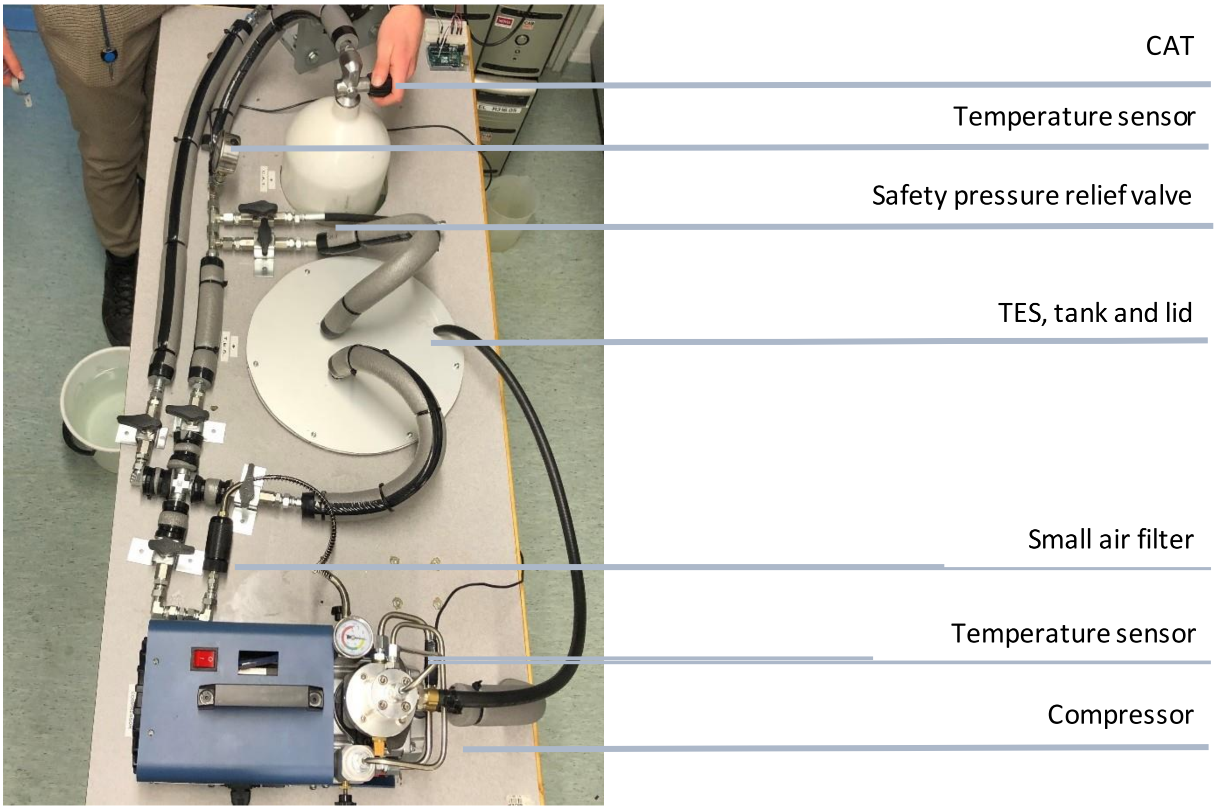
The TES is the biggest individual area where heat loss will take place and it exists out aluminum with a R-value of 1,25 m²K/W, which is considered a low isolation value. This does make the heat exchange to the surrounding area even bigger. To contain this lost energy, glass fiber isolation will be placed around the tank of the TES. The glass fiber owns a thermal resistance value of 0,036 W/mK (λ) and a thickness of 0,06m (d). The R-value can be calculated with the next formula: $R = \frac{d}{\lambda\lambda}$. The R-value is equal to 1,667 m²K/W, this is an increase of 25% in containing the lost energy.

The recommended insulation for the TES was available at STARKKI. The measurements of insulation are 20x140 mm with a length of 14 m.

Figure 75 Insulation on the TES tank

10 Final demo lay-out

With the complete setup of the Energy storage demo, the team was able to test and witness which phenomena took place. After the CAT was pressurized, the team used the compressed air to let the air motor functionate properly. The CAT is pressurized to 100 bar while the air motor only can take 6 bar. For further instructions, the user manual should be checked . From the moment the air motor was running, the team discovered that water was coming out of the motor. This phenomenon has a negative impact on the air motor, due to this it is highly recommended that the demo will not be used until the air filter is completed. The air filter is supposed to extract the water from the air and contain it. Because of ordering complications, this part could not be completed.



Another result is that there were no leaks detected through the whole cycle which is considered as a positive result.

Lastly, the pressure can be controlled by the valves whilst the pressure can be checked at the pressure gauge. This results in a safe

11 Safety plan

A safety plan was made by the team, to ensure the safety of future users of the demo.

General

- Keep the energy storage demo indoors with a temperature around 22°C.
- Do not touch the Energy Storage Demo while running the compressor due to heated pipes.
- Avoid touching moving parts, such as the gears, air motor and the generator.
- Always control the values that the pressure and temperature sensors are giving.
- In case of need, use the extra safety valve to remove any store that can remain in the system after a complete run of the cycle.

Compressor

- Make sure the voltage in the nameplate meets local power supply.
- Only use the compressor on a completely flat and dry surface.
- Make sure pressure setting is under 310bar.
- Double check the volume of the lubricate oil before running.
- Keep distance from compressor as there is a potential danger of connections blowing of or pipes bursting under high pressure.
- Do not leave the compressor out of sight when running. Keep an eye on until rated pressure is reached.
- Do not adjust the pre-set rated working pressure unless it is authorized.
- When in doubt: check the Operation Manual of the Yong Heng compressor.
- Always check the parts before starting the compressor. Make sure that every component is fixed. This reduces the chance of parts that come loose.
- Always wear headphones due to the noise that is generated by the compressor.

12 Demo user manual

In the operation procedure the team will explain how to run the energy storage demo including charging with/without TES, checking the compressor, air motor and water pump so that they can operate efficiently.

Before operation

Checking water cycle

1. Filling TES tank with 8 litres of water

Figure 76 TES tank filled up with water

2. Check correct fixing of pipes with selected clamps.
3. Check mode of the pump.

Figure 77 Mode of the pump

4. Wait 2-3 minutes, check that the water flow is arriving to the TES from the outlet of the compressor.

If step 4 is not completed successfully, the pump may be blocked due to inappropriate maintenance. Always take into consideration that even if the pump is turned off but the TES tank is full, some water will come out the pump due to hydrostatic pressure. Possible solutions are:

- Carefully removing the clamp and the pipe from the pump outlet and check if any dirty water comes out.
- Ultimately, after extracting the water from the tank, the pump can be removed and cleaned. It is recommended to use a dry duster to do it.

Checking compressor before operation

1. Make sure the voltage in nameplate meets local power supply.
2. Fill the compressor with lubricate oil until it achieves the middle of the oil glass.
   Note: if the oil level is too high, air valves will easy carbonize, if oil level is too low it will result in insufficient lubrication and piston cylinder sticking.
3. Install breather at oil filling port.
4. Check connect fitting, fasten strong and make sure no leakage.
5. Check rotary direction of motor
   Note: correct direction is cooling wind blow to pump body.
6. Trial running.
7. Open the condensate drain valve to make compressor will start immediately.
8. Close the charging valve to begin a short time test running.
9. Turn on the compressor, after it runs in steady 3-5 minutes.
10. Close condensate drain valve and the compressor begin to pressurize, turn off compressor when it reach the rating pressure.
    Caution: Continually running is not suggested because it may result in temperature-rising, parts damaged and the machine life shortened.
    Note: open the drain valves to release high pressure and condensate after every refill operation.

Checking pipe system

1. All the pipes must be strongly connected to avoid leakages.

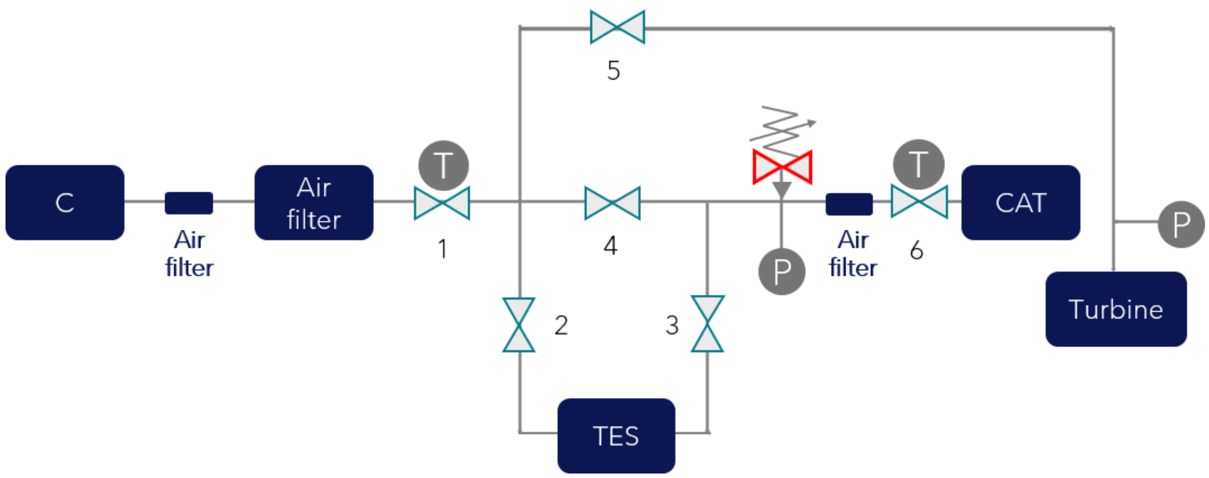


Figure 78 demo lay-out

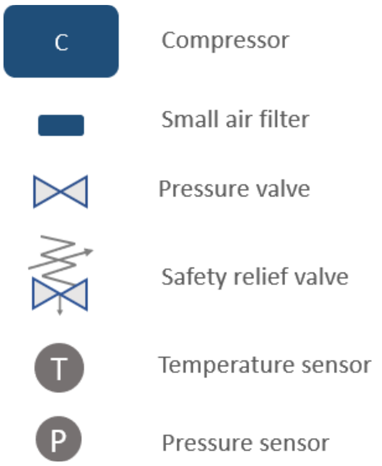


Figure 79 Legend demo lay-out

Operation procedure

Operation with TES

1. Check that the water cycle is working
2. Open all the green valves shown on the following figure:

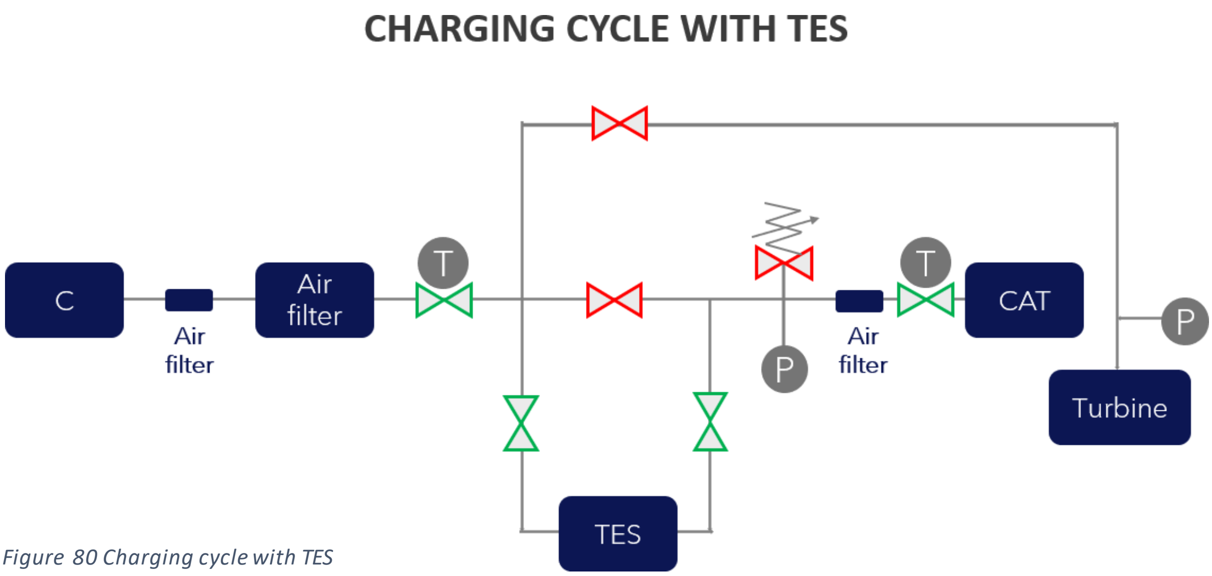


Figure 80 Charging cycle with TES

3. Open the charging valve for no loading start.
4. Turn on the compressor.
5. Close the charging valve after it runs 30 seconds smoothly.
6. When the pressure reaches the requirement, turn off the compressor and close valve number 6. Charging cycle is over.
7. Close valve number 1 and open charging valve of the compressor to release the accumulated pressure.
8. Open valves 5 and 6 controlling that the pressure before the turbine is 6 bar (figure 81)..

9. Collect information from the pressure and temperature sensor.

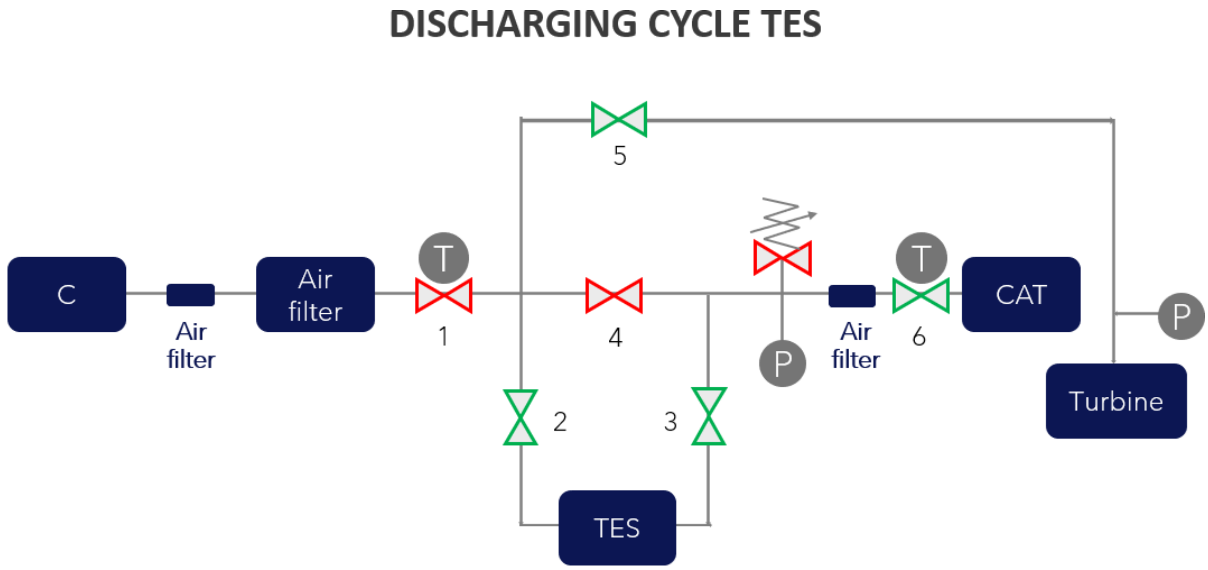


Figure 81 Discharging cycle with TES

Set-up of sensors

1. Open the code for the temperature and pressure sensor by clicking on “Documents”, select “Sensors_codes” → “Temperature_pressure_sensors_code”
2. Connect the Arduino to the computer through the USB port.
3. Connect the Arduino to the breadboard as shown in the picture below:

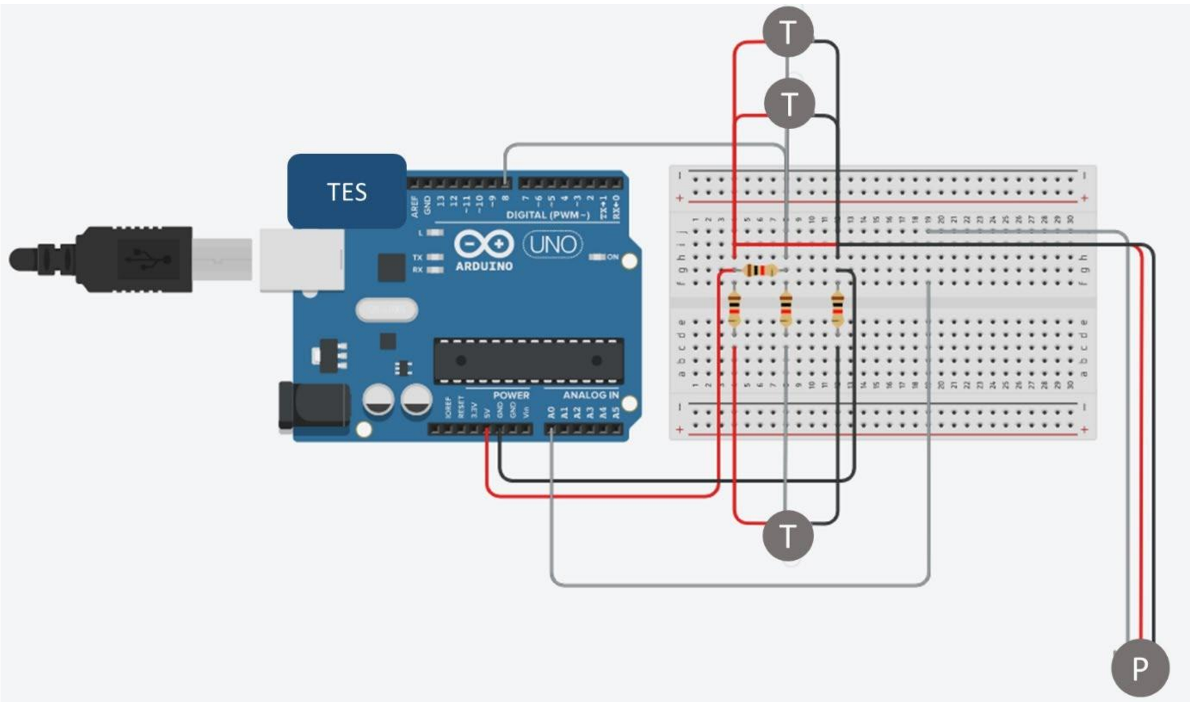


Figure 82 Arduino breadboard lay-out

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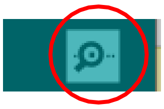
4. Press on the following arrow to run the code:

5. Open the serial monitor by clicking on the following symbol:



6. You should get the following results with different values:

```
sensorvalue: 99 // pressure: 0.99 Ba
Sensor 1 : 21.25C°   |   70.25F°
Sensor 2 : 21.37C°   |   70.47F°

sensorvalue: 100 // pressure: 1.00 Ba
Sensor 1 : 21.25C°   |   70.25F°
Sensor 2 : 21.37C°   |   70.47F°
```

Figure 83 Serial monitor values

troubleshooting: If -127°C appears on the Serial Monitor, the Breadboard is not well connected to the Arduino. You must check if the cables are well placed into the Breadboard or Arduino.

Operation without TES

1. Check that the water cycle is working.
2. Open the green valves shown on the following figure 84.

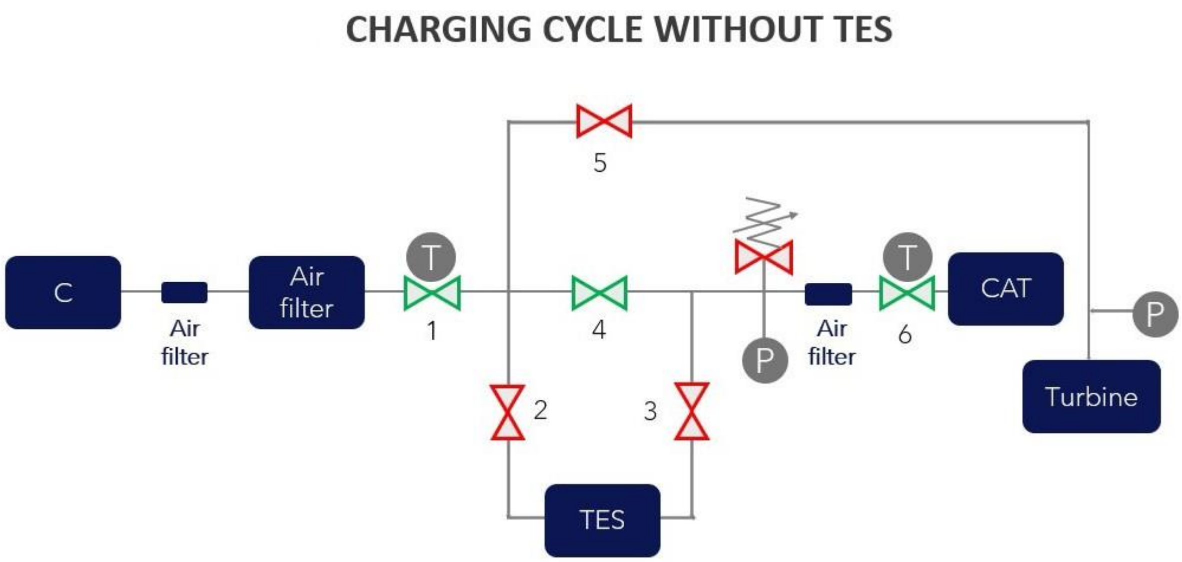


Figure 84 Charging cycle without TES

3. Open the charging valve for no loading start.
4. Turn on the compressor.
5. Close the charging valve after it runs 30 seconds smoothly.

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6. When the pressure reaches the requirement, turn off the compressor and close valve number 6. Charging cycle is over.
7. Close valve number 1 and open charging valve of the compressor to release the accumulated pressure.
8. Open valves 5 and 6, controlling that the pressure before the turbine is 6 bar (figure 85)

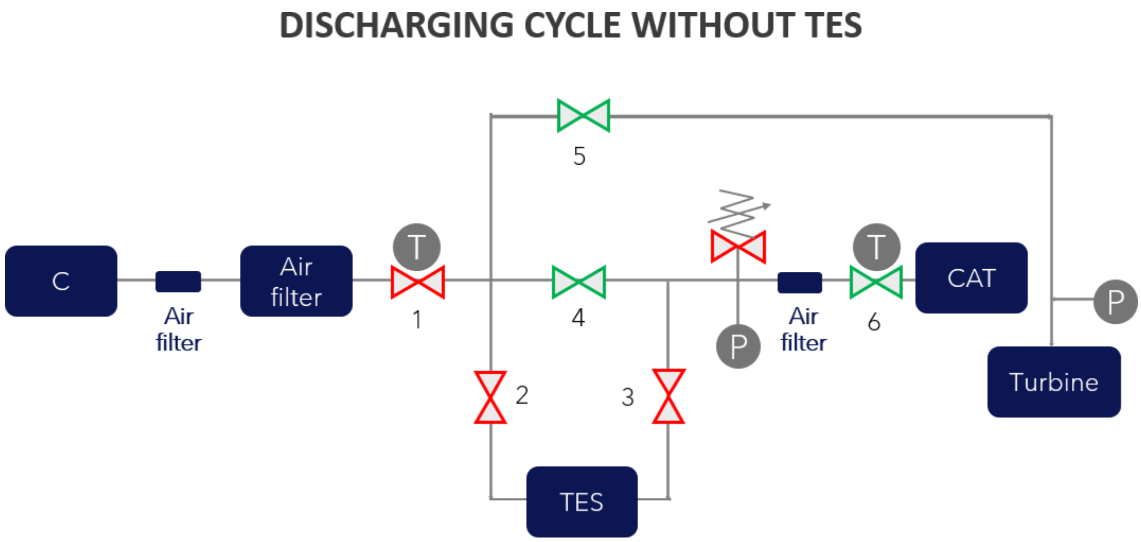

Figure 85 Discharging cycle without TES

After operation

To ensure the correct functioning and safety of the demo, the following steps should be completed:

1. Completely remove the water in the cycle when all the work is finished.
2. After every run, make sure there is no pressurized air in any part of the cycle. To do so, the usage of the safety release valve and the charging valve in the compressor is recommended.
3. Remove, clean, and dry the interior of the water pump with a dry duster before leaving the demo.

13 Conclusion

Project

The outcome of the project was similar to the scope of the project: the team delivered an improved demo and a user manual. The overall efficiency of the demo has been improved tremendously. However, unforeseen circumstances resulted in the team redefining the goal of having a completely functioning and especially tested demo. When this team started on the demo, many induvial main components were not functioning or optimized. Additionally, time constraints and delayed deliveries enforced more challenges. Therefore solely doing finalizing work and thereafter testing the demo was not possible.

The team found many leakages in the system and still water in the cycle caused corrosion in the pipe system, TES and CAT. The corrosion was deteriorating the pipe system, turbine and the overall efficiency of the demo. therefore an air filter was designed, which required many research.

Later on in the project, a dent was found in the TES. Consequently, the team built a new TES.

In addition the turbine and gear system were not optimized: there was a problem with energy loss due to friction, and this team aimed to increase the velocity of the of the generator up to 3000 rpm. As a result a system with to gears to transmit the power was implemented. As the gears (and the turbine) are the ultimate power transmitting elements, to produce electrical energy, a substantial amount of time and work was put into redesigning these components.

Lastly, the demo in its original state was incomplete and not constructed as a whole system. This addressed this incompletion by thoughtfully constructing a cohesive demo.

All the redesigning of the main components mentioned above, resulted in a deviation of the team from one of the main objectives of the project: testing and analyzing the demo as a whole. It was unfortunate that this objective had to be revised. However, the team decided it was better to aim for a demo with optimized main components, than to have a complete demo that works poorly and without any efficiency.

In conclusion, the team succeeded in delivering complete demo with a user and safety manual. And thereby essentially met the brief of this A-CAES demo-project. Further expectations and recommendations are discussed in the following chapter.

Team

During this EPS project, the team used different aspects of Project Management. Working with people from different study fields and backgrounds was a challenge for this team. Nonetheless each team member developed new skills and learned to work in a diverse multicultural team. This EPS semester was an experience on personal and professional level, which we are grateful for.

14 Recommendations

14.1 New housing and water pillow

The cooling system was not efficient enough due to heat loss from the compressor. The team wanted to use the lost heat, in an useful way. As a result, the group thought about designing a water pillow [WP].

The WP is connected with the water cycle. Due to this connection, the heat flows from the water pillow, to the water cycle. Afterwards, the heat will be sent to the air cycle. According to the following formula:

$$V = \frac{nRT}{P} \qquad (31)$$

The air cycle will heat up and consecutively will the volume enlarge. If the volume expands, the energy will grow proportional. The more energy is created because of expansion, the more energy can be saved in the CAT.

The team made the decision to not start building the cooling system due to lack of time. It would have been a useful extra feature to add but it was not a priority for this team. Therefore it is classified a recommendation for possible future workers on the A-CAES demo.

14.2 Ampere and volt measurements

Referring to chapter 9.3.3, there is the possibility to convert the data, that the measurement equipment is collecting, into a graph with for example Excel. The time can be chosen in between the first datapoint and the next, so the person in charge can determine what the most efficient way of harvesting the data is. At every rotation a different quantity of voltage and current is given. The servo motor has a maximum drive of 3000 rpm. This is equal to 50 rounds per second, which means that every second, 50 datapoints are given.

This would add value to the digitalization of the demo. This is a more efficient way of processing data than reading off the voltages and currents at a given time without saving anything. In the current situation, one cannot analyze and conclude optimally.

14.3 Small air filter

An initial goal of the team was to implement a small air filter in the demo cycle, right after the CAT. A small air filter is needed since the CAT is filled with rust due to the demo set-up of 2019. The team was unable to eliminate the rust manually inside the CAT, as there is only one entry, which is relatively small and difficult to reach.

Applying this air filter would give a boost to the efficiency rate and add extra insurance to work with high pressurized clean air because the filter does not only extract existing rust, it also prevents rust forming inside the CAT. Unfortunately, due to delays in delivery, the ordered filters did not arrive on time for this team.

14.4 Conic shape

As mentioned in chapter 8.2.1, the desired solution to improve the casing of the TES was to create a conic shape. Even though time and availability constraints came in the way of creating this conic shape, it is still recommended that future workers on the demo look into this solution. A conic shaped bottom of the tank would still improve the current water outlet.

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16 Appendix

16.1 Project management

In this chapter the project activities necessary to meet the project requirements were defined. This whole section was implemented to clarify the aim of the project. Firstly, the stakeholders were defined. Then, a clear idea of what the project was about and its challenges were created. In addition: schedules, a human resource, communication, risk, quality and cost management plan were made to give a structured and organized overview
of the project.

16.1.1 Problem analysis

Environmental pollution is one of the major concerns for humanity at the moment. Through the last decades, renewable energy solutions have been developed. These technologies are the foundation of a future with a high standard of living combined with a green environment. With new technologies, come new challenges. One of the challenges we face is the inefficiency of dealing with wind energy. When supply of energy is high but demand is low, there is no sufficient way of storing it. On the other hand when demand is high and energy supply is low, we have to get the electricity from somewhere else.

A modern battery is hardly scalable, very expensive in resources and bad for the environment.To deal with such high or low peak outputs, an alternative solution is necessary for further ecological development.

The purpose of the storage alternative is that the produced energy can be stored and distributed when needed.

A Co^2 neutral solution is an Adiabatic Compressed Air Energy Storage system, A-CAES in short. The main goal of the EPS-group is to get a functioning demonstration in Technobothnia, to promote both education and further research possibilities.

Our team continues an existing project from last year with a budget of €1000. On the existing model the following problems have to be fixed:

- Functioning compressor
- Prevent the compressor from getting warmer than 60°C
- Gentle working compressor
- Proper functioning heat exchanger
- Minimize heat energy losses
- Denseness of the demonstration (valves, pipes of both air and liquid circle)
- Functioning turbine
- Fast replacement possibility of the turbine (<5 min)
- Gearing mechanism

As addition to the existing problems there are following further requirements on the demonstration:

- List about dangers to ensure safe handling
- Suitable for learning purpose
- Easy understandable manual
- Be performable three times in three hours
- Target is an efficiency of at least 20% moveable
- Fit on a 2m x 1m table
- Independent functioning

16.1.2 Stakeholders

European Project Semester

This European Project Semester is a program offered by Novia University of Applied Sciences (UAS) for engineering students. Novia UAS is a modern class university with campuses located in five cities in Finland. Students participating in EPS meet together in teams of 2-10 international students to work on their dedicated projects which in this case is: an Energy Storage Demo Environment in Technobothnia Project. Complementary classes as Teambuilding, Project Management, English for Engineering Studies and Swedish should improve the student's intercultural communication and

Energilarging-project

The project owner is: Energy Storage in our Future Low Carbon Society (Energilagring) Project. It consists of a partnership between three universities/universities of applied sciences namely Novia UAS, Vaasa UAS (VAMK) and Åbo Akademi University and was funded by EU Regional Development Funds (Authority: Regional Council of Ostrobothnia) & project partners. Cynthia Söderbacka is the supervisor of this EPS Energy Storage project.

Technobothnia

Technobothnia consists of technical laboratories co-owned by the University of Vaasa, Vaasa University of Applied Sciences and Novia University of Applied Sciences, with almost 20 different laboratories. The laboratories are used for both educational and research purposes as well as providing different services for local companies. Their main goal is to increase and develop the cooperation between the education of Engineering students in Vaasa and the region's industry.

Project Team

This multicultural team exists out of 5 international students. Therefore Multicultural etiquette is a necessity. Team members need to have an understanding of both the basic protocols of international communities and observing how other cultures perceive your own.

The five teammembers are:

Álvaro Revilla-Martin	Spain	Bachelor of Mechanical Engineering
Björn Graul	Germany	General Engineering
Charlotte Hargreaves	Belgium	Product Development
Milan Lemmens	Belgium	Energy Management
Nona Van Laethem	Belgium	Product Development

Table 15 Teammembers

Study Fields

The team members possess the knowledge from the fields of study such as Energy Management, General Engineering, Mechanical Engineering and Product Development:

Energy Management

Energy management is a good pre-education for engineering and gives a good view on how to control energy levels in diverse categories. In this major you don't specify one subject but the learning material expands from electricity to thermodynamics to any kind of renewable energy. Asides the energy part, there is also a managing part. You get confronted with projects and group tasks to unlock/evolve/adapt what management skills you have. The goal of this major is to achieve the insight to add renewable energy solutions in combinations with the project skills that you have gained throughout the years.

Mechanical Engineering

In these years of studying mechanical engineering, the objective has been to acquire technical knowledge about many general topics. A wide range of subjects is covered, that includes thermo and fluid dynamics, structural mechanics, material science and manufacturing processes, mainly focusing on theoretical questions that arise in these fields. To do this, a good mathematical basis is required, to later apply it on more realistic problems.

Product development

Product development is based on three scientific disciplines: human science subjects, technological sciences and economics. During this field of study, students learn to combine these three aspects. The aim of this study is for the student to be able to deliver good quality products in every cycle of their lifespan, from raw material to disposal.

Furthermore, it's learnt to be a troubleshooter and to be creative whilst being critical. A product developer can isolate the specific cause of failure of a product or system by seen and studied methods. By working well within a team, using prototyping equipment and Design software, problem solving-skills can be used to the maximum.

General Engineering

Students get confronted with lots of real world technical problems. These issues have to be solved by calculations and by understanding the whole subject. After the first two years, the students can decide on which topic to specialize. Björn Graul has chosen Aerodynamics which includes fluid mechanics and also thermodynamics.

16.1.3 Objectives and WBS

Mission

Due to the more frequently renewable energy use, there are different time periods with their own peaks if it comes to electricity output. This leads to new problems because more electricity is produced than can be served. Therefore there is a huge demand for energy storage. For that reason, the mission of the energy storage project was to finalize the Adiabatic Compressed Air Energy Storage (CAES) demo started by an EPS Autumn Semester 2019 team. The demo should be used for education, research personnel and demonstrations.

The vision

The vision of the Adiabatic Compressed Air Energy Storage (A-CAES) demo is to create a promising sustainable energy storage technology with durability, high efficiency and low cost. This was done by finalizing the A-CAES demo based on the plans made by the Energy Technology Laboratory Lab Engineer Hans Linden, with former EPS Teams' reports as reference material where necessary.

- As an outcome the project results in:
- A fine-tuned CAES demo operating with optimal efficiency
- A suitable demo for students that should be used for education
- Creating a thriving entrepreneurial environment and culture
- A digitalized demo
- To get a better understanding of thermal energy storage impact on efficiency
- MoScoW model

The MoSCoW model is a way to organize activities by their priority. It consists of:

- Must haves: these are the requirements that have to be in the end results to speak of a successful project
- Should haves: these requirements are important but not a necessity for the outcome of the project.
- Could haves: these requirements will only be included if time and resources permit.
- Won't haves: these requirements are not planned in the schedule due to limited time and resources. They could be interesting to serve as recommendations for follow-up projects.

Must-haves

To build a working energy storage demo environment in Technobothnia for use in education, research personnel and demonstrations

- A-CAES demo user manual
- A safety management plan
- Digitalize the demo (sensors)
- Recalculating previous project work
- Improving the heat exchanger
- Water-free air inlet for the compressor
- New and improved TES
- Repairing the leak between the compressor and the CAT
- Improving the efficiency rate of the CAES demo

→ Extra cooling for compression

→ Putting insulation on hot/cold parts

→ Second layer for the TES

→ Drop shape for the turbine

Should-haves

- Replace cooling water by thermal oil
- Theoretical calculations in Excel
- Optimal ratio between efficiency and air pressure for the turbine

Could-haves

- Possibility for noise reduction produced during the compression cycle
- Redoing the simulation for the turbine
- 3D printing the gears in metal
- Presentation video
- Presentation of future possibilities

Won't haves

- A liquid air storage with liquid nitrogen cooling, too expensive.
- A pumped hydro storage plant, it doesn't fit the size requirements.
- A clutch for the gears

WBS

A work breakdown structure (WBS) in Project Management is a key tool that helps organize the project into manageable steps. By breaking the project down into smaller components, the team gets a better general understanding of what work needs to be done and how it will be divided.

In this WBS the project is first sectioned into four steps: initiation, ideation, execution and project closure.

In the initiation phase there are the Project Management tasks that needed to be done and the necessary background research of the A-CAES demo. In the next phase: the ideation, all focus was put on troubleshooting to rebuild and improve the efficiency of the A-CAES demo. In the third phase: execution, the practical work and the actual rebuilding of the A-CAES demo needs to be done. Lastly, in the final phase: Project closure, there should be a final report and a final presentation as an outcome.

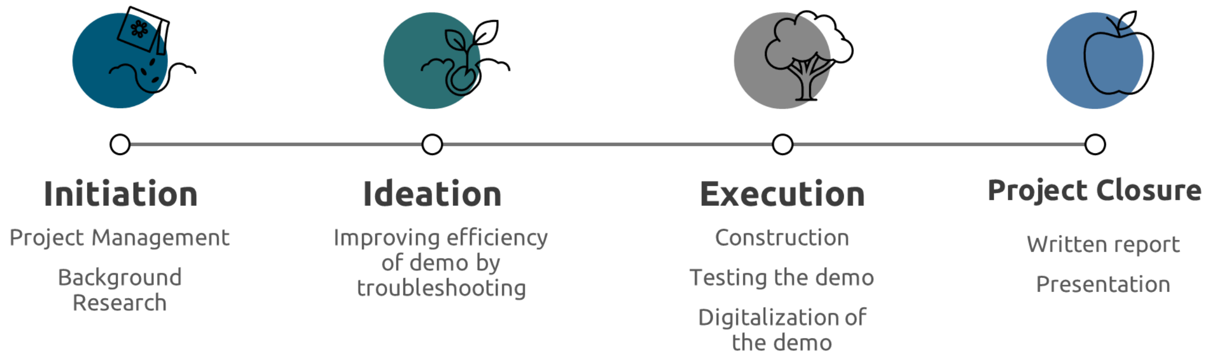

Figure 86 WBS summarized

Initiation

In the initiation phase a lot of emphasis is put on project management and how to work together in an international team with different fields of study. Furthermore the demo in its current state is researched and a general understanding of an A-CAES demo was developed.

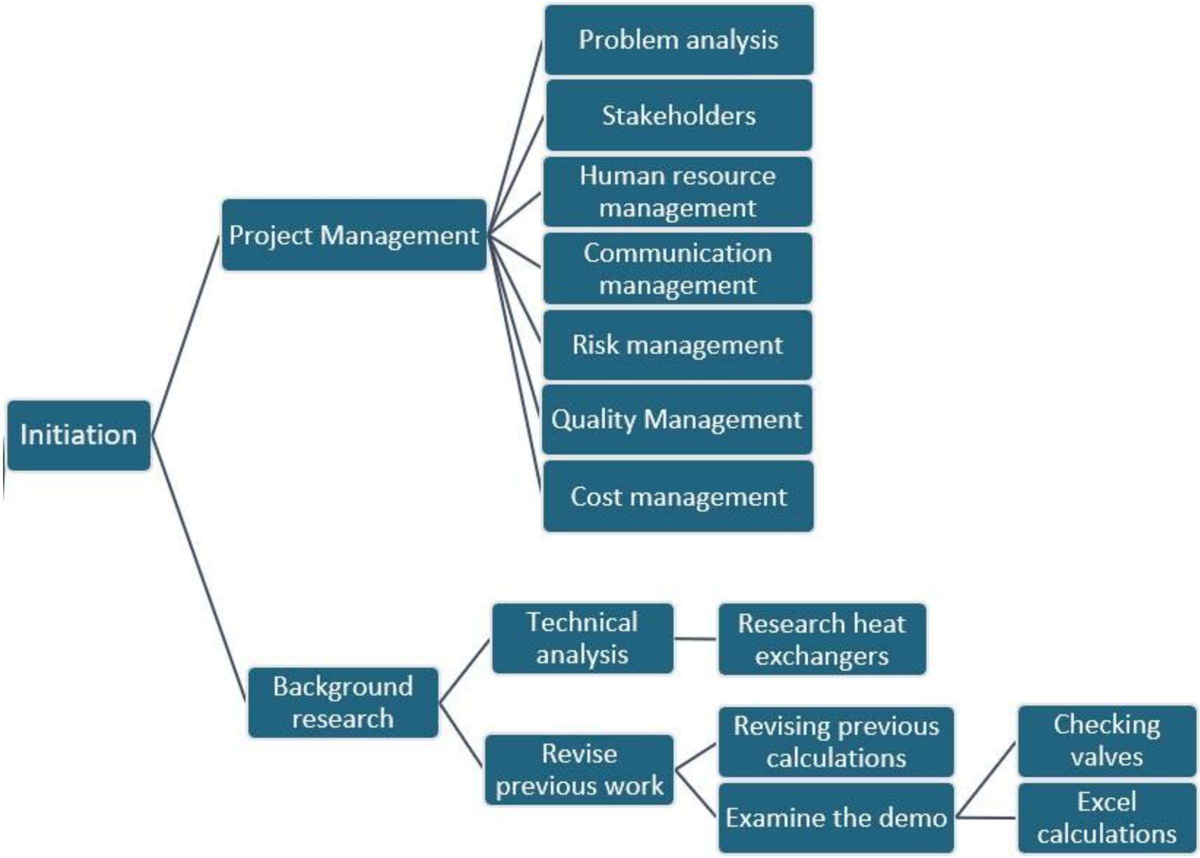

Figure 87 WBS initiation

Ideation

The ideation phase consisted of merely troubleshooting. The efficiency of the demo had to be improved and there were some illogicalities with its layout.

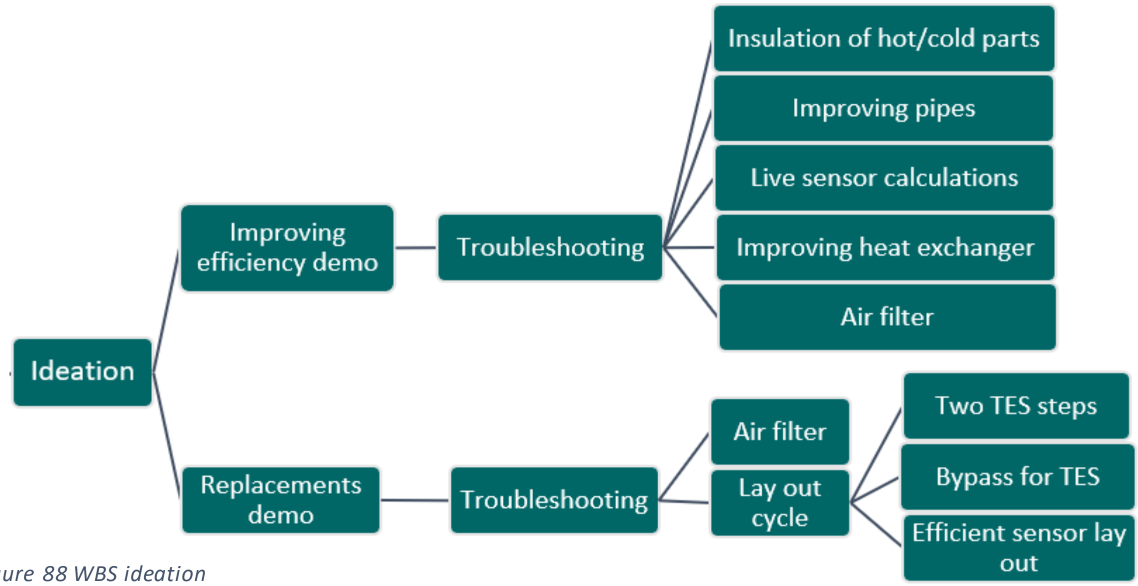

Figure 88 WBS ideation

Execution

In the execution phase the focus was put on the practical side of the A-CAES demo. All components to improve the demo and solve its problems had to be built. Afterwards numerous demo tests had to be done in order to reanalyze and revise the renewed demo.

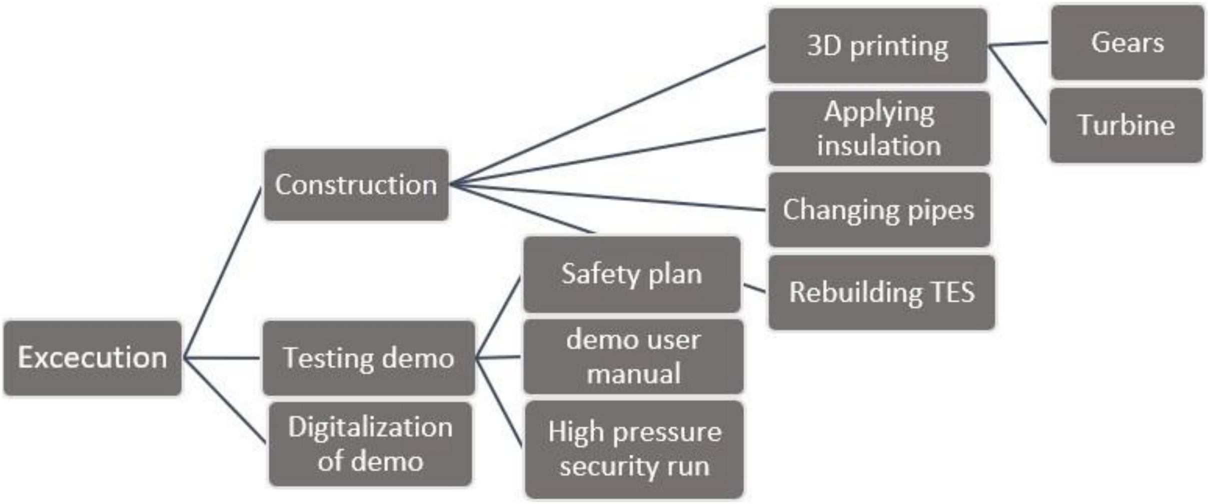

Figure 89 WBS execution

Finalization

In Project Closure the focus was put on the final deliverables of this project semester: a written report and a final presentation.

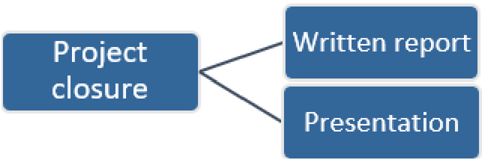

Figure 90 WBS filanization

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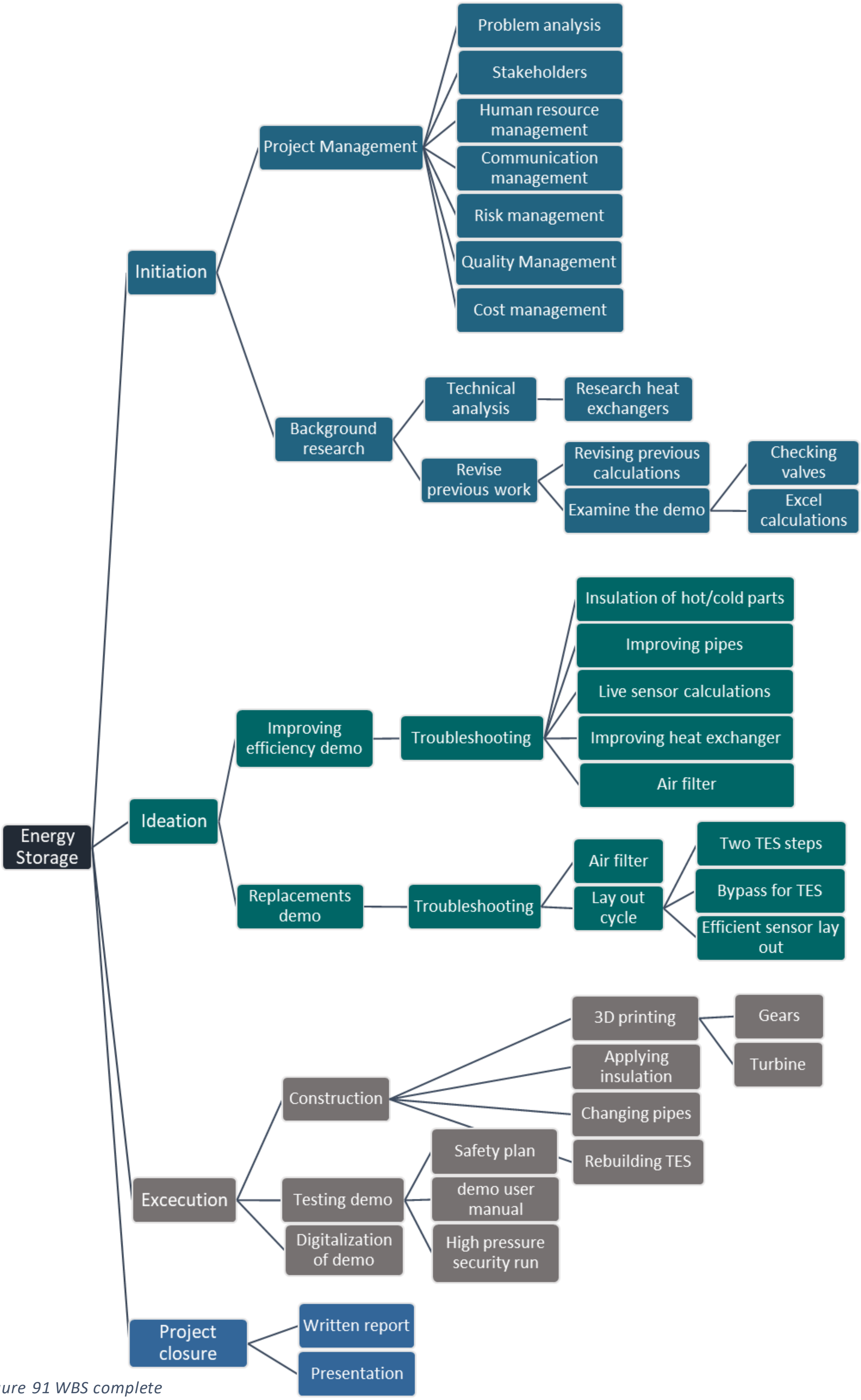

Figure 91 WBS complete

16.1.4 Scheduling the project

Critical Path method (CPM)

The CPM was developed by Du Pont and is a guidance tool to help identify the critical activities. A critical path is made by identifying the longest path of dependent activities and measuring the time required to complete them. In essence the CPM should avoid unforeseen delays.

ACTIVITY	PREDECESSORS	DURATION (days)
A) Revising calculations	-	7
B) General understanding	-	15
C) Project Management	-	37
D) Excel approximations	A	2
E) Checking demo	B	2
F) Pipes for first test run	D, E	3
G) Air filter	F	9
H) Test run	F	2
I) Research sensors	F	3
J) Milling	F	8
K) Pipes for the whole system	H	2
L) Insulation for TES	H	2
M) Buying sensors	I	3
N) Insulation for pipes	K	2
O) Midterm report	C	1
P) Building new TES	O	4
Q) Assembling the system	G, L, N, O,P	5
R) Installing sensors	M, Q	7
S) Tests runs	R	2
T) Analysis and Revision	S	6
U) Writing report	T	7

Table 16 CPM

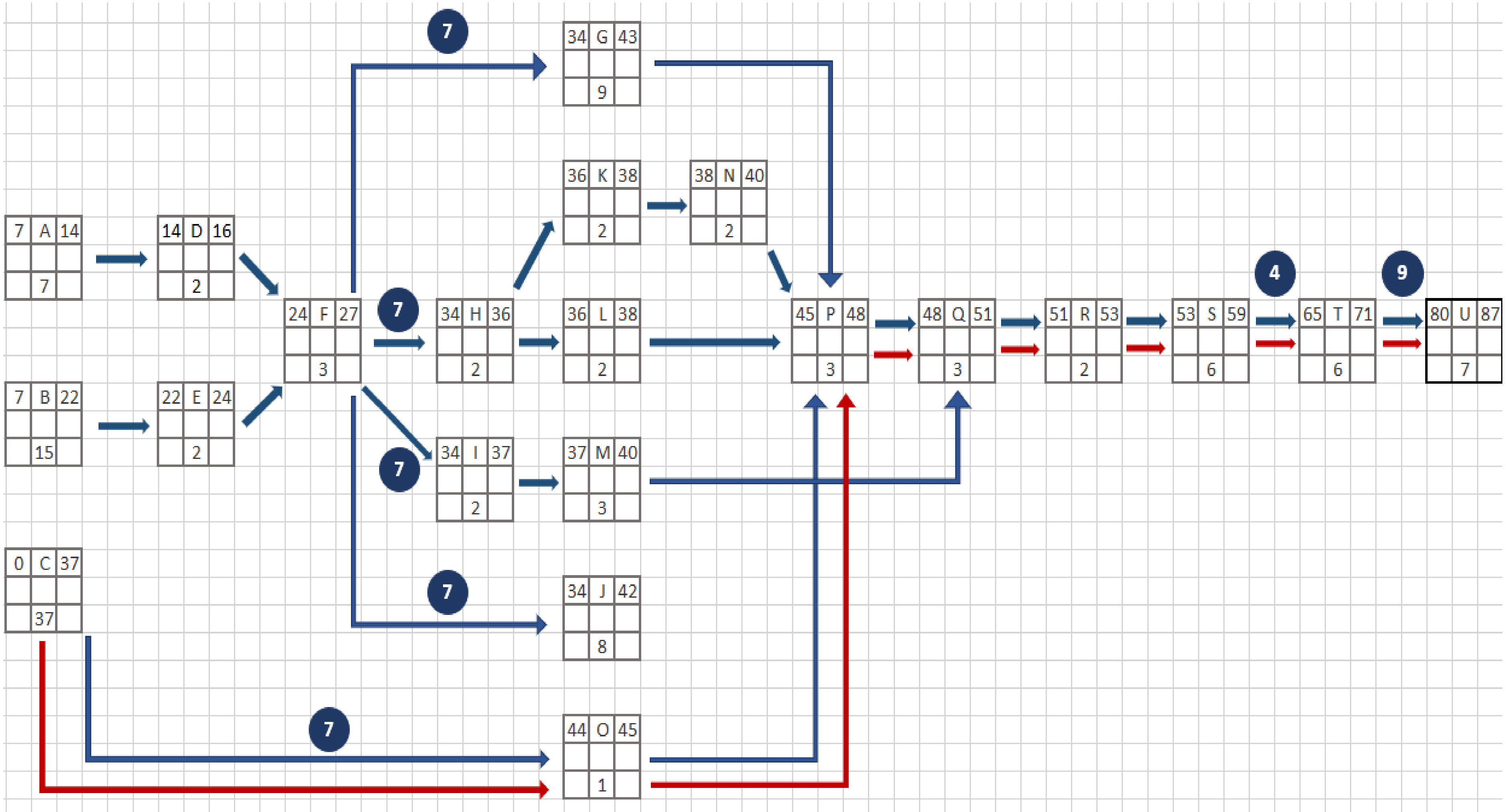

Figure 92 CPM

Gantt chart

A Gantt chart is a bar chart that illustrates a project schedule. This is a useful tool since it shows graphically what activities need to be finished before new ones .

EPS Energy Storage

Alvaro, Bjorn, Charlotte, Milan, Nona

Project Start Date 15/02/2021

Legend: On track | Low risk | Med risk | High risk

Milestone description	Category	Progress	Start	Days
Revising calculations	Med Risk	100%	15/02/2021	7
General understanding	High Risk	100%	15/02/2021	15
Project Management	Low Risk	80%	15/02/2021	37
Excel approximations	Low Risk	60%	22/02/2021	2
Checking demo	High Risk	50%	2/03/2021	2
Pipes for first test run	Med Risk	100%	11/03/2021	3
Air filter	High Risk		14/03/2021	9
Test run	On Track	100%	14/03/2021	2
Research sensors	On Track	100%	14/03/2021	3
Milling	High Risk		14/03/2021	8
Pipes for the whole system	On Track		16/03/2021	2
Isolation for TES	On Track		16/03/2021	2
Buying sensors	On Track	50%	17/03/2021	3
Isolation for pipes	Low Risk		18/03/2021	2
Midterm report	High Risk	100%	31/03/2021	1
Building new TES	High Risk		1/04/2021	4
Assembling the system	High Risk		5/04/2021	5
Installing sensors	Med Risk		10/04/2021	7
Test runs	High Risk		21/04/2021	2
Analysis and revision	High Risk		2/05/2021	6
Writing report	High Risk		8/05/2021	7

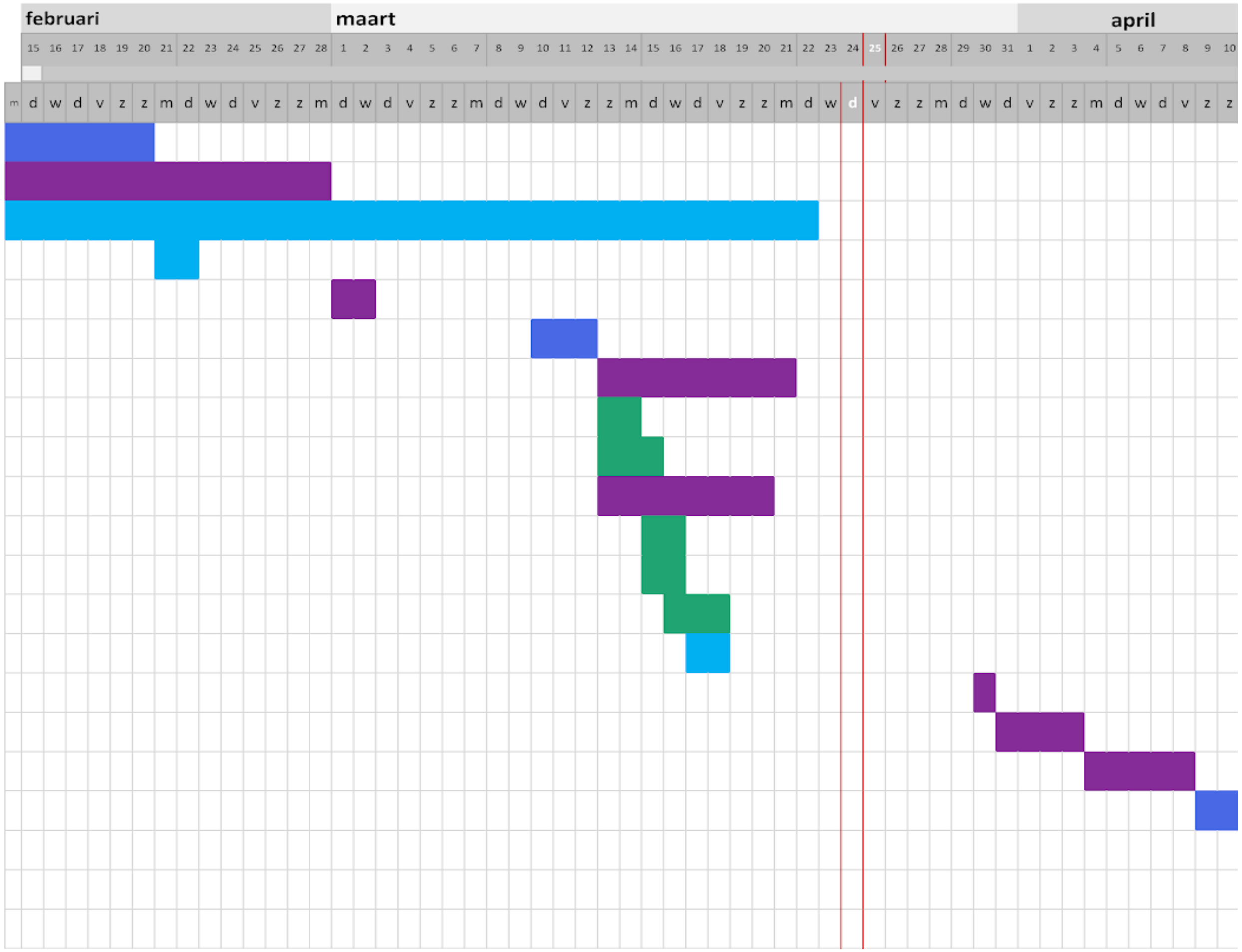

Figure 93 Gantt chart

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16.1.5 Human resource management

To discover the strengths and weaknesses of the group, the team made a Belbin test. The tool has been created by dr. Meredith Belbin for identifying team roles.

To deliver good team work, the group needed different people with diverse competencies and abilities. To get the project started, the group needed people with ideas and drive. Critical evaluators had to evaluate the ideas. Afterwards, someone was needed to coordinate the efforts. Every activity required some resources. Towards the end of the project, a shaper was needed to take the heat. Completers were necessary to ensure the project will be handed in on time. Team players were wanted for good teamwork.

Belbin identified nine roles: coordinator, shaper, plant, monitor, implementer, resource investigator, team worker and finisher.

All the team roles are divided over the 5 team members.

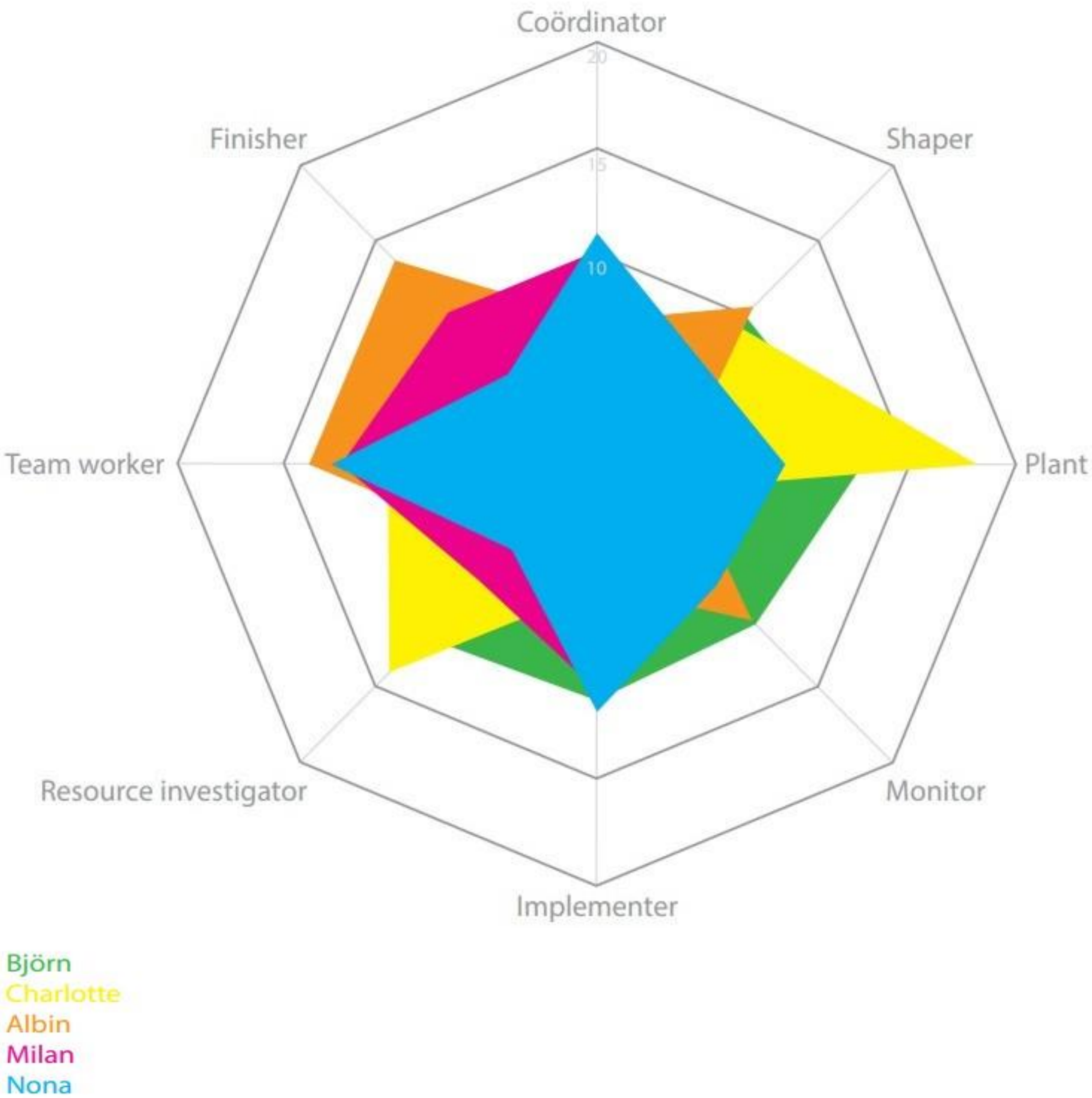

Figure 94 Belbin teamresults

Team members

All the team members made a Belbin test. Here, you can see the results of the Belbin test.

Nona Van Laethem

Nona was the implementer and coordinator of the group. In the following table, you can see the strengths and weaknesses of Nona.

Strengths	Weaknesses
Mature and confident	manipulative
Turns ideas into practical actions	offloads personal work
good chairperson	Slow to respond to new possibilities
clarifies goals	somewhat inflexible
promotes decision making	
delegates well	
Disciplined	
Reliable and efficient	
conservative	

Table 17 Strengths and weaknesses of Nona

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	2	0	2	1	2	1	2	0
2	2	1	1	0	2	1	3	0
3	1	1	2	2	0	2	1	1
4	2	2	1	1	2	0	2	0
5	0	1	2	2	2	0	1	2
6	1	0	0	2	2	1	2	2
7	3	2	1	0	2	1	0	1
Tot	11	7	9	8	12	6	11	6

think act

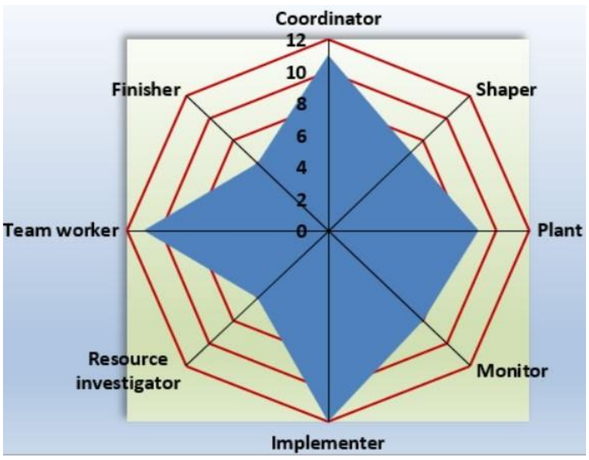

Figure 95 Nona's Belbin test

Milan Lemmens

The implementer and teamplayer of the group was Milan. In figure 23 are the strengths and weaknesses shown.

Strengths	Weaknesses
disciplined	somewhat inflexible
reliable	slow to respond to new
conservative	Indecisive in crunch situations
efficient	
turns ideas into practical actions	
diplomatic	
perspective	
mild	
Co-operative	

Table 18 Strengths and weaknesses of Milan

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	1	1	2	1	2	2	1
2	2	1	1	0	2	0	2	2
3	1	1	1	0	0	2	2	3
4	2	0	1	1	2	1	2	1
5	2	0	2	0	3	2	1	0
6	1	0	0	3	2	1	1	2
7	2	2	2	0	1	0	2	1
Tot	10	5	8	6	11	8	12	10

think ← | → act

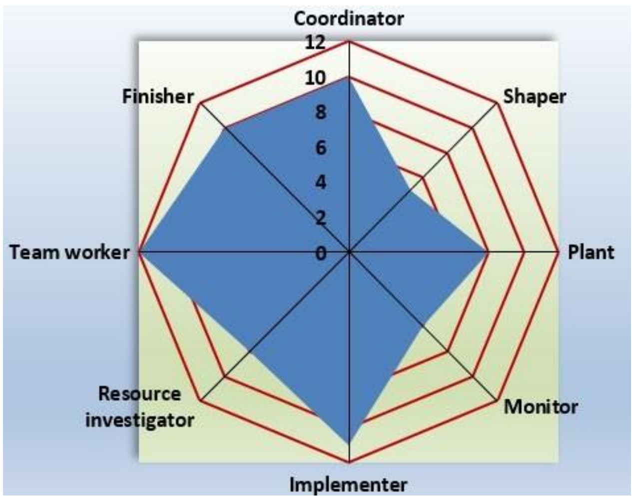

Figure 96 Milans Belbin test

Álvaro Revilla-Martin

Alvaro was clearly the finisher and shaper of the group. In figure 25 are the strengths and weaknesses shown.

Strengths	Weaknesses
challenging	prone for provocation
dynamic	offends people's feeling
drives	inclined to worry unduly
thrives on pressure	reluctant to delegate
has the courage to overcome obstacles	
painstaking	
anxious	
conscientious	
searches out errors and omissions	

Table 19 Strengths and weaknesses of AlvaroStrengths and weaknesses of Alvaro

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	2	0	1	1	0	2	2	2
2	0	2	0	1	1	1	3	2
3	1	2	1	2	0	1	2	1
4	2	1	0	1	2	0	2	2
5	1	1	0	2	1	0	1	4
6	0	1	0	3	2	2	0	2
7	1	4	2	1	0	0	1	1
Tot	7	11	4	11	6	6	11	14

think act

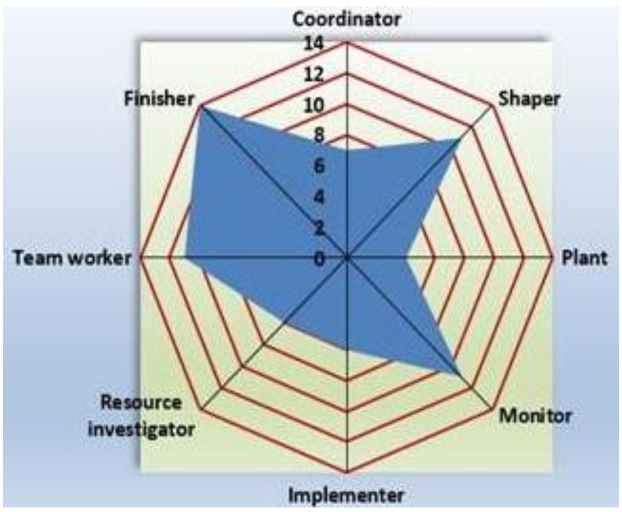

Figure 97 Alvaro's Belbin test

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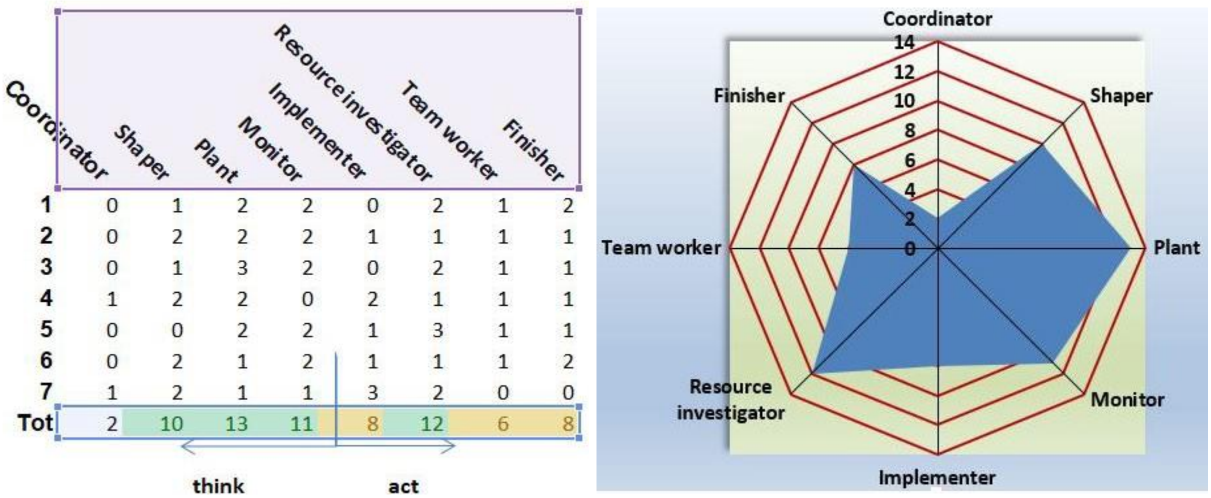
Björn Graul

Björn fulfilled the team role of plant and resource investigator. Take a look at figure 27 to get an overview of the strengths and weaknesses of the team members.

Strengths	Weaknesses
extrovert	over-optimistic
enthusiastic	interest once initial enthusiasm has passed
communicative	ignores incidentals
explores opportunities	too preoccupied to communicate effectively
develops contacts	
creative	
imaginative	
unorthodox	
solves difficult problems	

Table 20 Strengths and weaknesses of Björn



	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	1	2	2	0	2	1	2
2	0	2	2	2	1	1	1	1
3	0	1	3	2	0	2	1	1
4	1	2	2	0	2	1	1	1
5	0	0	2	2	1	3	1	1
6	0	2	1	2	1	1	1	2
7	1	2	1	1	3	2	0	0
Tot	2	10	13	11	8	12	6	8

Figure 98 Björns Belbin test

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Charlotte Hargreaves

Charlotte had the same team roles as Björn: plant and resource investigator.

Strengths	Weaknesses
extrovert	over-optimistic
enthusiastic	interest once initial enthusiasm has passed
communicative	ignores incidentals
explores opportunities	too preoccupied to communicate effectively
develops contacts	
creative	
imaginative	
unorthodox	
solves difficult problems	

Table 21 Strengths and weaknesses of Charlotte

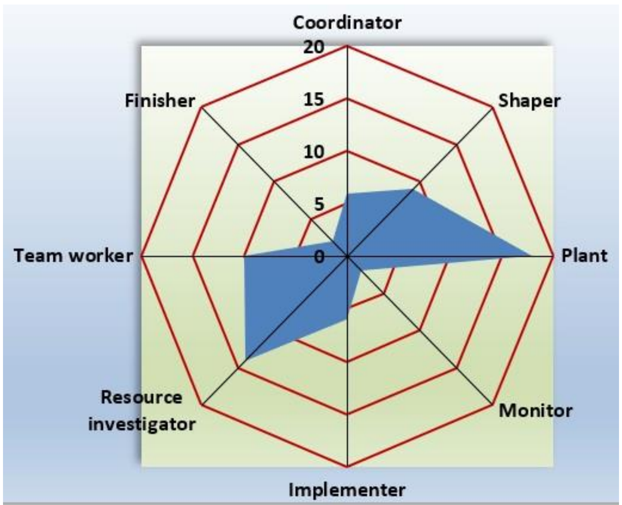

Figure 99 Charlotte's Belbin test 1

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	3	3	0	1	0	3	0
2	1	1	3	0	0	3	1	1
3	1	0	2	2	0	2	3	0
4	3	1	3	0	0	0	3	0
5	1	1	1	0	1	3	0	0
6	0	1	3	0	2	3	0	1
7	0	2	3	0	2	3	0	0
Tot	6	9	18	2	6	14	10	2

think **act**

Figure 100 Charlotte's Belbin test 2

16.1.6 Communication management

Stakeholders

The project had diverse stakeholders with different interests.

There is a partnership between three universities: Novia UAS, Vaasa UAS and Åbo Akademi University. The universities want to give the students a good working system where students can learn from. The project was funded by EU Regional Development Funds and project partners. The supervisor, Cynthia Söderbacka, was mainly overseeing and steering the project. The team members were: Milan Lemmens, Álvaro Revilla-Martin, Nona Van Laethem, Charlotte Hargreaves and Björn Graul. The group worked at Technobothnia.

Communication plan within the group

Communication management was an important part of the Energy Storage project. The management made the team aware of the objectives that needed to be achieved within a certain time.

In order to work efficiently, the team had agreed to make some arrangements.

The team had defined certain roles: Communication Director, Meeting Director, Check Director, Finance Director / Technical Leader and Social Director.

Communication Director: Nona Van Laethem

The communication director was made accountable for the communication outside the project group. The responsible person was in direct contact with the supervisor Cynthia, sponsors or other stakeholders. Furthermore, the subject had to make the presentations for meetings.

Meeting Director: Charlotte Hargreaves

The meeting director was responsible for: planning intern and extern meetings, the discussion points, the efficiency of meetings, notations during meetings and guiding the team. Thereafter, the meeting director was made accountable for short- and long term schedules and updates on Monday.com. It's a powerful platform that helps you manage and track all your work in one place.

Check Director: Álvaro Revilla-Martin

The check director was the finalizer of the team. The responsible person supervised: spelling / grammar, the state of affairs, the completeness of the task and that every assigned job was done.

Finance Director and Technical Leader: Björn Graul

The finance director was made accountable for the budget. As a technical leader, Björn Graul had a wide overview of all the technical problems and matters. The responsible person helped the team members with any difficulties that may arise during the project.

Social Director: Milan Lemmens

The social director was responsible for the atmosphere in the group. Milan Lemmens was the first person to contact if anyone had personal or group related problems. Furthermore, the social director had organized activities for the team to avoid disunity and to ensure good team dynamics.

Communication plan inside the group

There was a weekly meeting to update the team members and to divide tasks. Furthermore, the objective was to have fluid and responsive communication.

The team used an external application called Monday.com. It is a useful tool for project management. The platform allows the team members to keep track of deadlines, meetings, division of tasks and state of affairs .

Communication plan outside the group

Nona was responsible for the communication outside the group. The EPS group member informed Cynthia and other stakeholders. There was a weekly meeting with Cynthia to keep her updated. If we had urgent questions, we could always contact Cynthia on WhatsApp. The meetings were at Technobothnia or online with Teams. That was depending on the restrictions from the government.

16.1.7 Risk management

In risk management, There are some situations that needed to be avoided. All the components are listed with their own risks in the images underneath. A score will be determined on how substantial a consequence will be depending on the risk. This will be described as the severity of the risk.

Occurrence of a risk will give an overview on how many times in a certain period the risk will appear. Knowing the potential origin of the risk, indicates the possibility of preventing this scenario. The actions taken will help to reduce the occurrence or severity.

While there's a determination possible, it doesn't indicate how simple the risk can be identified. A score will be obtained based on the difficulty to find the risk.

When the severity, occurrence and determination are set on, all the factors can be multiplied with each other. That action will give a specific number, depending on the size of the number. The risk can be judged between tolerable and monitored really closely.

In the risk assessment there is an overview when a risk should be less/more taken care of.

Air Circulation Demo

Proces Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Causes	OCC	Current process Controls	DET	RPN	SEV X OCC
What step?	How can it go wrong?	What is impact on customer if failure mode is not prevented or corrected?	How severe is effect on customer?	What causes step to go wrong?	How frequent is the cause likely to occur?	What are the existing controls that prevent failure mode from occuring or detect it should occur?	propability of detection of failure mode or its cause?	RPN calculated as SEV x OCC x DET	SEV X OCC
Compressor	pressure drop	negative influences on following components	7	too much turns, too much pipe distance	7	decrease pipe distance, avoid turns, measure the pressure	4	196	49
	compress liquid	liquid can't be compressed, compressor will be broken	10	no good evaporation of the liquid	2	liquid is heated enough to turn it into a gas	10	200	20
	cavitation	compressor will be damaged	8	static pressure drops below a dangerous area	3	a softstarter to avoid cavitation	9	216	24
	overload	compressor will shut down after too much current	8	load force is too high	6	overload protection	1	48	48
CAT	overpressure	tank will explode	10	too much pressure than the tank can hold	1	pressure regulator	3	30	10
	pipes leaking	pressure/efficiency loss	8	bad quality of material, material fatigue	2	cover leaks, replace with new and different material of pipes	9	144	16
TES	rising temperature of cooling water	temperature of cooling water higher than should be	2	liquid inside the pipes is too hot	10	decrease temperature of liquid	1	20	20
	unefficient heat exchange	potential heat exchange efficiency percentage can't be reached	1	bad construction of the exchanger	10	a more efficient construction to exchange heat	1	10	10
Turbine	of weak material	material can depose while the process is running	6	/	10	reconstruct turbine in a different strong material	9	540	60
	center point of turbine not laminear	will be a resistance in airflow that will decrease efficiency of process	6	bad shape of the center point	10	reconstruct center point into shape of water drop to make it laminear and increase the efficiency	8	480	60
Generator	Overload	generator shuts down after too much current	8	load force too high	6	overload protection	1	48	48
	bad transition of gears	mechanical energy can't be transformed into electrical energy	9	gears are broken, torque is too high to handle for gears	2	adjust gears to right level of power transaction	5	90	18

Table 22 Air circulation demo

Liquid Circulation Demo

tep+A:TE8A1:T	Potential Failre Mode	Potential Failure Effect	SEV	Potential Causes	OCC	Current process Controls	DET	RPN	SEV X OCC
What step?	How can step go wrong?	What is impact on customer if failure mode is not prevented or corrected?	How severe is effect on customer?	What causes step to go wrong?	How frequently is the cause likely to occur?	Existing controls that prevent failure mode from occuring or detect it should occur?	How propable is detection of failure mode or its cause?	Risk priority number calculated as SEV x OCC x DET	SEV X OCC
Compressor	pressure drop	negative influence on following components	7	too much turns, too much pipe distance	7	decrease pipe distance, avoid turns, measure the pressure	4	196	49
	compress liquid	liquid can't be compressed, compressor will be broken	10	no good evaporation of the liquid	2	liquid is heated enough to turn it in to a gas	10	200	20
	cavitation	compressor will be damaged	8	static pressure drops below a dangerous area	3	netto Positive Suction Head (NPSHa, NPSHrp)	9	216	24
	overload	compressor will shut down after too much current	8	Load force too high	6	overload protection	1	48	48
TES	rising temperature of the cooling water	temperature of the cooling water rises too high	2	liquid inside the pipes is too hot	10	decrease the temperature of the liquid	1	20	20
	unefficient heat exchange	potential heat exchange efficiency percentage can't be reached	1	bad construction of the exchanger	10	make a more efficient construction to exchange heat	1	10	10
Water pump	cavitation	waterpump will be damaged	8	static pressure drops below a dangerous area	3	netto Positive Suction Head (NPSHa, NPSHrp)	9	216	24
	overpressure	load force will increase	9	load force too high	4	overload protection, pressure valve	2	72	36

Table 23 Liquid Circulation Demo

Risk Assessment

Severity		happening of occurrance				
		Highly likely (10)	Likely (8)	Possible (6)	Unlikely (4)	Remote (2)
	Fatality (5)	50	40	30	20	10
	Severe (4)	40	32	24	16	8
	Major (3)	30	24	18	12	6
	Minor (2)	20	16	12	8	4
	Superficial (1)	10	8	6	4	2

Table 24 Risk Assessment

Ishikawa Diagram

The goal of the Ishikawa-diagram is to acknowledge the factors that make a possibility of making a problem within a project or on the work floor. Every potential cause to a problem needs to be monitored through the period when the project is running.

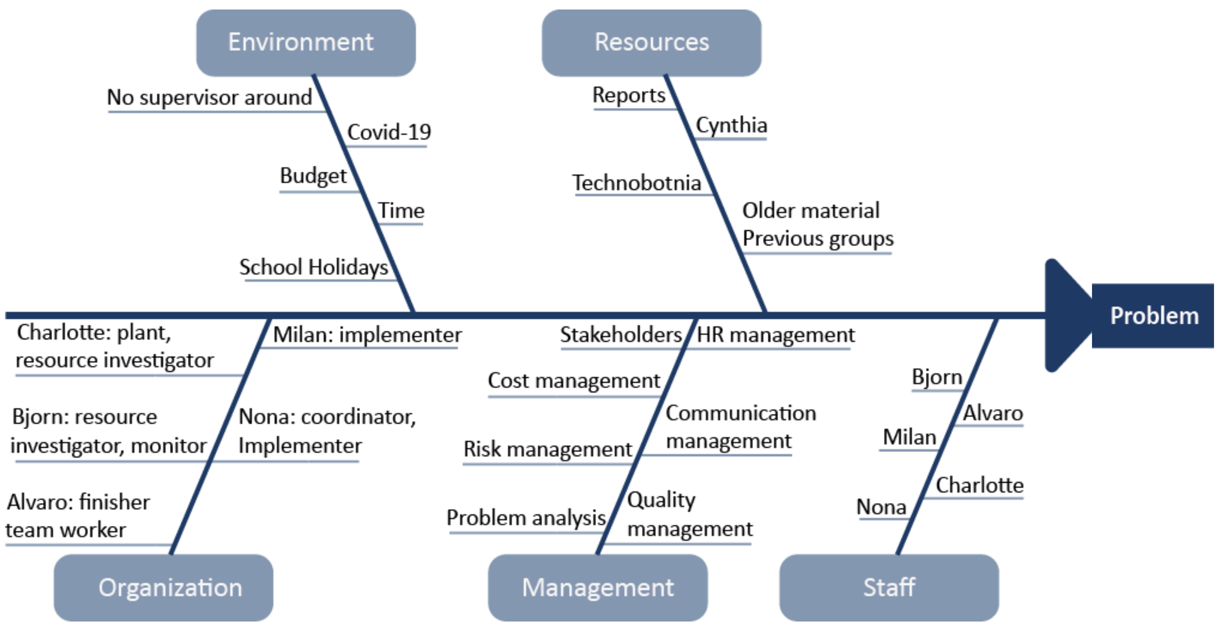

Figure 101 Ishikawa Diagram

16.1.8 Quality management

good quality management was required to effectively ensure product quality from project planning to delivery. The seven quality management principles are:

- Customer focus
- Leadership
- Engagement of people
- Process approach
- Improvement
- Evidence-based decision making
- Relationship management

These management principles will be used as a foundation to improve the organization and performance of our project.

Since a project’s failure/success inevitably depends on proper quality management, a plan was set up. A quality management plan consists of input, tools, technique and output. The input is the foundation for the output that defines the overall quality. The tools and techniques are used to reassure the right input.

Input **Tools and Techniques** **Output**

Figure 102 Quality management

16.1.9 Cost management

The Energy Storage team received a budget of 1000€ to finish the A-CAES demonstration. The EPS-student team decides which components are required. If Cynthia Söderbacka agrees, the components will be purchased. The Energy Storage team has access to the laboratory of Technobothnia and their resources are the same as for the program licenses at Novia University. The students are not paid for their labor. For further calculations the assumption is made that every student participating receives the Finnish average.

Students are not entitled to an hourly wage and are directly under the school to fulfil their tasks. Nevertheless, an estimation has to be made based on the average hourly wage of a working Finn, which is equal to 27 Euros per hour. It is assumed that each student spends an average of 35 hours per week on the project for a continuous period of 16 weeks. It is also assumed that everyone has an equal number of working hours, giving a total of 2800 hours. Multiplying these working hours by the average hourly wage yields a cost of 75,600 euros.

Names	Working hours
Nona	560
Alvaro	560
Charlotte	560
Björn	560
Milan	560
TOTAL	**2800h**

Table 25 Working hours

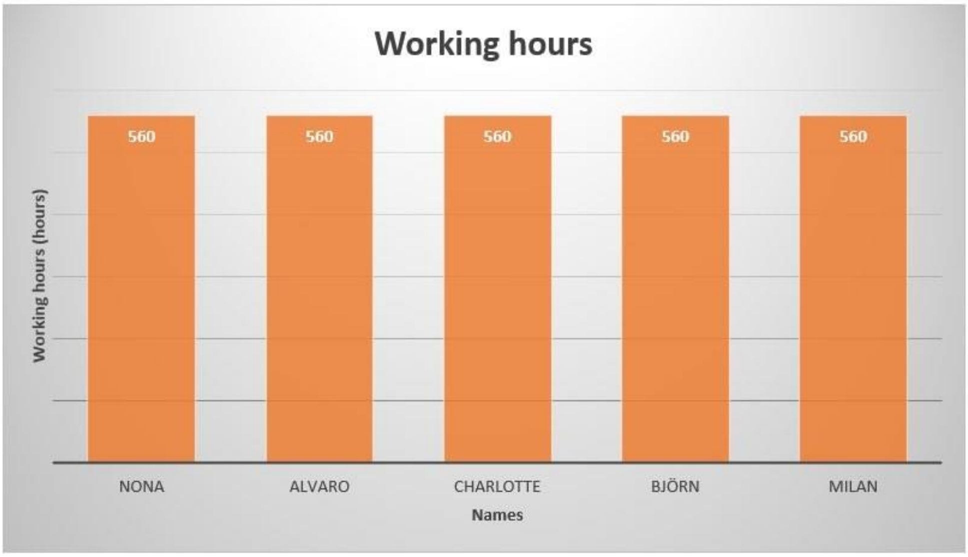

Figure 103 Working hours table graph

The image underneath represents the costs that have already happened and the costs that still need to happen. The grant total includes the costs that happened. The estimated cost is data that is not guaranteed and based on assumptions.

4/03/2021	Price	Quantity
42010204/V 10920104/V / 42010404/V L=1	€ 25,31	1
R 1/8"UF X R 1/8"UF	€ 0,90	1
R 1/8" kumiteräsprikka	€ 0,28	1
R 1/4" uk x JIC 7/8" uk	€ 0,64	1
TOTAL BILL 1	**€ 27,13**	

GRANT TOTAL	**€**	**312,96**

Expenditures that still need to be made	Price	Quantity
Copper pipes	€ 300,00	/
Small air filter	€ 15,00	1
Oil/water seperator (filter)	€ 300,00	1
Isolation	€ 50,00	/
Digital pressure sensors	€ 67,00	1
Pipes for water system	€ 30,00	/
Pipes for air system	€ 250,00	/
Isolation for the TES	€ 35,00	1
TOTAL ESTIMATED COST	€ 1.047,00	

25/03/2021	Price	Quantity	
Palloventtilli DN G 1/4"	€ 61,20	4	**Valves**
R 1/4" sk x sk x sk x sk ristiilitin	€ 34,56	1	
R 1/4" UF X R 1/4"UF	€ 5,05	4	
R 1/4" UF R 1/4" IR	€ 9,48	4	
R 1/4" kumiteräsPrikka	€ 2,66	8	
Palloventtilli DN G 1/4"	€ 15,30	1	**Other coupling + valves**
R 1/4" IR R 1/4" IR	€ 2,32	1	
R 1/4" kumiteräsPrikka	€ 0,33	1	
R 1/4"UF X R 1/4"UF	€ 1,26	1	
R 1/4" UF/UF/IR T	€ 9,38	1	
R 1/8"IR R 1/4" IR	€ 2,52	1	
R 1/4"UF X R 1/4"UF	€ 1,26	1	
R 1/4" kumiteräsPrikka	€ 0,33	1	
42010404/V / /V / /V L=0	€ 6,75	1	
R 1/8"UF X R 1/8"UF	€ 1,00	1	
R 1/8" kumiteräsprikka	€ 0,31	1	
42010404/V / /V / /V L=0	€ 7,55	1	
42010404/V / 11056304/V / /V L=0,5	€ 10,32	1	
R 1/4"UF X R 1/4"UF	€ 3,79	3	
R 1/4" kumiteräsPrikka	€ 1,00	3	
010404/V / 11056304/V / 42010404/V L=	€ 9,96	1	
42010404/V / 11056304/V / /V L=0,2	€ 8,17	1	
R 1/4" UF R 1/4" IR	€ 2,37	1	
R 1/4" kumiteräsPrikka	€ 0,33	1	
Auton lämmittimenletku 10 mm	€ 17,06	5,00m	
R 3/4" sk x R 3/4" sk MS	€ 6,43	1	
R 3/4" uk x R 3/8" sk MS	€ 3,71	1	
R 3/8" uk 3/8" MS	€ 10,89	3	
R 1" uk x R 3/8" sk MS	€ 16,47	2	
Kaksoisnippa B11 R1/8-R3/8 uk	€ 9,19	2	
G3/8"IR 3/8"	€ 8,21	2	
Nippuside 390x4,6 T50L	€ 16,67	100	
TOTAL BILL 2	**€ 285,83**		

Table 26 Cost management 1

The cost baseline is an assumption on how the funding is spread through the period when the project is active. The *expenditures* are the actual costs that have been made. On week 8 (now), the biggest expenses are going to take place when the team is in the execution phase.

In the beginning of week 8 to week 12, the other costs that need to be incurred are spread out. The following weeks are equal to the costs assumed in the cost baseline.

	Cost baseline	**Cummulative**
week 1	€ 0,00	€ 0,00
week 2	€ 0,00	€ 0,00
week 3	€ 50,00	€ 50,00
week 4	€ 50,00	€ 100,00
week 5	€ 100,00	€ 200,00
week 6	€ 100,00	€ 300,00
week 7	€ 100,00	€ 400,00
week 8	€ 400,00	€ 800,00
week 9	€ 200,00	€ 1.000,00
week 10	€ 200,00	€ 1.200,00
week 11	€ 200,00	€ 1.400,00
week 12	€ 200,00	€ 1.600,00
week 13	**€ 200,00**	**€ 1.800,00**
week 14	**€ 200,00**	**€ 2.000,00**
week 15	**€ 0,00**	**€ 2.000,00**
week 16	**€ 0,00**	**€ 2.000,00**
TOTAL		€ 2.000,00

	Expenditures	**Cummulative**
week 1	€ 0,00	€ 0,00
week 2	€ 27,13	€ 27,13
week 3	€ 0,00	€ 27,13
week 4	€ 0,00	€ 27,13
week 5	€ 0,00	€ 27,13
week 6	€ 0,00	€ 27,13
week 7	€ 285,83	€ 312,96
week 8	€ 315,00	€ 627,96
week 9	€ 300,00	€ 927,96
week 10	€ 117,00	€ 1.044,96
week 11	€ 280,00	€ 1.324,96
week 12	€ 235,00	€ 1.559,96
week 13	**€ 200,00**	**€ 1.759,96**
week 14	**€ 200,00**	**€ 1.959,96**
week 15	**€ 0,00**	**€ 1.959,96**
week 16	**€ 0,00**	**€ 1.959,96**
TOTAL		€ 1.959,96

	Fundings	**Cummulative**
week 1	€ 1.000,00	€ 1.000,00
week 2	€ 0,00	€ 1.000,00
week 3	€ 0,00	€ 1.000,00
week 4	€ 0,00	€ 1.000,00
week 5	€ 0,00	€ 1.000,00
week 6	€ 0,00	€ 1.000,00
week 7	€ 0,00	€ 1.000,00
week 8	€ 1.000,00	€ 2.000,00
week 9	€ 0,00	€ 2.000,00
week 10	€ 0,00	€ 2.000,00
week 11	€ 0,00	€ 2.000,00
week 12	€ 0,00	€ 2.000,00
week 13	€ 0,00	€ 2.000,00
week 14	€ 0,00	€ 2.000,00
week 15	€ 0,00	€ 2.000,00
week 16	€ 0,00	€ 2.000,00
TOTAL		€ 2.000,00

Table 27 Cost management 2

The categories cost baseline, expenditures and funding are shown in the graph. expenditures started later than was foreseen, after week 6 the progression was made and catched up with the cost baseline. The costs that need to be made are already included in the expenditures to have a view on how good the expenditures are on schedule.

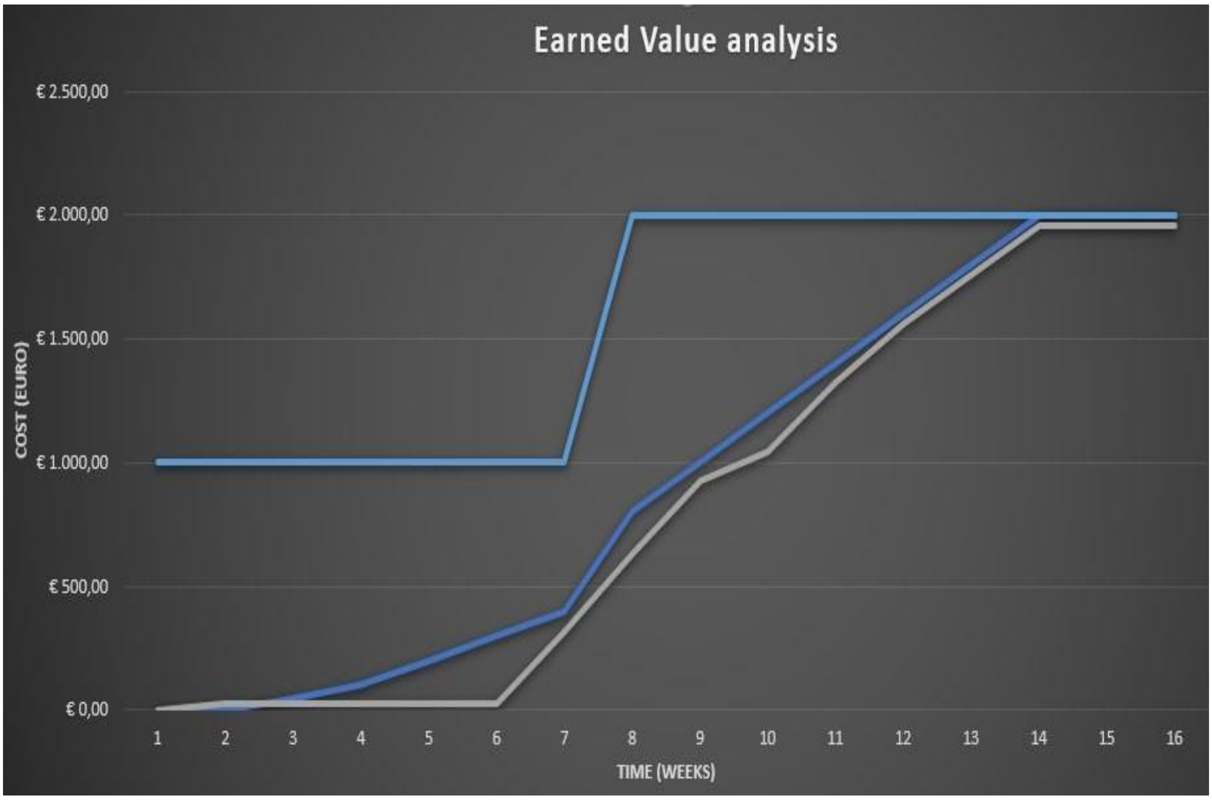

Figure 104 Earned value analysis

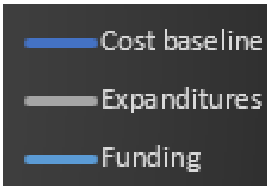

Figure 105 Earned value analysis legend

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