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Energy storage demo environment in Technobothnia

Adiabatic Compressed Air Energy Storage demo

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Abstract

This report deals with the research, design and construction of a Compressed Air Energy Storage (CAES) demo, which was built by a group of students, taking part in the European Project Semester program.

In the research about Compressed Air Energy Storage it was concluded, that the biggest problem is temperature change of the air, through the system. During compression the pressure and temperature increase, which leads to energy loss. During expansion the pressure and the temperature decrease. To solve this problem, there are three different methods of CAES: Diabatic, Adiabatic and Isothermal Compressed Air Energy Storage. An Adiabatic-CAES is the most suitable method to store energy in a small scale demo. This is because a Diabatic-CAES needs fossil fuels to heat the air. Isothermal-CAES is still in development, which increases the costs and the complexity.

With further research about possible components and calculations, a selection of individual components for the system was made. The compressor, air tank, pressure regulator, air motor, pipes, valves, generator and water pump are standardized component, which were acquired through the university or bought from local companies.

The air turbine was designed by the project team, because the air motor does not have a high efficiency and commercial air turbines were out of the budget. A 3D model was created in Solid Works and then the device was 3D printed.

Thermal Energy Storage (TES) was also designed by the project team. With a numerical simulation, using MatLab the necessary dimensions and properties of the TES were determined in order to design and build the TES.

All the components were assembled on the demo table. All the components where tested individually and worked as expected. The overall performance of the system could not be tested, because the air motor did not arrive on time and there is a air leakage what could not be solved in time.

To complete the system, the leakage should be closed and the air motor should be installed. After performing individual test of the components the conclusion has been made, that the capturing of the heat and giving it back to the air, could be improved.

Contents

1 Introduction

A sustainable energy storage system is one of the most important part in the transition to make it possible to make the energy market more sustainable. All around the world people want to have a cleaner environment, for example the European Union wants to be completely decarbonized by 2050. This requires a lot of renewable energy sources, but they have a great disadvantage compared to fossil sources. Renewable energy sources are highly fluctuating, due most of them their dependence on sun and wind. This means that the energy generated with renewable energy sources can not meet the energy demand at any given time, due to weather conditions and the shifting position of the sun throughout the day and season changing. To meet the demand of having electricity(energy) at any given moment of the day, it is important to store the surplus energy so it can be used when there is no energy generated.

The Energilagring project is a partnership of three universities, the University Novia UAS, Vaasa UAS (VAMK) and Åbo Akademi University. The Energilagring project have the objective to "build an energy demo environment comprising different energy storage technologies to promote energy storage competence growth in the region". Therefore, the Energilagring project gave the EPS project the mission to build an energy storage model, that allows students to gain deeper insights into the principles of the technology. There are many energy storage solutions but this project will focus on Compressed Air Energy Storage systems. The objective of the project is to build a Compressed Air Energy Storage demo

This report provides information about why this project will focus on Compressed Air Energy Storage (CAES). Also, an insight on the theory of CAES technology and how to demo is built. Finally, recommendations will be made about how the demo could be improved and used for education, research and demonstrations purposes. This report is mainly made for the EPS program that is why the report starts with a chapter about project management.

2 Project management

In this section the goal of this project will be described, with the requirements that are given the aim of the project will be clarified. The different stakeholders of this project will be introduced with their responsibility and benefits. In addition, a human resource, communication, risk, quality and cost management plan is made to give a clear view of the organizational structure from this project. Moreover, how this project could be worked on as best.

2.1 Problem analysis

The energy storage in Our Low Carbon Society (Engergilaring) project has an objective of building an energy storage demonstration environment in Technobothnia Education & Research Center. The aim is to promote energy storage know-how by bringing the practical aspect of energy storage to education.

The goal of this EPS-group will be to build a Compressed Air Energy Storage demo in Technobothnia. The following requirements and conditions needs to be considered. The demo has to be suitable for learning purpose. So there has to be a manual so students can work independently with the experiment set-up. The system should have some changeable parameters, so students can research the influence of this variables on the efficiency of the system. The experiment with the demo has to be finished within 3 hours. Safety of the students is priority one. The amount of energy storage has to be enough to light a bulb. The demo can not make to much noise, because other students have to work in the same lab. For the same reason the set-up has to work independent from other projects. The set-up can not by higher then 4,5 meters and has to be compact, so it fits in the energy lab of Technobothnia. The budget for the project is €9.000,-.

The project will start at 9-9-2019 and ends at 18-12-2019. The focus of this project will lay on building the demo. Even though the exact working points for the students have been identified, the exact work layout of the lab exercises are out the scope of the task.

With the different requirements and previous research of the Energilagring-project a decision about the sort energy storage has to be made. Novia UAS is responsible for the EPS-group, so the group will work further on the research already done by this university. That means that the decision has to be made between the following principles: hydro pump, compressed air energy storage and liquid air storage.

- *Pumped hydro*
  In pumped hydro storage plants, the energy is stored in the form of potential energy from water that is pumped into a higher basin and then converted back into electricity by flowing off via a turbine with a connected generator. Pumped storage power plants are technically mature and currently the only storage technology in Europe that can be used to any appreciable extent. The requirements state that the demo can not be higher then 4,5 meters. This means that an imitated high has to be created to really show the principle.

- *Compressed air energy storage*
  Excess electricity is used to press air into underground salt domes or former gas caverns (compression). When electricity is needed, the compressed air flows through a turbine and generates electricity again. The heat generated during compression can be used to improve efficiency. This system meets the requirements. A nice challenge is to look into the efficiency of the system with adding a heat storage.

- *Liquid air energy storage*
  Liquid air storage was already investigated by Shiva Sharma(Project Researcher in Novia) and he concluded that it would not fit in the budget. That means this set-up will not meet the requirements.

With this in mind the EPS-group decided on a compressed air energy storage demo the energy lab in Technobothnia. The main objectives that will be delivered on 18-12-2019 are a compressed air energy storage demo, a manual how to use the demo and a final report. In the beginning of the project a schedule with all the different objectives will be made and more clarified. In the appendix a table with the described objectives can be found.

2.2 Stakeholders

This section will inform about all the different stakeholders and how this project will benefit them.

European project semester

The project is commissioned by Novia university of applied science, a multi-professional university of applied sciences (UAS) with campuses located in five cities in Finland. They offer high quality practice-oriented higher education at both Bachelor's and Master's levels as well as further education in Swedish and English. (Novia, 2019)
Since 1994 European Project Semester (EPS), has become a huge success. Within a EPS, students work in international and interdisciplinary teams of 3–6 students on a project. Beside the project the semester consist of short courses. At Novia university of applied science, the different courses are team building, project management, English academic writing and local language Swedish.

Energilagring-project

The stakeholder of the project is the: Energy Storage in Our Future Low Carbon Stociety (Energilagring!)-project, later referred to as Energilagring-project. The project is an partnership of three local universities in Vaasa: Åbo Akademi University, universities of applied sciences Novia UAS and Vaasa UAS(VAMK). The supervisor of this project is Cynthia Söderbacka, chairman of the Energilagring- project.

Technobothnia

Technobothnia is a wide ranged laboratory unit that is co-owned by three universities, the University of Vaasa, Vaasa University of Applied Sciences and Novia University of Applied Science The laboratory unit serves to the educational need of the approximately 2400 technical students of the three schools, and also functions as a platform for research and close interaction with the local industries. All to ensure the regions position as one of the leading technology hubs of Finland. (technobothnia, 2019)

Project members

The project group exist out of 5 members. With three different nationalities and three different study backgrounds. The members are:

- Carles Perrez, Spain, Mechanical Engineering
- Eeke de Jong, The Netherlands, Applied Physics
- Felix Pogats, Austria, Urban Renewable Energy technologies
- Leon Verberne, The Netherlands, Mechanical Engineering
- Renier Looijen, The Netherlands, Mechanical Engineering

There is a different in the amount of working hours every member can contribute in the group. Because four will earn 22 ECTS for the project, that equals to 32 hours per week. The fifth person will earn 15 ECTS credits for the project, that equals to 22 hours per week.

Study background

Everyone will bring his own experience and knowledge to the project. There are three different study backgrounds.

- *Urban renewable energy technologies*
  Within this discipline the students learn at the interface between energy technology, building services engineering and plant engineering. Students receive a technical-engineering education with a focus on our increasingly renewable energy system (especially in urban areas). The course of studies imparts knowledge about the functionality and operating behaviour of renewable energy technologies, the dimension of technological components and their integration into the overall system.

- *Mechanical engineering*
  Mechanical engineering is the discipline that applies the principles of engineering into the design, analysis, manufacturing, and maintenance of machines and mechanical production techniques.

- *Applied physics*
  Within physics even complex systems can be described and understood with just some simple and basic universal key concepts. In a structured and applied research a physicist digs up new knowledge and information. The activities are aimed to answer the research question or to solve a problem.

2.3 Human resource management

To make sure the project group performs as good as possible all members of the project made a Belbin test. With the results of the test we can see where are strength lie and what will be risky for our group. In the appendix a complete result of the Belbin team roles and the project team is given. In figure 1 is a summary of the overall team with

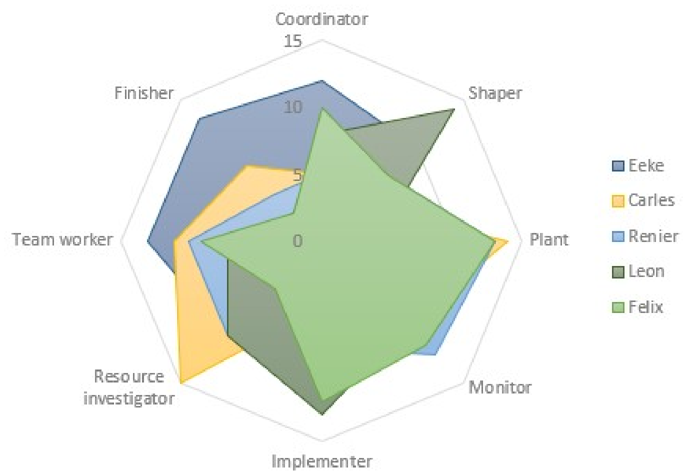


Figure 1: Belbin team roles of the project group

the differen Belbin team roles. The results from the Belbin test shows that the project team has the following team roles: Team worker, finisher, plant, implementer, shaper, monitor resource investigator. The missing team role are coordinator. According to the description on the Belbin website, it can be that people have to act according to three team roles. If that is the case all the team roles are present in our group. Eeke de Jong had a score of 12 out 14 on coordinator as well, so that one is present in the team as well.

2.4 Communication management

Communication management is important for this project to achieve a high quality outcome. In this section among others the different stake holders and the meeting structure is discussed. With this knowledge an plan of communication. This will be done by looking within the project group and outside the project.

Stake holders

The first part in identifying the stakeholders is listing them, who is involved in any lengths. Within the project there are many different kind of stakeholders such as, project sponsors, customers, universities and project members. All of these stakeholders have different interests within the project. The project members mostly want to pass there assignment with a high grade. The universities want to a good working system students can learn from. The companies want to see there sponsorship in good use and not going to waste. With in the EPS-project Energy storage the project members are, Leon verberne, Eeke de Jong, Felix Pogats, Carles Perrez and Renier Looijen. The universities are Novia, Åbo Akademi, VAMK and Univerity of Vaasa. The sponsor companies are Wärtsilä, Vaasan Sähkö, Danfoss, Gigafactory and the Regional Council of Ostrabothnia. The project supervisor, Cynthia Söderbacka is mainly overseeing and steering the project.

Identified stakeholders

the stakeholders within our project are mostly universities and students. Within the project Cynthia the supervisor of the CAES project is a typical monitor with high influence over the project. The supervisor will be updated at least weekly about the project and has direct interests with the success of the project.

The students within the project are the workers, the workers tasks and risks are intertwined the more work a worker puts in the more the worker stands to lose if the project fails. The workers need to mainly updated each other and the rest of the stakeholders. Within the project there are different roles with different risks. The project leader in the group will have the highest risk since everyone will ask him why it failed under his leadership. Although everyone working on the project should bare the same sense responsibility.

The universities only monitor the project but with a far more distant relationship from the one doing the project. The representatives of the universities will be updated will more likely be updated monthly than weekly. They oversee and make the decisions on the budget and make sure the project doesn't go over budget.

The sponsors of the project bare the least risk, there money they sponsored might be lost but that would be the worst result. There interested in the project success is limited, but might result into catastrophic cuts in support for future projects.

Outputs

The significant stakeholders in the CAES-project are Cynthia and the students making the project, They have most to lose and gain from the success. The students need their ECTS to go on with there studies. So is the supervisors interest to present the universities a good working system. The universities want a demo system with which they can give future students a deeper understanding about energy storage technologies, with regard to CAES in this case.

Communication plan within the project group

Communication within the project group we made a plan to streamline our communication. The language we use while speaking with the other group members is informal and direct. It is easy to ask for someones attentions and it is promoted to do, although the languages that is used in verbal communication in informal it urged upon to use the passive voice in everything written. All the minutes and meeting reports are written in a passive style and so are the rest of the rapports.

To coordinate the work that has to be done, there are planned meetings. Usually the meeting is scheduled at the end of the last meeting, it also happens that there is a emergency meeting which is planned that day. Emergency meetings are only planned when there are certain points we need a answer on and that can not wait till the next meeting.

Every morning the day is started with what we call a coffee meeting, during there is a simple structure and reason for doing those meetings. The structure in those meetings is that we first just talk about how we are doing and if there is any problems you would like to discuss. After we are all spoken out and want to get to work we first tell the rest of the group what we are going to do today. These meeting can be helpful to keep a good group dynamic.

The project group will meet every Wednesday with the five of them. The project members will work in the EPS room in Technobothnia or in the library Tritonia. The guideline for the working hours is to work between 9:00 until 17:00.

Communication plan outside the project group

The meetings with the supervisor are planned weekly, it can be hard to plan a meeting upfront. The meetings are usually planned over email so both parties can have a look at their calendars. The goal is to plan the meeting a week upfront and to keep at least a couple of days between the meetings. During the meetings there is discussed what the project group has done since last week, what work still needs to be done, questions from the group and up coming deadlines. For those meetings there is always a agenda with certain points that need to be discussed.

Communications to the project owner is being done by giving presentations during meetings and updates through the supervisor. These presentations are planned months in advance and are purely informative. The project groups present what they are working on and how it is going.

2.5 Risk management

With the philosophy that everything could go wrong at some point. That is why you have to be proactive about risk management to avoid mistakes. To identify risk it is easier to first define all the objectives of the project. After that the probability of the risk will be estimated on a scale of low, medium and high. The impact will be also be estimated and scaled on low, medium and high. With the use of probability and impact the risk matrix can be used to make an risk assessment for every identify risk, that will identify how careful you have to avoid that risk. With the use of this steps an plan of control can be created how to response when a risk takes place.

The following schematic shows which step will be made to make a plan of control.

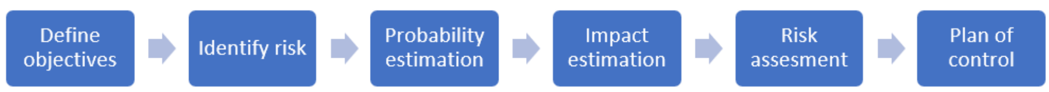


Figure 2: Plan of control Risk management (own illustration, 2019)

The following schematic is the risk matrix what shows the risk assessment depending on the probability and impact:

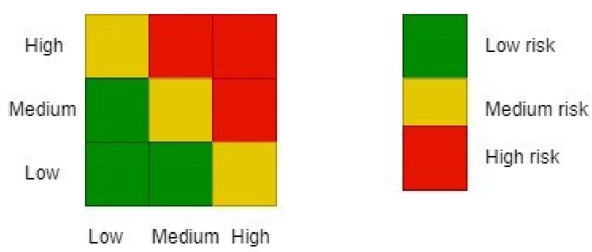


Figure 3: Risk matrix (own illustration, 2019)

After going through the objectives the following problems are the main potential risks for the project:

1. Not keeping up with the project schedule. This could happen for a lot of different reasons. For example someone of the group could get sick. Also there could be made a wrong time estimation of an objective or because of a possible changing of an objectives of the project.

2. Misinterpretation of information or making use of incomplete information is a possible risk. This is a possible risk because this technology is still in development and at is difficult to make assumptions how reliable the information sources.

3. Incorrect calculations due to making wrong assumptions. For example about the temperature in the laboratory, this could change during the year because of the outside temperature.

4. The component after being ordered could have a delayed delivery. If you get the components to late there is a possibility that we can't complete the assembly before the end of the project.

5. Going over budget because the components for our solutions are too expensive or that there are unexpected costs of the project.

6. Risk could be that the components are not the dimensions or performance what was expected.

	Risk	Probability estimation	Impact estimation	Risk assessment	Plan of control
1	Delay schedule	Medium	Low	Low risk	Check weekly, adjust schedule and make everybody aware of the adjustment
2	Mistakes information	Medium	Medium	Medium risk	Make use of multiple sources for the same knowledge to make sure that the information is correct
3	Incorrect calculations	Medium	Medium	Medium risk	Check with people outside project the calculations if the calculation assumptions and steps are logic.
4	Delivery time components	Low	High	Medium risk	Check if there are more companies how could deliver an component
5	Going over budget	Low	High	Medium risk	Make an overall view of al the cost and calculated unexpected cost
6	Problems assembly	Low	Medium	Low risk	Leave a lot of tolerance space for the assembly and

Figure 4: Risk control table (own illustration, 2019)

In table 4 are the risks appointed with the estimated probability and impact with the following control plan:

If the project team recognize on time that one of these risk are taking place and act on it by using the appropriate control step, than the project has an overall medium risk because the risk assessment is medium to low.

2.6 Quality management

To assure the quality of the project, it is important to make a quality management plan. The quality is important because it will reflect on the performance of demo and the other objectives. Also for the costs it is a good thing to look in the quality on for hand, because with a little effort put on the quality, can save costs on failures, such as rework and lost hours.

A quality management plan consist of input, tools and technique and output. The output is the quality of a certain objective, what has an influence on the overall quality. The input is the foundation for the output that makes the quality as it is. The tools and technique are the connection between the in- and outputs. There are seven quality management principles that guide ISO 9001:2015.

For different projects a different approach of quality management is desired. If it is an ongoing development and production process then a PDCA cycle (Plan, Do, Check and Act cycle) would be beneficial. This means in practice that a production process is monitored constantly to see if it lives up to the expectations. If a new plan is conceived and put in to action the monitoring stage starts over again.

Also for every project the quality triangle has the be taken in account. The triangle explains that scope, costs/resource and time can not all be as high as possible. One of the three needs to be sacrificed. In this project there is a limit amount of time and budget. This will have a huge influence on the quality of the outcomes, such as the demo. The budget is in between the professionals and the hobbyists, this makes that some components of the demo will me suitable for the hobbyists and some more for the professionals.

The seven quality management principles are:

- *Costumer focus*

  to meet customer requirements and to strive to exceed costumer expectations

- *Leadership*

  Leaders establish unity of purpose and directions and create conditions in which people are engaged in achieving the organization's quality objectives

- *Engagement of people*

  competent, empowered and engaged people throughout the organization are essential to enhance its capability to create and deliver value

- *Process approach*

  consistent and predictable results are achieved more effectively and efficiently when activities are understood and managed as interrelated processes that function as a coherent system

- *Improvement*

  focus on improvement

- *Evidence-based decision making*

  decisions based on the analysis and evaluation of data and information are more likely to produce desire results

- *Relationship management*

  manages its relationships with interested parties, such as supplier

The importance of those seven principle variable with every project. First all principles will shortly be described. After that the two most important principles for this principles will be analysed and applied on this project.

Important for this project is the engagement of people and evidence-based decision making.

Engagement of people

To manage an project effectively and efficiently, it is important to involve all project members and respect them as individuals. In this project to group consist of three different nationalities and three different study backgrounds, so it is really important to recognise everyone his/her strengths. To get everyone an equal level involved with the project and give everyone the responsibility that suits for them.

Communication between the project members is important to give everyone the same level of understanding. It is important that there is a place to have open discussions and to share previous experience and knowledge. This will improve their personal contribution. When the personal contribution increases, the feeling of being responsible will grow as well and that contribute in a project group that wants to achieve as high as possible quality on there objectives.

Evidence-based decision making

In this project a lot of different decision has to be made, soon in the project already. This can be a complex process and it involves a great deal of uncertainties. During decision making it is important to understand cause-effect relationships and potential unintended consequences. That is why it is important to collect facts, evidence and data analysis, that will lead to greater objectivity and confidence in decision making.

Different ways to improve decision making are:

- Make all data needed available to the project members and stakeholders
- Make sure all data and information is reliable
- Analyse and evaluate data and information using different methods
- Make use of competent people for the analyse and evaluate of the data and information

This way all the needed background information is checked and analysed, so decision can be made with the data and information kept in mind.

2.7 Cost management

The budget of this project is theoretical since the team members are not getting paid for their work. However there is a budget for material and software, over viewed by the board of the project team in "Energilagering!". In order to carry out a Earned Value Analyses certain assumptions have to be made:

- The team members work 32 hours per week on the project
- The payment is € 10,- per hour
- The project has a time frame of 16 weeks

The graph of shows curve BCWP – Budgeted Cost of work performed in blue and the ACWP – Actual Costs of Work performed. These graphs show the accumulated labor and material costs of the project over the duration of the project. If the work is behind schedule, for example the necessary materials haven't been ordered or purchased yet, the ACWP will lie below the BCWP. That means that the project is behind schedule, but still within the budget. Then usually time is of the essence, because the project might not be finished within the deadline. This issue is called a schedule variance.

When the curve of the ACWP lies over the curve of the BCWP the project is within schedule, but exceeds the predicted budgeting for that specific periode of the schedule, this is called a cost variance. This is not necessarily a problem, since the project might be in front of the schedule. However, if the ACWP rises higher than the maximum of the BCWP on the y axis, the project exceeds its budget, which means that additional funding has to be arranged.

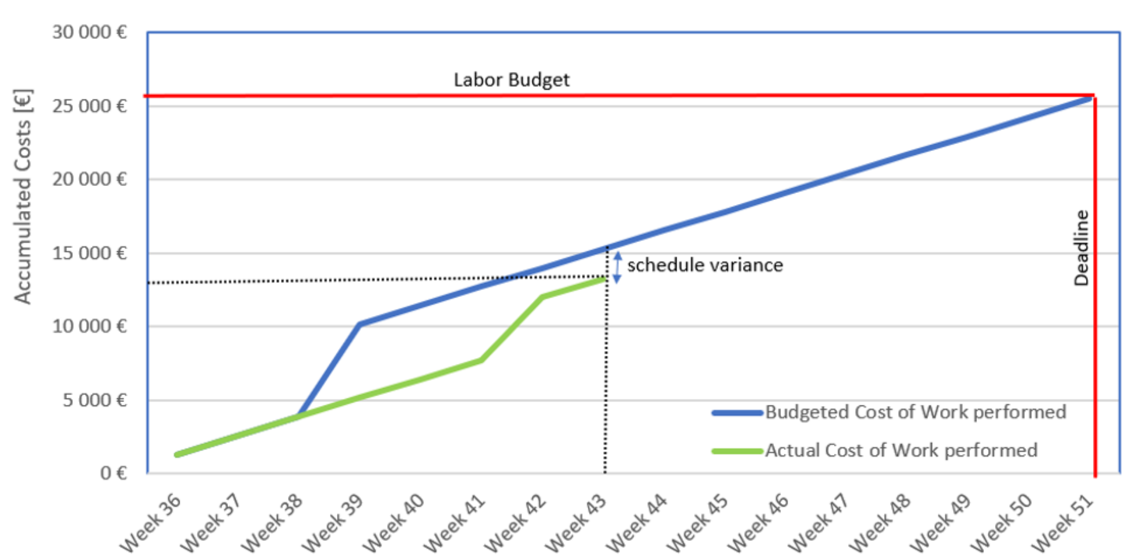


Figure 5: Earned Value Analysis(own illustration, 2019)

As shown in the graph 5, the ACWP curve lies below the BCWP curve, this means that the project is underlying a schedule variance. After a thorough investigation of the project, this can be attributed to two causes.

- The predicted budget for the materials of the project was € 5000,- , since the team was confronted with problems with the material procurement, the actual costs of the materials was reduced to € 3000,-
- For the same reason the purchase of the materials was delayed for three weeks, this implies for the earned value analyses that the ACWP curve rises later, compared to the BCWP.

This causes, as mentioned before, a schedule variance, which might result in conflict with the deadline, if left untended.

3 Research

At first the basic principles of a CAES system will be explained. Secondly, the different types of CAES-systems will be discussed. At last, the needed components will be researched.

3.1 Compressed Air Energy Storage (CAES)

Energy can be stored by compressing air and storing that compressed air in tanks. When the energy is needed again it can be retrieved by expanding it within a turbine. The turbine will drive a generator, that will convert mechanical energy, into electrical energy. This system is then called a compressed air energy storage (CAES) (Barnes & Levine, 2011, p. 24). The planned lab-scale A-CAES stores also thermal energy, which is why it cannot be categorized as a purely mechanical energy storage. CAES systems can be built in a broad power range, the following distinction can be made:

- Large scale CAES: > 100 MW
- Small scale CAES: 100 kW to 100 MW
- Microscale CAES: < 100 kW

Principle of CAES systems

When air is being compressed, heat will be generated, usually this heat is a waste product of the compression, the thermal energy is dissipated into the environment with cooling fins, as shown in figure 10. The whole process is therefore inefficient, compared to other storing technologies, due to the heat loss. To solve this problem the thermal energy can be stored and reused when the air is expanded. When air is expanded, it will set free the exact amount of energy, it takes to compress it. This is the law of conservation of energy (Barnes & Levine, 2011, p. 49). This, of course, is only true in theory, in reality losses occur within compression, storage, and expansion. See figure 6 with the steps and what kind of enery losses occur.

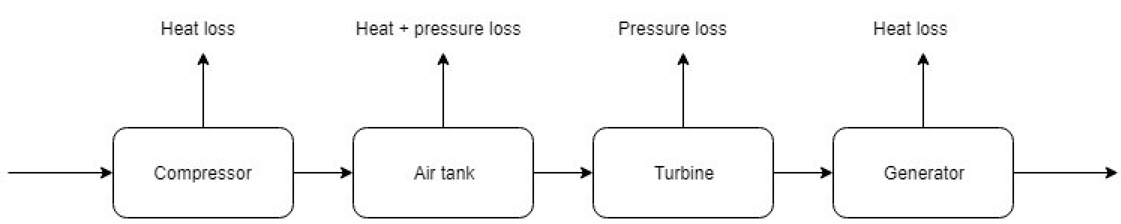


Figure 6: Schematic energy lost (own illustration, 2019)

Within a CAES system the adjustable variables that can influence the efficiency are:

- Temperature of the cooling water
- Pressure in the storage tank
- Pressure level of the expander
- Volume flow of air

The temperature within the thermal energy storage can be influenced by how much cooling water is put into the system. The less cooling water is used, the higher the water temperature rises. This, however, affects the operation of the compressor, since it is not cooled sufficiently enough, in case the water temperature rises over a certain threshold. This threshold varies from compressor to compressor. The water temperature in the system should therefore always remain within safe values (Barnes & Levine, 2011, p. 46). The pressure in the compressed air tank (CAT) and the inlet pressure of the expander can be regulated with a pressure valve. This assures that the turbine is fed with the right pressure, according to its specifications. (Barnes & Levine, 2011, p. 39) In the following chapter, the three main types of CAES systems will be described. In the Appendix, an oversight over further technologies and research projects will be given, which are of no further importance to this project.

Diabatic CAES system

Diabatic CAES systems dissipate the excess heat from the compression process into the environment, to reheat the air during expansion the exhaust heat from a gas turbine has to be used. This implements that a D-CAES system cannot run independent, it requires to be associated with a gas turbine power plant. It cannot be used in other types of power plants such as coal-fired, nuclear, wind turbine or solar photovoltaic plants, due to the lack of exhaust heat. More importantly, the combustion of fossil fuels leads to the emission of contaminants such as nitrogen oxides and carbon oxide which render the CAES less attractive (Barnes & Levine, 2011, p. 67).

Current CAES technology has a long storage period, low capital costs, but relatively low efficiency. The typical ratings for a CAES system are in the range of 50 to 300 MW and currently manufacturers can create CAES machinery for facilities ranging from 5 to 350 MW. The rating is much higher than for other storage technologies, other than pumped hydro (Barnes & Levine, 2011, p. 37). The storage period is also higher than other storage methods, since the losses during the storage period are very small - a CAES system can be used to store energy for more than a year. The typical value of the storage efficiency of CAES is in the range of 60-80% (Barnes & Levine, 2011, p. 53). Capital costs for CAES facilities vary depending on the type of underground storage but are typically in the range from 400 €to 800 €per kW (Barnes & Levine, 2011, p. 63). The typical specific energy density is $3-6kWh/m^3$ or $0.5-2kW/m^3$, which is rather low compared to chemical fuels or batteries. The typical lifetime of a CAES plant is 20-40 years. Similar to pumped hydro storage. The major barrier to the implementation of CAES is also the reliance on favorable geography, such as caverns. Hence an installation is only economically feasible for power plants, that have nearby rock mines, salt caverns, aquifers or depleted gas fields (Barnes & Levine, 2011, p. 67). In addition, in comparison with pumped hydro storage and other currently available energy storage systems.

In figure 7 a schematic of this principle is shown.

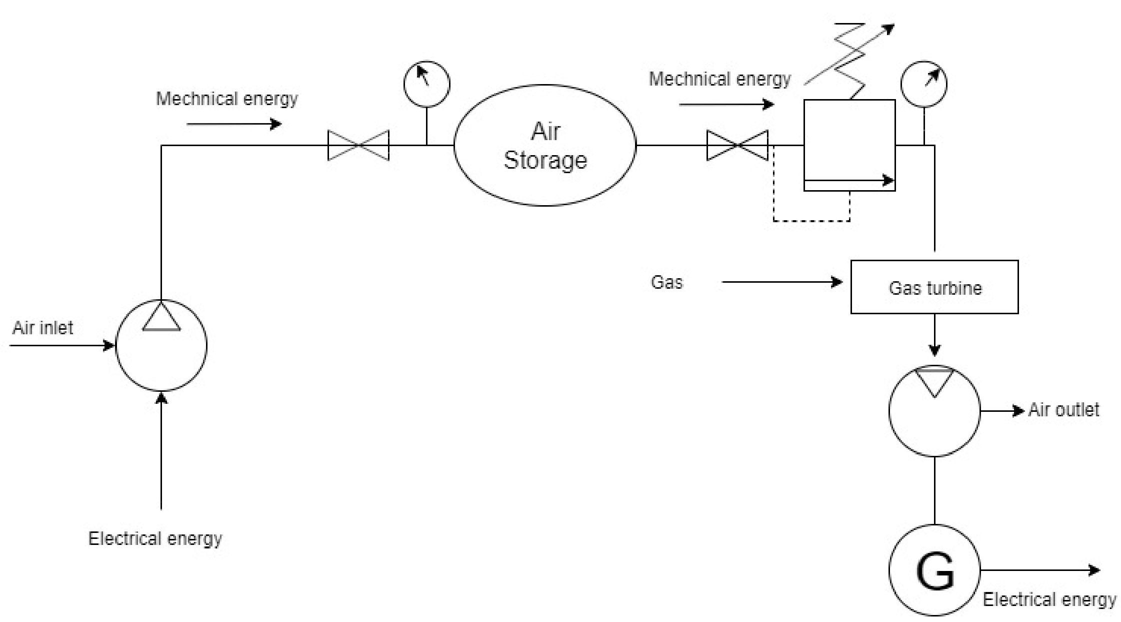


Figure 7: Schematic Diabatic CAES (own illustration, 2019)

At the moment there are two Compressed Air Energy Storage plant and will briefly discussed:

- Huntorf Germany

  CAES plant was built in 1978 and is world's first. During low-cost off-peak load periods (compressed) air will be stored in the underground salt domes. During peak load periods a reverse process takes place. The air will be released to the surface and is used to burn natural gas in the combustion chambers. The resulting combustion gas is expanded to spin the generator and produce electricity. The CAES plant produces 321MW for 2 hours, the air compressing takes up 8 hours. Operating in a pressure range between 4.8 MPa and 6.6 MPa. The total cavern volume is 310.000 m^3 and 600 m below the ground. Two different caverns are used for this CAES plant because:

  - Redundancy cavern shut-down
  - Easier cavern refilling after drawing down the pressure in a cavern to atmospheric pressure.
  - Start-up procedure for plant compressor requires a minimum pressure

  It has been reported that the plant has run in good condition and consistently shown excellent performance with 90% availability and also 99% starting reliability respectively.

- McIntosh Alabama USA

  McIntosh CAES was built in 1991 and produces 290MW for 26 hours. Recharging is partially done during weekday nights and is fully recharged at weekends. The storage capacity is about 560,000 m^3, 450m underground. And the operating pressure range is 4.5 MPa to 7.4 MPa. The design of this CAES is almost the same as Huntorf. One major improvement is a heat recuperator to reuse part of the heat energy from the exhaust of the gas turbine section. This way it is tried to create a pure energy storage system and makes it more a adiabatic CAES system. Unfortunately in practical this is not the case. Still the fuel consumption is reduces by 22-25% and improves the cycle efficiency from 42% to 54%, in comparison with the Huntorf plant. The reliability between the year 1998 and 2008 has been between 91.2% and 92.1%.

(Wei & Jihong, 2018)

Adiabatic CAES system

Adiabatic CAES systems (A-CAES) store the mechanical and thermal energy of compressed air separately and recover them during expansion. During compression the compressor and the air is cooled. Before storing the thermal energy, it first needs to be transferred from the compressor to a storing medium. When this medium is heated up, it needs to be moved away from the compressor, to an insulated storage unit. When the system is being discharged again, the stored heat has to be retransferred to the air again, before the air enters the expander (Barnes & Levine, 2011, p. 52). This way it can be assured, that the compressed air does not cool down during the expansion, to a temperature below the freezing point of water. This could lead to a loss of efficiency and damages to the turbine.

Although the cost is about 20 to 30% higher than the conventional power plant, this system eliminates the combustor and is a fossil-free system. A-CAES is currently getting commercially viable, due to the improvements in thermal energy storage, compressor and turbine technologies (Barnes & Levine, 2011, p. 54). The proposed efficiency for such systems is 70-75%. Another technology under current investigation is an A-CAES with multi-stage radial compressors, which allow the use of a low-temperature TES, the proposed efficiency is about 52-60 % (Barnes & Levine, 2011, p. 56).

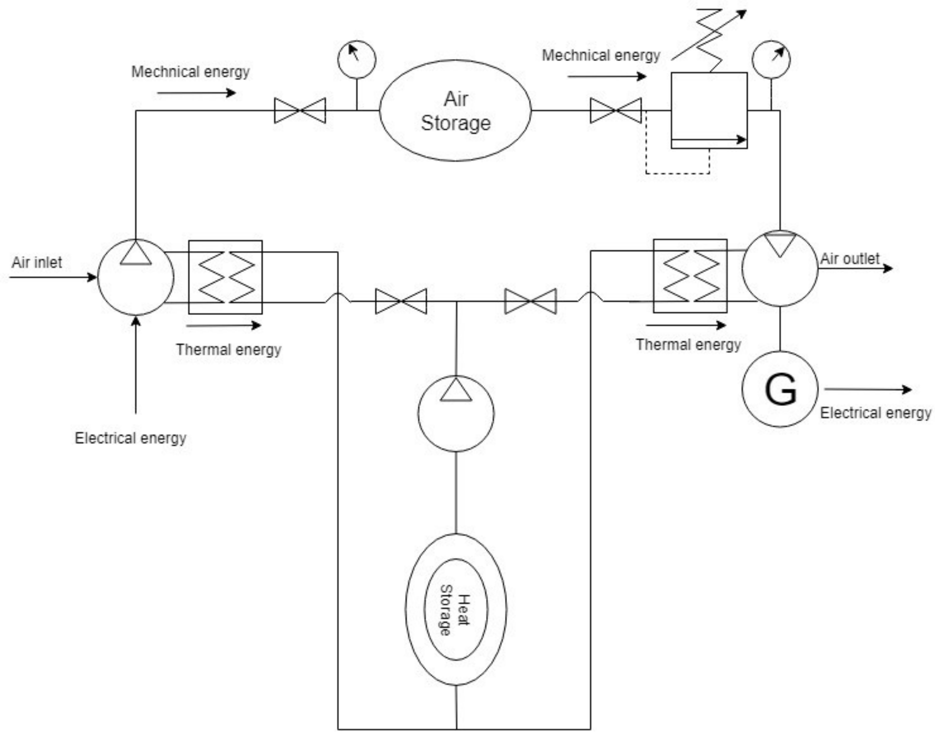


Figure 8: Schematic Adiabatic CAES (own illustration, 2019)

Figure 8 shows the schematics of the system with a heat storage.

Isothermal CAES system

During the compression-process water is sprayed into the airstream to cool the air, in order to achieve an isothermal compression of the air. This leads to a reduction of work for the compressor during this stage (Barnes & Levine, 2011, p. 74). The thermal energy, stored in the water, is then captured in a TES, similar to the A-CAES system and released during the expansion process, once again by spraying water into the airstream. This procedure is supposed to increase the efficiency by up to 90 % (Barnes & Levine, 2011, p. 74).

In figure 9 the schematic of an isothermal CAES system is shown.

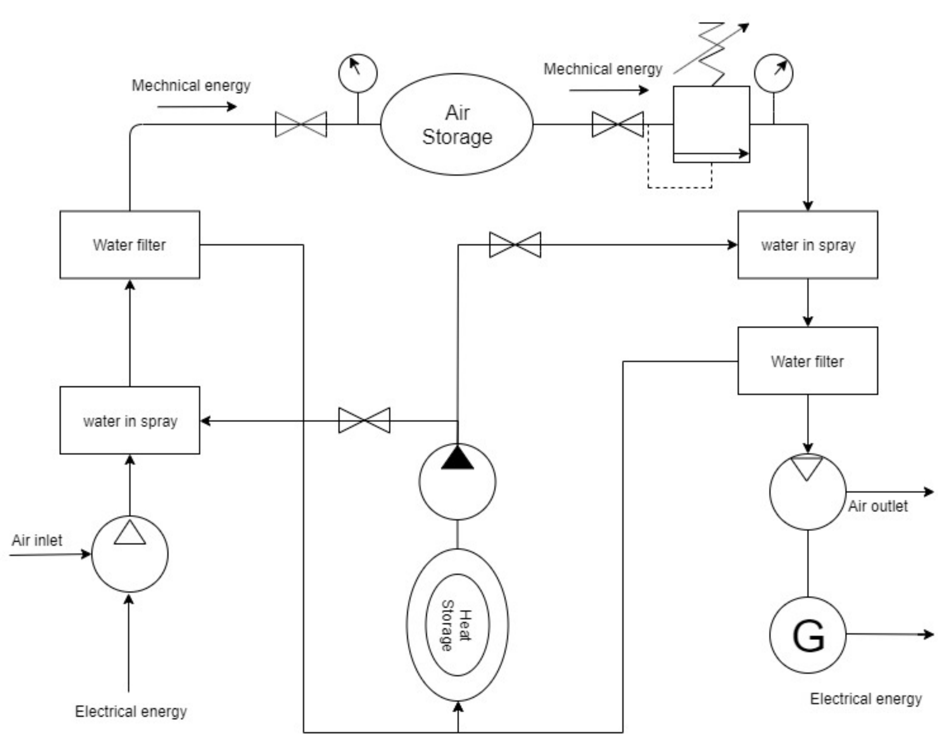


Figure 9: Isothermal CAES (own illustration, 2019)

3.2 Comparison CAES systems

The initial costs of a Diabatic-CAES are the lowest, compared to other CAES systems, due to its simple principle. This is also the only system that is used so far on an industrial scale. It has the lowest efficiency, because it loses a significant ammount of energy due to heat loss. Huntorf CAES has an efficiency of 42% and McIntosh CAES had an efficiency of 54%. Another problem with Diabatic CAES is that the European Union wants in the future zero C02 produced. This means that there will not be a future for this system because of the use of fossil fuel to heat the air. Adiabatic and Isothermal CAES are probably the future for compressed air energy storage.

Adiabatic could reach an efficiency of 79,2% hypothetically. Isothermal CAES could even reach an efficiency of 90%. The efficiency of these systems are very dependant on the heat exchanger and heat storage of the system.

The efficiency of the Adiabatic and Isothermal CAES compared to the Diabatic-CAES is significantly higher but there also down sides of these systems. Diabatic is a mature technology that has been in use for a long time. Adiabatic CAES and Isothermal CAES are still in development. This hence that the components are more expensive and not reached the same reliability as diabatic.

The most suitable CAES system to build as an demo is the Adiabatic-CAES system. Diabatic-CAES is not a suitable system because it is not a closed system and is depending on fossil fuel. Isothermal-CAES systems are not an suitable solution. This is because it is more complex and still in development. What means that a lot of components are not available in the given price range. (Wei & Jihong, 2018)

3.3 Fluid energy machines

In physics, a basic distinction is made between working and power machines, as can be seen in figure 10. If a machine supplies energy to a fluid, using mechanical energy, it is a working machine. If energy is extracted from the fluid and converted into mechanical work, then it is a power machine. In other words: work is added to or removed from the shaft of the machine. An overview over fluid energy machines is given in figure 10. (Weber, 2019)

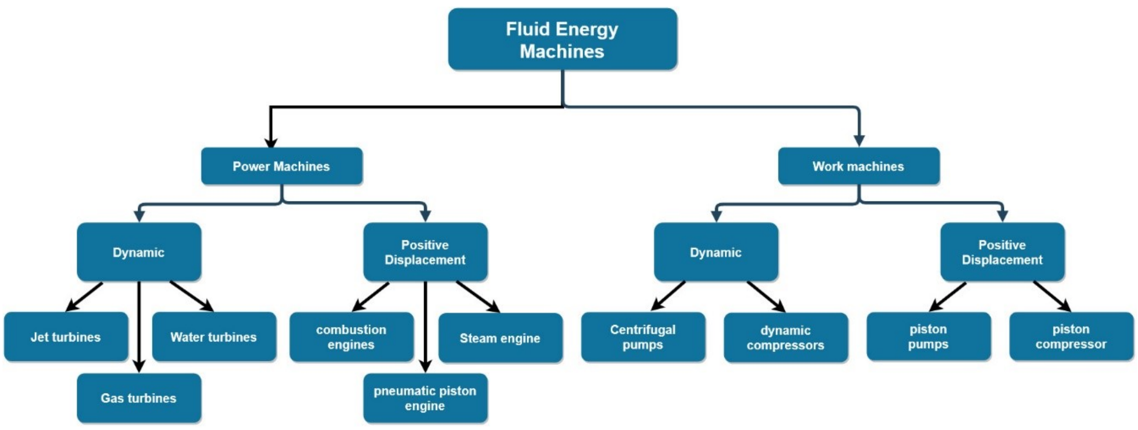


Figure 10: Overview of Fluid energy machines

In principle, every power machine can be operated as a working machine, by reversing the direction of flow and rotation. Also, every working machine can be operated as a power machine, in practice however, this can lead to losses in efficiency, as the machines are usually optimized and designed for one function only (Weber, 2019, p. 14). An example of this principle are pump turbines for pumped hydro power plants, where a lower overall efficiency is accepted in order to minimize installation costs. The energy carriers for working and power machines are gases and vapors in thermal flow machines, water in hydraulic fluid flow machines and air for wind turbines, propellers, etcetera.

A further distinction can be made by the building principle of the machine; namely *positive displacement and dynamic (flow) machines.* (Weber 2019, p. 13) (Heckmann H., 2019) These machines are used for energy conversion. Through both flows a fluid, from which energy is drawn or to which energy is released. In power machines mechanical energy is drawn from the fluid and delivered to the coupling, such as steam engines, combustion engines, turbines, etc. The fluid is expanded or loses height (potential energy). In work machines, the process is reversed, these machines use mechanical or electric energy for conveyance or compaction of fluids. The power of the engine is produced by the fact, that the piston or rotor blade moves under the influence of a force. This occurs in the piston machine, because the pressure of the medium on the piston delivers work. (Weber, 2019, p. 209) In flow machines, the pressure of the fluid is first converted into velocity through a nozzle. With the increased velocity the fluid hits the rotor blade - the speed is changed in the rotor blade. This change in speed is, in the sense of mechanics, an acceleration and therefore a mechanical force. (Watter, 2017, p. 74) The blade forces occurring and operating in the flow machine are thus only caused by changes of speed, while the forces in the piston machine occur from the pressure on the piston surface.

Characteristics of flow machines are the higher rotational speed and lower weight. Flow machines are suitable for high volume flows, small pressure differences, high performance and speed. Piston machines are generally suitable for small volume flows and high-pressure differences. (Weber 2019, p. 12) (Heckmann H., 2019)

Dynamic Machines

The characteristic feature of every dynamic (or flow) machine is the rotating wheel, which is fitted with a ring of curved blades. The flow of the working medium around these rotating blades is continuous, as shown in Figure 2. The flow pressure, created by the flow around the curved blades, of the rotating wheel, together with the rotational movement, causes the energy to be transferred from the working medium to the wheel or vice versa (dynamic principle). (Heckmann H., 2019)

In flow power machines, the primary energy enters the machine in the form of potential energy or as enthalpy difference (heat). The first partial energy transformation takes place in the control device. Potential energy or enthalpy is converted into kinetic energy, as a result of a pressure drop. (Weber, 2019)

A further energy transformation then takes place in the impeller. Due to the deflection and recoil effect of the accelerated working fluid, it exerts a circumferential force on the blades of the impeller, as it flows through the blade channels. Kinetic energy is thus converted into circumferential work, which can be taken as torque at the shaft. (Weber, 2019)

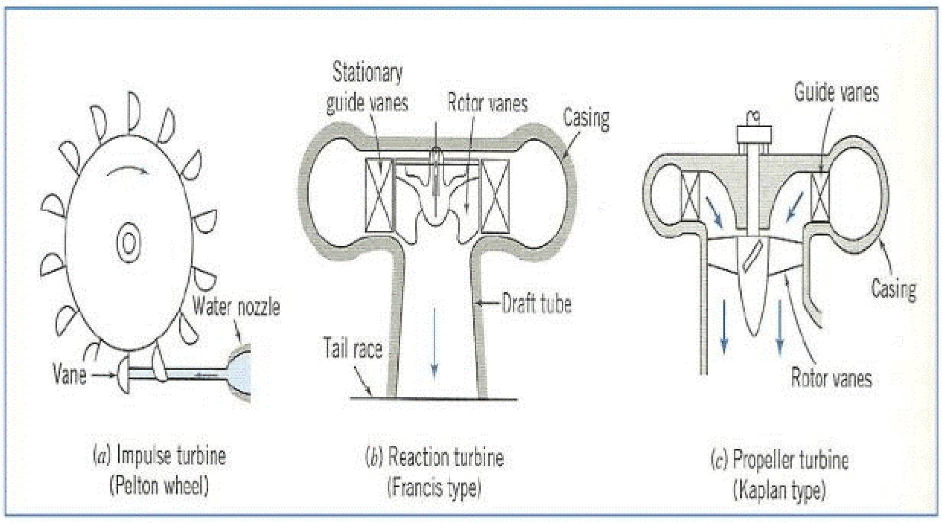


Figure 11: Turbines are dynamic fluid energy machines, the figure shows the most common types of water turbines, namely Pelton, Francis and Kaplan turbine.

In working machines, the drive energy hits the blades through a torque from the coupling via shaft and wheel. The first energy transformation takes place in the blade channels. The pressure and centrifugal effect of the rotating blades on the working medium displaces and accelerates it. The turning energy introduced by the torque is thus converted into kinetic energy and possibly already partly into potential energy. The second energy transformation takes place within the guiding device. Kinetic energy is converted into potential energy diffusing it in an expansion of the fixed housing behind the impeller. (Weber, 2019)

Positive displacement machines

Positive displacement machines (Figure 12) operate according to the displacement principle. With the movement of the displacer (e.g. piston), the outwardly sealed working space changes periodically within the volume limits. A distinction is made between reciprocating and rotary machines. In the latter case the displacer does not correspond to a cylindrical piston (e.g. rotary piston compressors). Rotary piston machines are free from oscillating mass forces. (Weber, 2019, p.205)(Heckmann H., 2019)

In reciprocating piston machines, this piston moves back and forth in a cylinder between two end positions - the dead centers. In rotary piston machines, a rotating displacer changes the working space, which can also rotate relative to the displacer. (Weber, 2019, p.203)

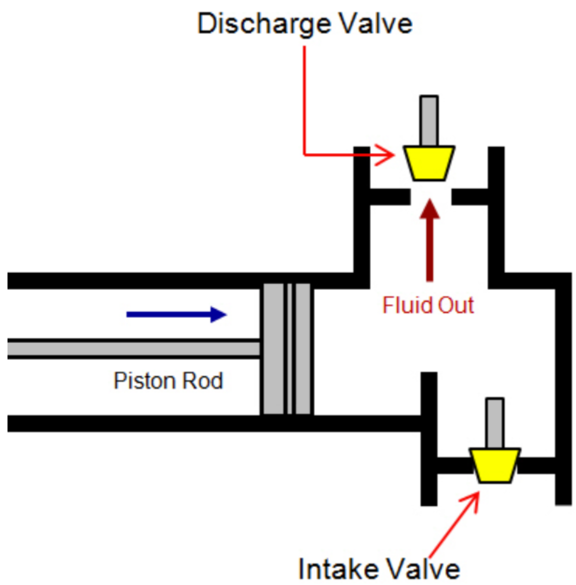


Figure 12: working principle of a pisten

3.4 Pneumatics

Pneumatics as a technology is nowadays mainly used for control and automation techniques. In science and technology, the use of compressed air is called pneumatics. The term pneumatics comes from the ancient Greek word pneuma, which means air. Compressed air is used to perform mechanical work, control components or transmit signals. (Watter, 2017, p.4)

Compressed air systems are used to convert the energy of compressed air into mechanical energy. A compressed air system generally consists of four subsystems, namely generation, preparation, distribution and expansion. In pneumatics, there are various possibilities of drive technologies. These include the pneumatic cylinder, the pneumatic muscle and the compressed air motor. (Watter, 2017, p.46)

Air compression

Compressed air is produced by sucking in and compressing the ambient air with a compressor. It is therefore a mixture of gas and water vapor. After filtering and drying, it is then fed to the application via a compressed air network in the form of pipes and hoses, where it is technically used. Another possibility is storing the compressed air in a compressed air tank. (Heckmann H., 2019)

Important parameters of air compression are:

- Delivery quantity - volume of fluid delivered per time unit. $[m^3/h]$
- Operating pressure - achievable over pressure. $[bar]$
- Pressure ratio = Ultimate pressure/suction pressure. [-]
- Output - The ratio of the volume flow conveyed to the theoretically possible volume flow (due to the geometry). [-]

To better compare compressors of different types and operating points, the standard volume flow rate is often considered. This is the volume flow of the compressor, converted to standard conditions (temperature, pressure, humidity). (Weber, 2019, p. 47)

Compressed air treatment

In addition to compression and compressed air preparation, drying is of great importance. This means that the aforementioned water vapor in the intake air must be removed. When the compressed air is expanded again, the water vapor would first condense and then freeze, due to the temperature decrease during the expansion of the air - this would restrict the operation of the system. (Heckman H., 2019)

The compressed air preparation process, including transport to the consumers, is carried out as follows:

- Compression heat cooling with intercooler or oil injection
- After-cooling with ambient air or cooling water with compressed air condensate discharge
- further dehumidification by means of a refrigerating machine with direct evaporator or compressed air

(Watter, 2017, p.48)

Compressors

Compressors are a subgroup of fluid energy machines that supply mechanical work to an enclosed gas in order to increase the pressure and density of the gas. Machines where low compression is a side effect when transporting gases are called fans or blowers and are generally not counted as compressors. Machines that increase the pressure of liquids are called pumps.

As mentioned before processing of the air is necessary because there are many dirt and dust particles in the air and the moisture contained can lead to corrosion damage to the machines. If the treatment of the compressed air does not meet the appropriate quality standards, machines will fail, and high additional operating costs may be incurred.

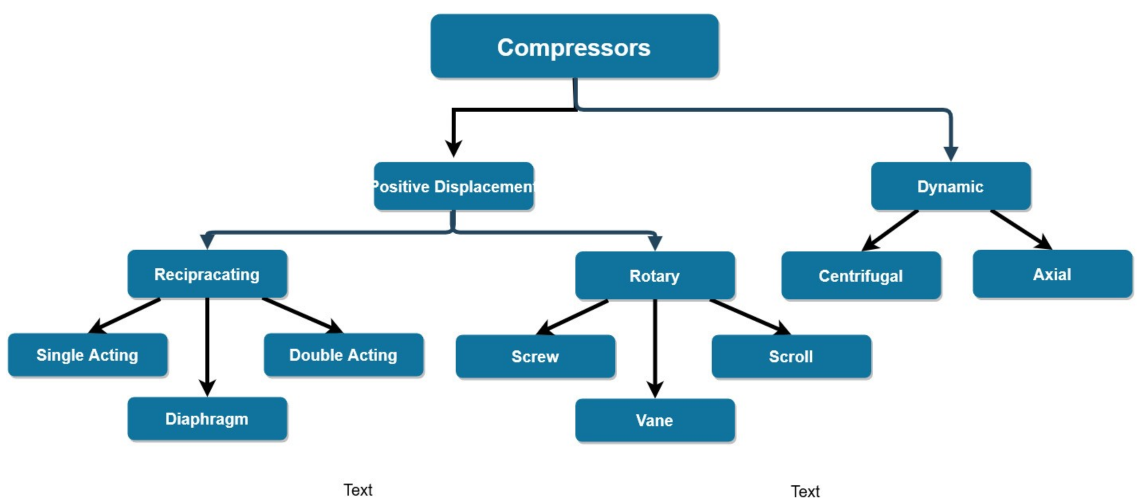


Figure 13: types of compressors (own illustration, 2019)

As shown in the figure 13 a distinction is made between positive displacement and dynamic compressors, in the following chapter the main types of compressors will be described. Generally, it can be said, that positive displacement compressors are used, when high pressure changes are necessary, whereas dynamic compressors are mainly used if high volume flows are demanded. For the lab scale A-CAES model, to be investigated, a piston compressor will be used. (Weber, 2019) **Positive**

displacement compressors

In a positive displacement compressor, air is drawn into a chamber. The trapped air is then compressed, physically reducing the volume of the chamber using various mechanisms (12. The temperature of the air will increase, due to the higher pressure, and released out of the compression chamber into the system.

There are different types of rotary piston or rotary compressors (roots blowers, vane compressors, screw compressors, scroll compressors). They all have in common that the working space is formed between the housing and one or more displacers (rotary pistons) which rotate or move on a circular path. The gas is sucked in and expelled through slots that the piston releases and closes as it moves.(Weber, 2019, p.205)

In reciprocating piston compressors, a subgroup of positive displacement compressors, the gas is sucked into the working chamber in a cylinder by a reciprocating piston, where it is compressed and ejected again. These compressors operate cyclically, have low volume flows and high-pressure ratios. Suction and discharge valves are automatic plate valves. (Weber 2019, p. 213)

Expansion machine

Expansion machines (Figure 14) are a subtype of fluid energy machines, to be exact they are power machines. The energy of the expansion of gases is used to put force on a piston or a rotor blade, in order to transmit energy to the shaft. This energy is transmitted to the shaft by rotation, which can power other machines, like generators, pumps or compressors. In this thesis two types of expanders will be examined, in order to generate power through the expansion of the compressed air.(Weber, 2019, p.111)

In this thesis a radial piston engine will be used for the lab scale A-CAES model. In a further step a compressed air turbine will be designed, and 3D printed in order to test its performance on the system.

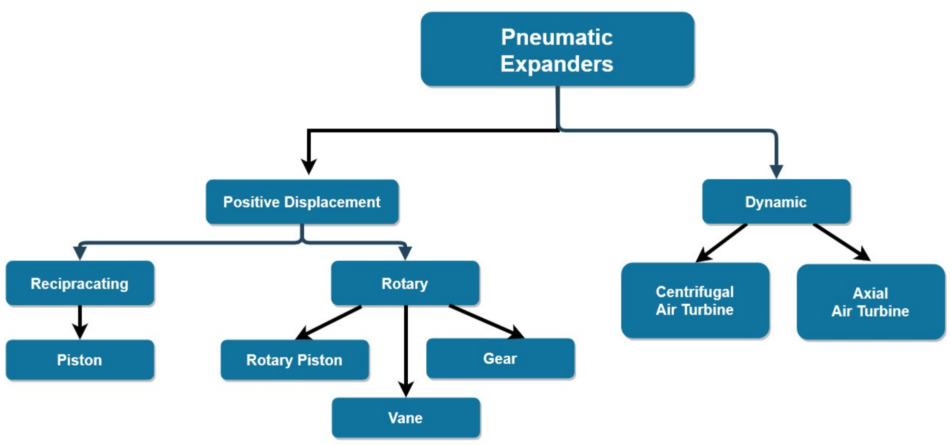


Figure 14: Classification of Pneumatic Expanders (own illustration, 2019)

Compressed air turbine

Compressed air turbines, as seen in 15, are dynamic machines with a single-stage axial or radial design. The gas is expanded in the nozzles and thus accelerates. When it hits the blading of the turbine and is deflected, it releases its kinetic energy. The axial turbine is also characterized by a high degree of efficiency, even outside the nominal operating conditions. This enables very economical operation even at partial load. In contrast, the radial turbine achieves a higher efficiency directly at the design point. Here, the gas in the nozzles is only partially expanded. The remaining expansion and deflection take place in the impeller. However, the efficiency in partial load operation is lower, compared to the axial design. (Hallman H., 2019)

Figure 15: Compressed Air Turbine, it works after the same principle as a dynamic compressor, only as a power machine.

Radial Piston Engine

The star-shaped working pistons (Figure 16) roll on a curve incorporated inside the housing. They are supplied with compressed air from the center via a travelling control ring and a fixed control shaft. This means that the pistons are positively driven. The control ring is floating connected to the cylinder disc, which is doubly mounted on the control shaft. When rotation occurs, the supply air or the exhaust air will alternately ventilate or vent the working pistons with compressed air. By reversing the supply and exhaust air, immediate left or right rotation can be generated. In the single-stage version, three of the seven working pistons are always involved in generating the torque. The working pistons are forced back and vented at the highest curve point. This corresponds to the function of a single-acting cylinder. Its highest torque is thus already available during start-up. (Kehrli, 2019)

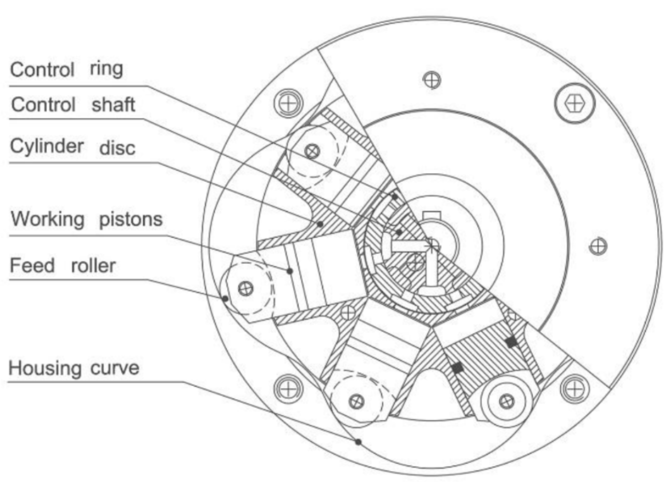


Figure 16: Radial piston motor

Compressed air bottle

The compressed air tank is a reservoir for compressed air. Applications include the use as a breathing gas storage tank or as an energy storage and compensation tank for technical systems and machines. Compressed air tanks are a component of compressed air diving equipment for divers and of self-contained breathing apparatus for the fire brigade and many other users. (Drager, 2019)

The compressed air cylinder consists out of a pressure vessel, made of steel, aluminum or a composite; a thinner steel inner body reinforced with fibre-composite plastic. Compressed air cylinders can be filled with an overpressure of up to 300 bars. The cylinder bodies of compressed air cylinders for breathing apparatus have a cylindrical thread, into which the shut-off valve is screwed and sealed with an O-ring. The regulator and/or a bridge for connecting several compressed air cylinders is screwed onto the shut-off valve. These valves are commonly used in various designs, as single valve for one regulator or as a double valve with a second connection for a reserve regulator. A third option is a bridge valve for connecting usually two cylinders to form a package. (Drager, 2019)

Pneumatic pressure reducer

As a rule, every compressor emits a certain maximum pressure. This pressure is often too high for the planned application. For example, downstream components could not be designed for the compressor pressure and thus be damaged. This is where a so-called pressure reducer comes into play.

The two central components of a pressure reducer are the pressure sensor and the valve coupled to it. The designs can differ depending on the intended use, the medium (gas or liquid) and the expected pressures, but the principle is the same. The pressure on the outlet side acts on one side of the diaphragm, while the air pressure and an adjustment spring act on the other side. The diaphragm is mechanically coupled to the valve. The higher the pressure rises on the outlet side, the further the valve closes, and when the adjustable nominal outlet pressure is reached, it shuts off the flow. The compressed air reducer can be adjusted to the desired pressure, which can be controlled and monitored by means of an integrated pressure gauge. In the event of a malfunction of the unit, an emergency valve will blow off the over pressure. (Drager, 2019)

In addition, a compressed air pressure reducer is very often equipped with a so-called water separator, which dehumidifies the compressed air. Some models are equipped with an oil separator, because if your compressor is oil-lubricated, the compressed air will contain a small amount of oil and is therefore not necessarily suitable for all jobs. (Drager, 2019)

Pressure meassurement

Manometers are devices used to measure the overpressure in liquids and gases and the pressure exerted by the solid body. The simplest form of manometers are U-tube manometers, also known as liquid manometers, and membrane manometers. Pressure sensors of different types are also used for pressure measurement. Devices for measuring ambient air pressure are called barometers. (Drager, 2019)

The most frequently used type in pneumatics is the diaphragm pressure gauge. This consists of an elastic diaphragm located in a housing. It is connected to a movable rod, which in turn is coupled to a pointer. This pointer is located in front of a scale. If a pressure acts on the diaphragm, it is deformed. This also causes the rod connected to the diaphragm and the pointer to move. The scale is calibrated in pressure units so that the pressure can be read directly. (Watter, 2017, p.111)

3.5 Hydraulic components

The word hydraulics originates from the Greek and is composed of "hydro" (water) and "aulos" (tube). Hydraulic is therefore the science of the flow behavior of liquids. In technology it is understood as the use of fluid for signal, force and energy transmission. (Watter, 2017, p.2)

Hydraulic systems work with a fluid that is put under pressure. Pressure can build up when the fluid is in a closed pipe system, if space is taken away from the fluid in the pipe system, the pressure increases. Since liquids are incompressible, this pressure is transmitted immediately. This is used in various ways in hydraulics.(Watter, 2017, p.7)

Another area of hydraulics is energy distribution in systems, this is usually done by means of the energy carrier water. Water offers various advantages in thermal energy distribution, it is cheap, non-toxic and has a high specific heat capacity. In such a system, various components are required to control the volume and energy flow, such as pumps, valves, heat exchangers and accumulators.

The aim of hydraulics is to integrate the elements required for this process into a circuit between energy supply and energy consumer, in such a way that optimum operating conditions are created. (Watter, 2017, p.7)

Pumps

Pumps are work machines, a subgroup of fluid energy machines. They take in energy over a shaft and add it to a fluid. The energy which is given to the fluid is converted into kinetic or potential energy, or pressure. A distinction is made between pumps according to their mode of operation or design, as shown in Figure 17. (Watter, 2017, p.139)

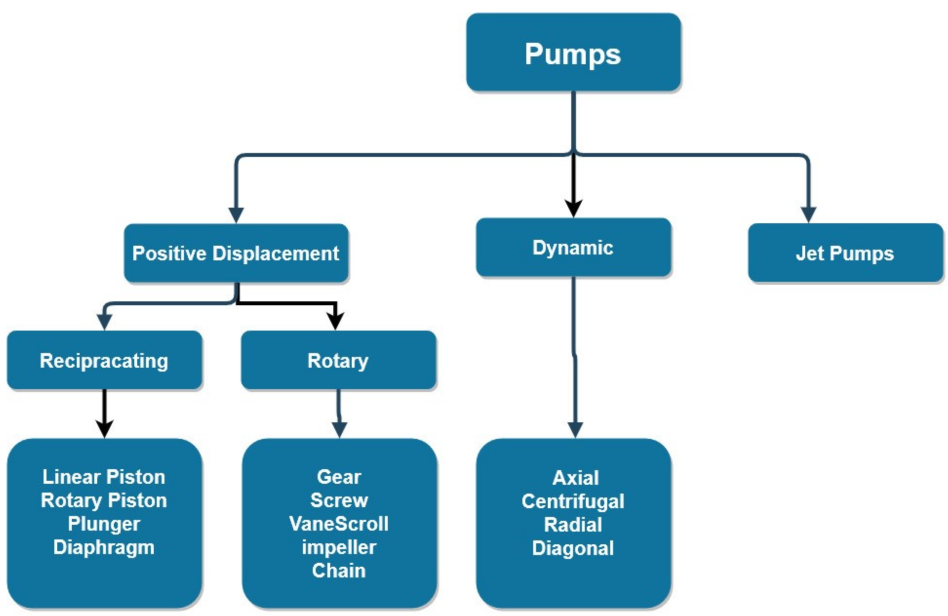


Figure 17: Classification of Pumps (own illustration, 2019)

Excluded from this definition are machines which convey or compress gases. Such machines, which often follow a similar functional scheme, are referred to as compressors, or blowers.

There are further design differences between pumps. However, the distribution of such pumps can be regarded as very small. These include, for example, pump types such as electrochemical gas pumps, the mammoth pump or the titanium sublimation pump, which are not topic of this thesis.

For the cooling system of the A-CAES model a flow pump will be used. Flow pumps are by far the most widely used pump types. This operating principle is based on the fact, that the fluid is set in motion by the pump design - a hydrodynamic power transmission takes place.

Neither valves nor flaps are required for the basic application. The flow direction can also be changed by changing the direction of rotation of the impeller.

A special feature to be emphasized, is the fact that these pumps must always be immersed in the respective fluid. If, for example, a fluid is to be pumped upwards through a pipe containing air when the pump is at the top, the flow pump cannot operate (pump at the top, container with liquid at the bottom, pipe filled with air in between). To do this, the pipe must first be filled with the appropriate fluid. This means that flow pumps are not self-priming. (Weber,2019, p.140)

Cavitation and NPSH value

The lowest pressure occurs directly at the impeller inlet of the pump - the suction mouth. Liquid can evaporate here due to local pressure reduction, tiny vapor bubbles form. These are carried along by the liquid and disintegrate abruptly, when they return to areas with higher pressure. This can result in pressure peaks of up to 100,000 bar. If the pump is now operated under cavitation conditions for a longer period of time, the impeller of the pump, the pump cover and the pump casing are damaged. To avoid steam formation, the total energy level in the inlet cross-section of the pump must be greater than the steam pressure level of the medium. This energy difference is referred to as the Net Positive Suction Head (NPSH) value and is identical to the earlier term holding pressure head and is given in meters. At all times, therefore, the pressure of the pumped medium must be above its vapor pressure at the respective temperature at every point in the pump. The vapor pressure is taken from tables of the corresponding pumped medium. The NPSH value of the system must be at least 0.5 m higher than the NPSH value of the pump.(Weber, 2019, p.149-150) For safe, cavitation-free operation, the following applies: $NPSHsystem + 0.5m > NPSHpump$

The vapor pressure of the pumped medium depends on the temperature. It increases as the temperature of the medium rises. In the case of changing temperatures of the pumped medium, the highest value of the vapor pressure must always be used when determining the NPSH value of the system. (Weber, 2019, p.150)

3.6 Thermal energy components

Heat exchanger

Heat exchangers are devices which transfer thermal energy between fluids. Heat exchangers are important components in hydraulics, in HVAC systems they are used to cool or heat buildings, to regain waste heat, they are used in heat pumps etc. Depending on their build the fluids are in separate compartments, they can be mixed, or moisture can be transferred. Distinctions can be according the following factors. (Kakac, 2002, p.42)

Regenerator
Regenerators are a single system through which two fluids of different temperatures flow alternately. First, the fluid with a higher temperature flows through the system. The heat is stored by the heat exchangers storage-capable basic body. Then the fluid at a lower temperature flows through the system and the regenerator transfers the stored heat to this fluid. The most common regenerators are the change of the exchanger, push and pull ventilation and rotation heat exchanger. (Kakac, 2002)

Recuperator
These heat exchangers consist two separate systems, separated by a heat-permeable wall. The fluid with a higher temperature releases heat through the wall to the fluid with the lower temperature In this case there is no intermediate storage of the heat in the heat exchanger itself. The most common recuperators are the shell and tube, plate and plate fin heat exchangers. (Kakac, 2002, p.49)

Mix heat exchangers
The heat transfer from the fluid of higher temperature to the fluid of lower temperature takes place by the direct contact of both fluids. This is used, for example, in wet cooling towers, where cooling water is cooled again with direct air contact. This principle can also be used in thermal energy storage systems, where the two fluids, mostly water, are mixed in a container without the use of an actual heat exchanger. The most common mix – heat exchangers are the wet coling towers and the heat storage tank. (Kakac, 2002, p.67)

Thermal Energy Storage - TES

THermal energy can basically be stored by three different principles:

Sensitive heat storage
Sensitive heat storage systems undergo a temperature change during charging or discharging. Heat capacity is one of the most important parameters for sensitive storage materials. As this type does not undergo any phase transformations, it can be used over a wide temperature range, especially in the high temperature range. A widespread example for a sensitive heat storage is a buffer storage for heating systems, water is used to sore heat for a later use.

Latent heat storage
During charging or discharging, latent heat storages undergo no change if temperature, but the heat storage medium changes its physical state. This is usually the transition from solid to liquid (or vice versa). The storage medium can be loaded or unloaded beyond its latent heat capacity, which only then leads to an increase or decrease in temperature. A widespread example are ice storage systems, they change from liquid water to ice when energy is drawn out of the system.

Thermochemical heat storage
Thermochemical heat storage systems store heat by means of endo- and exothermic reactions, e.g. with silica gel or zeolites. When water evaporates and brought into contact with silica gel, it is absorbed by the material. This is an endothermic reaction; this means that energy can be stored in the system. By reversing the principle, the heat can be regained.

3.7 Generator

Electric generators convert mechanical energy into electrical energy. This will be done with the principle of Faraday's law and Ohm's law.

Faraday's law states that electrical energy can be generated through the mechanical process of passing a conductor through a magnetic field. Through the movement of the conductor an induced electromotive force (emf) is generated. As described in the following equations:

$$emf = \frac{dJ_B}{dt} \tag{1}$$

$$J_B = \int B(t)dA \tag{2}$$

J_B stands for the magnetic flux, B is equal to the magnetic field and A is the surface of the used area.

Induced emf can be seen as a potential difference between the opposite ends of the conductor. As described in Ohm's law when the conductor is placed in a closed loop, connected to an electrical circuit with a resistance (R), an electric current (I) will flow. As seen in equation 3

$$I = \frac{emf}{R} \tag{3}$$

(Giancoli, 2008)

Electrical generators are definable in two categories, dynamos and alternators. Dynamos generate a direct current (DC) and alternators generate an alternating current (AC). AC moves back and forth with the changing magnetic field. This principle is also used for the power supply in households. In DC the current travels only in one direction, this is what happens in batteries.

Most electrical generators use the convenient way of producing an emf in stationary conductors. The conductor is located in the stator, a part in the machine which does not rotate. In these generators the magnetic field is moved instead. (McDonald & Carroll, 2006, P159-192)

4 Design

This chapter covers the selection of the components for the selected system, as well as the necessary calculations. After analyzing the different CAES systems, adiabatic compressed air energy storage (A-CAES) is a feasible choice for a lab scale demo, to be built in Technobotnia Education & Research Center. When compared to the other two systems, A-CAES is a closed loop system and does not require fossil fuels to heat the air like in D-CAES. Also, it does not have the same complexity as the isothermal system (I-CAES) which is still in development stage and requires more expensive components. The principle of A-CAES system is described in the research. This type of system ensures a flexible experimental setup for students. The connected Thermal Energy Storage (TES) can be switched on or off, depending on the task, enabling the students to evaluate and compare the operating performance and therefore the different levels of efficiency of the system.

To ensure an operation time of approximately one hour per cycle, without increasing the space requirements of the system, the decision has been made, to operate the system with 150 bars. This allows a constant operation of the air motor, without a decrease in power output. This would prove problematic in a system operated with 8 bars, as was originally proposed by the steering group. This is due to the fact that air motors usually work on a pressure of 6 bars. The pressure in an 8 bar CAT would decrease under that value, within the first seconds of operation time. By increasing the storage pressure in the CAT to 150 bars, the pressure level of 6 bars can be held until the very last seconds of the operation cycle, granting a stable operation of the air motor. The size of the CAT itself can be reduced significantly, this being the bulkiest component of the system, the overall size of the lab-scale A-CAES model can be reduced. The high-pressure components of the system (compressor, tubing and CAT) however, will be designed to withstand a pressure of 300 bars, in order to guarantee a safe operation of the system. Furthermore, the cost of all components has to be within the budget and a delivery time of 4 weeks must not be exceeded.

In order to design and calculate the system correctly, the key components, which are critical for the system and therefore determine its parameters and other components, have to be identified. The expander has been identified as the most critical component of the system and will therefore be the starting point of the design and calculation procedures. The flow rate, or air consumption, of the expander determines the running time of the system, the necessary surface of the heat exchanger, as well as the size of the CAT. The other components will be chosen according to this procedure:

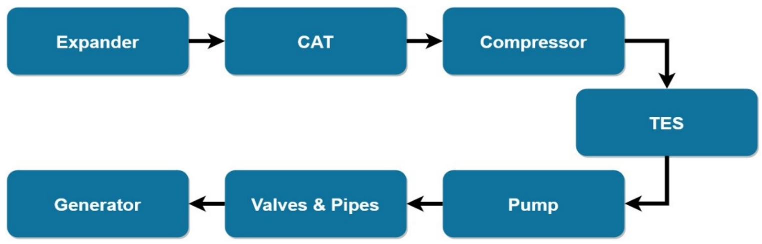


Figure 18: Design phase procedure (own illustration, 2019)

In Figure 19 the schematic of the planned lab – scale A-CAES model is shown. The process runs in two steps. In the first step the compressor loads the CAT. During the loading time, it is cooled by the water pump, the excess heat is stored in the TES. In the second step of the cycle the CAT is discharged, the air is expanded to six bars and reheated in the heat exchanger of the TES. Finally, the air is expanded through the turbine to ambient pressure. The turbine drives the generator, which produces electricity.

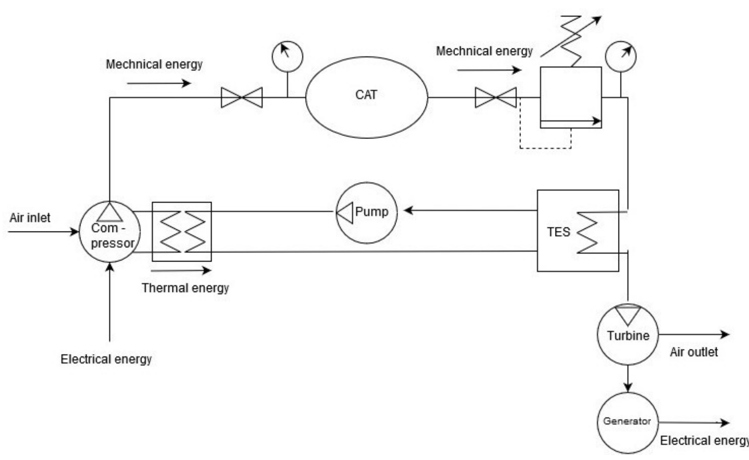


Figure 19: Schematics of A-CAES system (own illustration, 2019)

The maximum time for the whole lab experiment is three hours, it was decided to do three runs with a run time of one hour each. The run time is divided according to Figure 20.

As can be seen in Figure 20, the phases preparation, adjustment and subsequent works have a planned duration of five minutes each. This leaves approximately 22,5 minutes for the charge and discharge phase.

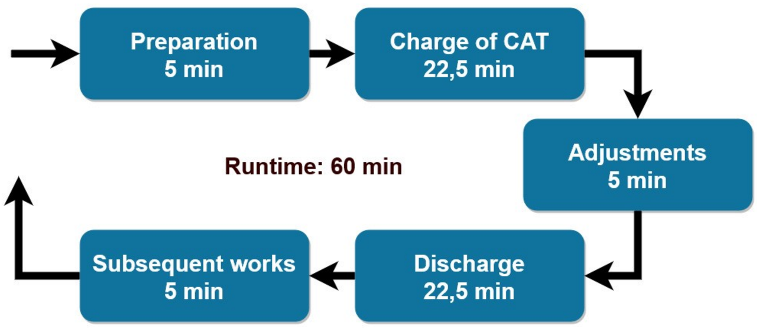


Figure 20: Schedule of one run (own illustration, 2019)

4.1 Assumptions

In order to start the theoretical calculations on the system, some assumptions have to be made. To maintain the comprehensibility of this thesis, all assumptions will be listed in Table 1. Those parameters will be used throughout the entire report. With this information the system can now be designed and calculated. All thermodynamic properties for air and water will be taken from VDI Wärmeatlas 2019, in following referred to as VDI W.a.

Parameter	Assumption	Substantiation
$p_{amb.}$	1 bar	Air pressure at sea-level
$T_{amb.}$	20 °C	Room temperature in laboratory
$Kappa$	1,4	Isotropic exponent for expansion and compression
$T_{Waterinitial}$	15 °C	Initial water temperature for TES (tap water)

Table 1: Assumptions

4.2 Expander

As mentioned before the expander will be selected as the first, and therefore most critical component. With the requirements, wishes and schedule the following guidelines where formulated:

1. Low power output
2. Low air consumption (flow rate)
3. High efficiency

After the initial research four expanders came in the shortlist as seen in table 2.

Type	Power [W]	Efficiency [-]	Air consumption $[m^3/h]$	Price [€]	Delivery time [weeks]
Bibus Easy DrivePMO 0450 Radial Piston Engine	75	31	-	1.500	3
Deprag Vane Motor	200	10	18	280	1
Deprag Green Energy Turbine	5000	85	-	13.000	5
Deprag Gear Motor	-	-	-	14.000	53

Table 2: Short list of expanders

According to the research, it can be concluded that vane motors are the least efficient expanders, whereas turbines are the most efficient expanders. The smallest and cheapest turbine, that could be found, has an output of 5 kW, which renders it incompatible for the project, due to its high-power output. The decision has been made to purchase the model Bibus PMO 0450 Radial Piston Engine, with a maximum power output of 75 W. This decision has been made due to the low air consumption, the price and the efficiency of the model.

4.3 CAT - Compressed Air Tank

With the requirements, wishes and schedule the following guidelines where formulated:

1. Running time of expander: approximately 6 minutes
2. 300 bars (security reasons)
3. High quality

The necessary airmass in the CAT, pressurized with 150 bars, will be calculated, in order to establish a running time of approximately 22,5 minutes (1350 seconds) for the discharging process.

m_{AirCat} stands for the mass of air stored in the CAT. $V_{AirExpander}$ is the air volume flow through the expander, what equals to $5*10^{-3}$ according to the datasheet. $v_{amb.Air}$ is the specific volume of air at 1 bar and equals to 0.83. $t_{c}ycle$ equals the running time of discharge cycle that is set on 22 minutes. This gives the following equation.

$$\begin{aligned} m_{AirCAT} &= \frac{V_{AirExpander}}{v_{amb.Air}} * t_{cycle} \\ &= \frac{[\frac{m^3}{s}]}{[\frac{m^3}{kg}]} * [s] \\ &= \frac{5*10^{-3}}{0.83} * 360 = 2.16kg \end{aligned} \tag{4}$$

With equation 5 the volume of the CAT (V_{CAT}) can be calculated. The specific air volume in the CAT at 150 bar is $v_{AirCAT} = 5.6*10^{-3}$. The mass of the stored air in the CAT is calculated before.

$$\begin{aligned} V_{CAT} &= v_{AirCAT} * m_{AirCAT} \\ &= [\frac{m^3}{kg}] \\ &= 5.6*10^{-3} * 2.16 = 12*10^{-3}m^3 = 12l \end{aligned} \tag{5}$$

The closest available standard size of CAT has a volume of 12 l. This will only slightly increase the running time of the air motor and can be compensated by the running time of the compressor. The decision has been made to purchase the model 12L/ 300 bar cylinder - wet paint + irregular neck paint, due to the low price and the short delivery time.

Energy in CAT

In the next step, a calculation can be made on how much energy can be stored within a 12 litre CAT, pressurized with 150 bars. It can be assumed that the compression of the air is isothermal, due to the cooling system of the compressor. Therefore, the stored amount of technical work ($Work_{t.isoth.CAT}$) in the CAT can be calculated as follows:

$$\begin{aligned} Work_{t.isoth.CAT} &= m_{AirCAT} * T_{amb.} * R * ln(\frac{P_{CAT}}{P_{amb}}) \\ &= [kg] * [K] * [\frac{kJ}{kg*K}] * ln[\frac{bar}{bar}] \\ &= 2.14 * 293.15 * 0.287 * ln(\frac{150}{1}) = 902.1kJ \end{aligned} \tag{6}$$

As stated before the technical work stored in the CAT is $Work_{t.isoth.CAT}$. The ambient temperature is described in $T_{amb.}$ and is assumed on 293.15 K. R is the gas constant and equals to $0.287\frac{J}{kg*K}$. The pressure of in the CAT is defined as P_{CAT} and P_{amb} is the ambient air pressure and this is assumed at 1 bar.

4.4 Compressor

The guidelines for the selection of the compressor are as following:

1. Working pressure > 150 bars
2. Water - cooled
3. High efficiency
4. Minimal flow rate: $3\frac{m^3}{h}$

After the initial research three models came in the shortlist shown in table 3.

Type	Power [W]	Efficiency [-]	Flow rate [m^3/h]	Price [€]	Delivery time [weeks]
TOPQSC 300 Bar Piston compressor	1800	20	4,8	339	2
Yong Heng YH-QB01	1800	16	3,5	137	3
Mengs PCP Compressor	1800	14	3,2	251	1,5

Table 3: Short list of compressors

According to the research, it can be concluded that piston compressors are the most suitable option for the CAES demo; high pressures have to be achieved, whereas the flow rate is of minor importance. The decision has been made to purchase the TOPQSC 300 Bar Piston compressor, due to the water-cooling system, the price, the positive online reviews and the high efficiency.

Temperature of adiabatic compression

During the compression the air will heat up, without cooling the compressor it can therefore reach temperatures which might be damaging to components. This can lead to complete failure of the system. The air temperature during adiabatic compression can be calculated.The temperature of the air during adiabatic compression ($T_{CATadiab.}$) can be calculated with equation 7.

k is the isotropic exponent and is set on 1.4 for this situation.

$$\begin{aligned} T_{CATadiab.} &= \frac{T_{amb}}{(\frac{p_{amb.}}{p_{CAT}})^{\frac{k-1}{k}}} \\ &= \frac{[k]}{(\frac{[bar]}{[bar]})^{\frac{k-1}{k}}} \\ &= \frac{293.15}{(\frac{1}{150})^{\frac{1.4-1}{1.4}}} = 1226.96K = 953.81°C \end{aligned} \tag{7}$$

Assuming that there occur no heat losses during the compression, the air in the CAT would reach a temperature of $953, 81°C$, which is unsafe for the operation of the system. Therefore, the air must be cooled during the process. This leads to heat loss, which decreases the efficiency of the system. Therefore, the decision has been made, to attach a TES. This enables the system to store most of the excess heat during compression and return it into the air volume flow during expansion.

Excess heat during compression

The amount of heat, released during compression, assuming an isothermal compression can be calculated with the work of an adiabatic compression and work of an isothermal CAT. The stored amount of technical work ($Work_{t.isoth.CAT}$) in the CAT is calculated in 6. The work of adiabatic compression has to be calculated, this is done with equation 8.

$$\begin{aligned} Work_{t,adiab.CAT} &= m_{AirCAT} * \frac{k}{k-1} * v_{amb.Air} * [(\frac{p_{CAT}}{p_{amb.}})^{\frac{k-1}{k}} - 1] * 10^5 \\ &= [kg] * \frac{k}{k-1} * [\frac{m^3}{kg}] * [(\frac{[bar]}{[bar]})^{\frac{k-1}{k}} - 1] * 10^5 \\ &= 2.16 * \frac{1.4}{1.4-1} * 0.83 * [(\frac{150}{1})^{\frac{1.4-1}{1.4}} - 1] * 10^5 \\ &= 1980.3kJ \end{aligned} \tag{8}$$

The excess thermal heat, which has to be transferred out of the system can now be calculated by subtracting $Work_{t,adiab.CAT}$ from $Work_{t.isoth.CAT}$ as shown in equation 9.

$$\begin{aligned} Q_{isot.compr.} &= Work_{t.adiab.CAT} - Work_{t.isoth.CAT} \\ &= [kJ] - [kJ] \\ &= 1980.3 - 902.1 = 1078.2kJ \end{aligned} \tag{9}$$

The excess heat during the isothermal compression is approximately 1 MJ, this however is only a part of the excess heat, to be stored in the TES. In the next step the waste heat of the compressor engine will be taken into consideration.

Running time of compressor

In order to calculate the loading time of the CAT and therefore the running time of the compressor, the air mass flow of the compressor ($m_{AirCompr.}$) has to be calculated according to equation 10.

$$\begin{aligned} m_{AirCompr.} &= \frac{V_{Compr.}}{v_{amb.air}} \\ &= \frac{[\frac{m^3}{h}]}{[\frac{m^3}{kg}]} \\ &= \frac{4.8}{0.83} = 5.78\frac{kg}{h} = 1.6 * 10^{-3}\frac{kg}{s} \end{aligned} \tag{10}$$

According to the data sheet the air volume flow of the compressor per hour ($V_{Compr.}$) is equal to $4.8m^3$.

The CAT can hold 2,16 kg of air, pressurized with 150 bars, with this data the loading time of the CAT ($t_{loading\ CAT}$) per cycle, can be calculated:

$$\begin{aligned} t_{loadingCAT} &= \frac{m_{AirCAT}}{m_{AirCompr.}} \\ &= \frac{[kg]}{[\frac{kg}{s}]} \\ &= \frac{2.16}{1.6 * 10^{-3}} = 1344s = 22.4min \end{aligned} \tag{11}$$

The duration of one loading cycle of the CAT to 150 bars is 22,4 minutes, with this information the dimensions of the TES can be determined. For security reasons a maximum loading time of 30 minutes will be assumed, this allows the compressor to run longer, without overheating.

4.5 TES - Thermal Energy Storage

The air will be expanded from 150 to 6 bars after leaving the CAT, therefore it will cool down. To increase the efficiency and prevent damage on the airmotor due to condensation or freezing, the air has to be heated up again. In order to heat up the air before it enters the air motor, it has to pass the heat exchanger in the TES.

Size of TES

To calculate the amount of heat, that has to be stored in the TES, not only the excess heat of the compression, but also the excess heat of the engine which drives the compressor, has to be taken into consideration. Different steps are needed to calculate the size of the TES.

In the first step the work of compressor over the loading cycle of the CAT is calculated, therefore a loading time of 1800 seconds is assumed:

$$\begin{aligned} Work_{Compr.} &= P_{Compr.} * t_{loadinCAT} \\ &= [kW] * [s] \\ &= 1.8 * 1800 = 3240kJ \end{aligned} \tag{12}$$

According to the data sheet the power consumption of the compressor ($P_{Compr.}$) is equal to 1.8 kW.

In the second step the stored mechanical energy in the CAT is subtracted, the difference is the heat, which has to be stored in the TES:

$$\begin{aligned} Q_{TES} &= Work_{Compr.} - Work_{t.isoth.CAT} \\ &= [kJ] - [kJ] \\ &= 32440 - 902.1 = 2338kJ \end{aligned} \tag{13}$$

Work of compressor during on loading cycle is defined as $Work_{Compr.}$.

In this step the mass of water for the TES will be calculated, it can be assumed that the initial temperature of the water is 288 Kelvin. The maximum temperature is set to 333 Kelvin. (Note: If the maximum temperature would rise further, the compressor may shut down, due to overheating.)

$$\begin{aligned} m_{WaterTES} &= \frac{Q_{TES}}{c_{pWater} * (T_{max.TES} - T_{initialTES})} \\ &= \frac{[kJ]}{[\frac{kJ}{kg*K}] * ([K] - [K])} \\ &= \frac{2338}{4.2 * (333 - 288)} = 12.4kg \end{aligned} \tag{14}$$

The thermal capacity of water (c_{pWater}) is equal to $4.2\frac{kJ}{kg*K}$. The different temperatures needed for this equation are: the initial water temperate of the TES ($T_{initialTES}$) and the maximum temperate of the TES ($T_{max.TES}$).

In the last step the volume of the water can be calculated, the density of water with the temperature $T_{max.TES}$ will be used for this calculation, due to the expansion during the heating process.

$$\begin{aligned} V_{TES} &= \frac{m_{WaterTES}}{\rho_{WaterTES}} \\ &= \frac{[kg]}{\frac{kg}{m^3}} \\ &= \frac{12.4}{983.2} = 12.6 - 10^{-3}m^3 = 12.6l \end{aligned} \tag{15}$$

To determine the volume of the TES (V_{TES}), the mass of the water in the TES ($m_{WaterTES}$) and the density of the water ($\rho_{WaterTES}$) is needed. The $\rho_{WaterTES}$ is eqaul to $983.2\frac{kg}{m^3}$ with a temperature of the water at $60°C$.

Desing of TES

The TES, as can be seen in Figure 21 will be constructed out of aluminum sheets, with a thickness of 2,5 mm, in order to weld the parts together, using the MIG (metal inert gas) method. The dimensions of the cylinder are 300 mm (diameter) to 340 mm (height). The openings for the air and water cycle will be installed in the lid, to guarantee the impermeability of the container. The draining valve will be installed into the bottom, sealed with a rubber O ring. In a last step the TES will be thermally insulated, with 100 mm mineral wool.

The heat exchanger will be built out of a copper pipe, with an inner diameter of 10 mm. To determine the length of the pipe, a simulation in MatLab will be carried out. The first step however is calculating the initial temperature of the air, at the inlet of the heat exchanger. The desing of the TES is shown in figure 21.

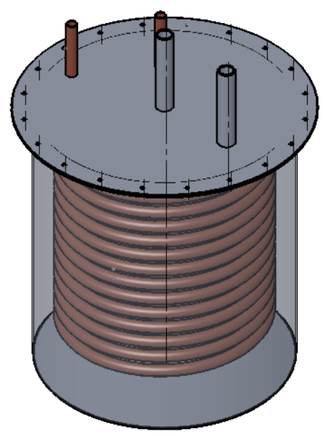


Figure 21: 3D image of TES (own illustration, 2019)

Air temperature at TES inlet

The air motor is working with 6 bars, so the air has to be expanded after leaving the CAT. When air is expanded, the temperature decreases. To calculate the air temperate at inlet of the heat exchanger in the TES ($T_{AirTESin}$) the air pressure at the inlet of the heat exchanger in the TES ($p_{AirTESIn}$), p_{CAT}, $T_{amb.}$ and the constant k is needed. The equation is as follows:

$$\begin{aligned} T_{AirTESin} &= \sqrt[k]{(\frac{{p_{CAT}}^{1-k} * {T_{amb.}}^{k}}{{p_{AirTESIn}}^{1-k}})} \\ &= \sqrt[k]{(\frac{[bar]^{1-k} * [K]^{k}}{[bar]^{1-k}})} \\ &= \sqrt[1.4]{(\frac{150^{1-1.4} * 293.15^{1.4}}{6^{1-1.4}})} = 116.9K = -156.3°C \end{aligned} \tag{16}$$

$T_{AirTESin}$ is a theoretical temperature, in reality the there will be a heat flow over the expansion valve and the air temperature will not drop to $-156°C$. The actual temperature however has to be measured as soon as the system has been set up.

Before designing the heat exchanger the effectivity of the device has to be calculated, in order to dimension it right. The effectivity of the heat exchanger is mainly influenced by the air speed, the heat transfer coefficient, the material and the surface of the pipe.

The efficiency of the heat exchanger will be simulated in MatLab, the protocol can be found in the appendix.

To determine the temperature of the outlet air and the temperature of the water in the tank when the air motor is running, a MatLab script has been created.The following assumptions were made:

- The thermal resistance of the pipe is negligible.
- The inner surfaces of the pipe is smooth.
- The flow is hydrodynamically developed when the pipeline reaches the tank.

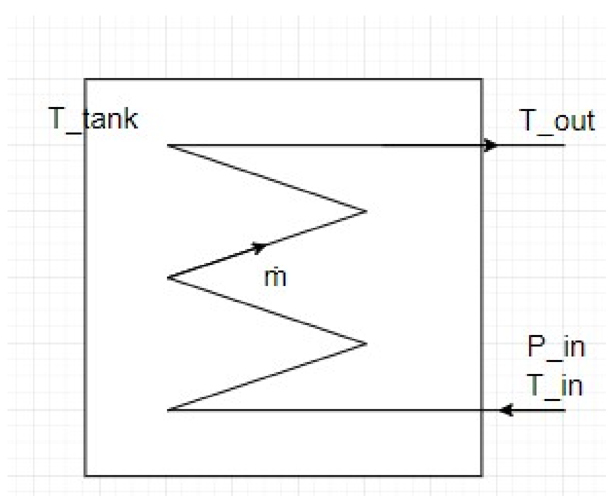


Figure 22: Heat exchanger diagram (own illustration, 2019)

This case is a forced convection process. The air flows into the TES and is heated up. Constant values of system:

- Mass rate: $\dot{m} = 1.467 * 10^{-3}$ [kg/s]
- Temperature air inlet: $T_{in} = 117$ [K]
- Pressure air inlet: $P_{in} = 6$ [bar]

- Temperature initial tank: T_{tank}= 333 [K]

The continuity equation states that the airmass of the input, has to be equal to the airmass of the output. The formulas used in this type of heat exchange process are the following [Cabeza, 2017]:

1. Mean temperature:

$$T_m[K] = \frac{T_e+T_i}{2} = \frac{[k]+[K]}{2}$$

2. Section of the pip:

$$A_{pipe}[m^2] = \frac{\pi * D^2}{4} = \frac{\pi * [m^2]}{4}$$

3. Volume flow rate:

$$V[\frac{m^3}{s}] = \frac{m}{\rho} = \frac{[\frac{kg}{s}]}{[\frac{kg}{m^3}]}$$

4. Speed of the air:

$$\omega[\frac{m}{s}] = \frac{V}{A} = \frac{[\frac{m^3}{s}]}{m^2}$$

5. Reynolds number:

$$Re = \frac{\omega * D}{v} = \frac{[\frac{m}{s}]*[m]}{\frac{m^2}{s}}$$

6. Nusselt number:

$$Nu = \begin{cases} Laminar \rightarrow 3.66 \\ Turbulent \rightarrow 0.023 * Re^{0.8} * Pr^{0.4} \end{cases}$$

7. Heat transfer coefficient:

$$h[\frac{W}{m^2 * K}] = k * \frac{Nu}{D} = [\frac{W}{m * K}] * \frac{Nu}{[m]}$$

8. Surface of the pipe:

$$A_s[m^2] = \pi * D * L = \pi * [m] * [m]$$

9. Outlet temperature:

$$T_e[k] = T_t - (T_t - T_i) * e^{-\frac{h * A_s}{m * Cp}} = [K] - ([K] - [K]) * e^{-\frac{[\frac{W}{m^2 * K}]*[m^2]}{[\frac{kg}{s}]} * [\frac{J}{kg * K}]}$$

10. Logarithmic temperature increase:

$$\Delta T_{in}[K] = \frac{T_i - T_e}{ln(\frac{T_t - T_e}{T_t - T_i})} = \frac{[K]-[K]}{ln(\frac{[K]-[K]}{[K]-[K]})}$$

11. Heat transferred:

$$Q[W] = h * A_s * \Delta T_{in} = [\frac{W}{m^2 * K}] * [m^2] * [K]$$

12. Change of the temperature of the water in the tank:

$$T_{t_f}[K] = T_{t_0} - \frac{Q}{m_t * C_{p_t}} = [K] - \frac{[J]}{[kg]*[\frac{J}{kg * K}]}$$

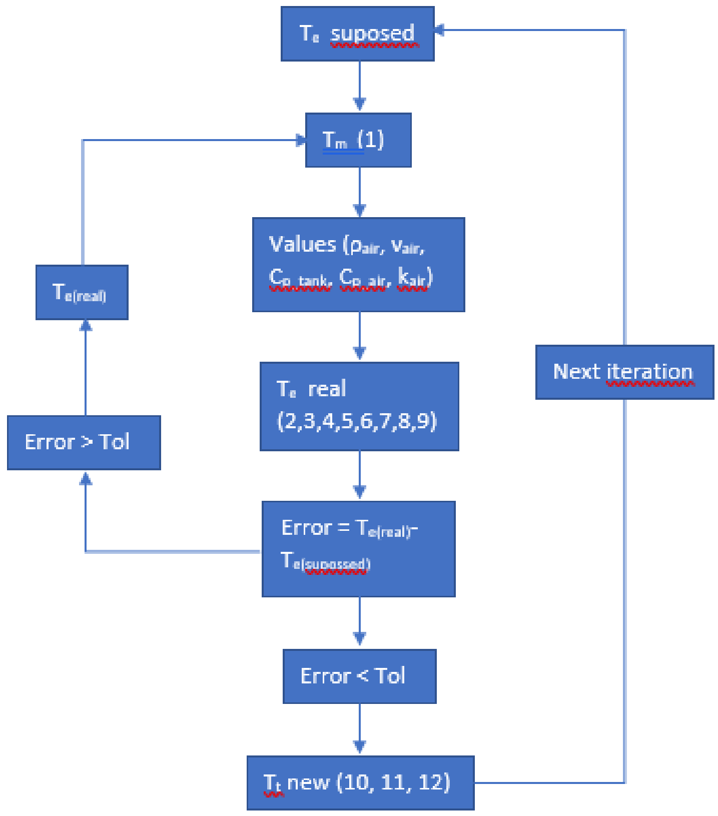


Figure 23: Organization chart of the iterative process (own illustration, 2019)

To calculate the evolution of the outlet air temperature and the temperature of the water in the tank the following iterative process is implemented (figure 23).

First, the temperature of the outlet air is calculated with equations 1 to 9, using the properties of the air at the inlet temperature. The properties are taken from the database CoolProp. If the difference between temperature, obtained with the first part of the script, and the inlet temperature is higher than the tolerance, the process is repeated. Therefore the mean temperature, between the inlet and the outlet air temperature is taken, to determine the air properties.

With these new properties the script calculates a new outlet temperature. If the difference between this new outlet temperature and the previous one is less than the tolerance, the script will accept the last temperature as a valid value. If not, the script will repeat the process indefinitely, until the difference is lower than the tolerance.

With the outlet and the inlet temperature, the total heat exchange of the process in one second is found, which allows the script to find the decrease of temperature in the tank with equations 10, 11 and 12.

The process is repeated as many seconds as the air motor will be running.

Results

Figure 24 shows a graph that shows that the temperature of the outlet air and the temperature of the tank have very similar behaviour. This means that the heat exchanger has a very high efficiency.

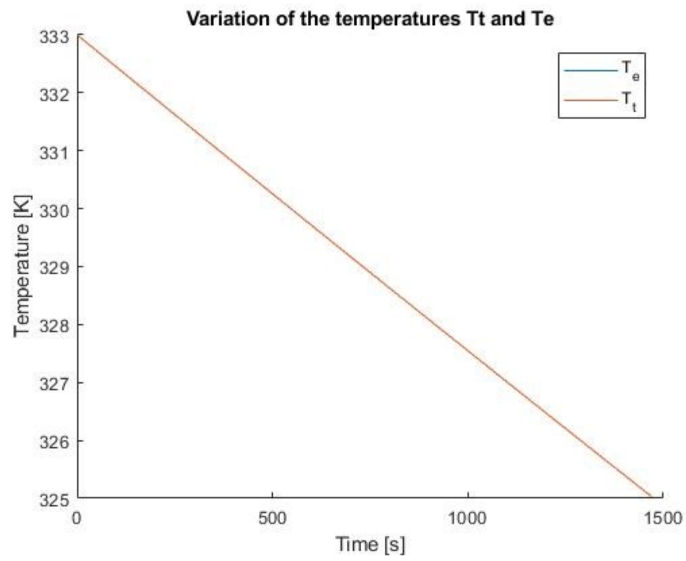


Figure 24: Value of the temperature of the tank and the temperature of the outlet air in function of the time (own illustration, 2019)

Graph 24 give the following results:

	$T_{TESwater}$	$T_{Airoutlet}$
Initial	333 K	333 K
End	325.03 K	325.03 K

Table 4: Results of the simulation

The efficiency of reusing the stored heat can be calculated as follows:

$$\begin{aligned}\eta_{useofstoredheat} &= \frac{Heattransferredtoair}{heatstoredinTES} \\ &= \frac{Cp_{water} * m_{water} * (T_{max.TES} - T_{endTES})}{Cp_{water} * m_{water} * (T_{max.TES} - T_{initialTES}} \\ &= \frac{T_{max.TES} - T_{endTES}}{T_{max.TES} - T_{initialTES}} \\ &= \frac{[K] - [K]}{[K] - [K]} \\ &= \frac{333 - 325.0284}{333 - 293} \\ &= 0.1993 = 19.93\% \end{aligned} \tag{17}$$

Despite the high efficiency of the heat exchanger, the energy that is returned to the system through this process is 19.93 % of the amount of energy, extracted from the heat losses of the compressor. It should be noted that this is an ideal situation. Therefore, the results of the experimental part should look similar but with less efficiency.

4.6 Water pump

With the requirements, wishes and schedule the following guidelines where formulated:

- Variable flow rate
- Low elevation difference
- Low NPSH value
- High efficiency
- Heat resistant up to 70 °C

For the cooling system of the CAES model a high flow rate is needed, whereas a high pressure difference is not given. According to the research in chapter 3, it can be concluded that centrifugal pumps are the most suitable option for this application. After the initial research three models came in the shortlist:

Type	Power [W]	Efficiency [-]	Flow rate [m^3/h]	Price [€]	Delivery time [weeks]
Wilo Yonos Pico 25	4 - 40	95	3,5	127,45	1
Wilo Yonos Pico Plus 25	6-50	95	4,5	268,75	1
Shyliu RS 15	120	85	144	85,99	0,7

Table 5: Short list of water pumps

The decision has been made to purchase the model Wilo Yonos Pico 25, due to the price and the efficiency.

4.7 Valves and pipes

The pipes and fittings have been selected with advice of the company Vaasa LVIS-Center Oy. The pipes and fitting for the water and air are selected separately. All the pipes in the system are designed for a a maximum pressure of 700 bar. The water pipes have an outside dimension of 18 mm because this size is on stock, and affordable. The air pipes have an outside dimension of 8 mm.

4.8 Generator

The generator has to be chosen according to the power output and the rpm (rounds per minute) of the chosen air motor. The Bibus Easy Drive PMO 0450 has a power output of max 75 W, with 240 rpm. The chosen generator has no further influence on the system. The selected generator is SANYO Super R type: R406-011E. This generator is given through the university and came the closes to the requirements of the system. With a relative high RPM and a voltage of 12 V. Because the generator is provided by the university it was possible to increase the budget for other components.

4.9 Turbine design

Air motors have a lower efficiency than turbines, which are better suited for this purpose, but are out of the given budget. A solution for this is to design a turbine and produce it with a 3D printer. The rotor design was taken from the open source platform GrabCAD. The rotor that has been selected is designed by HD solving.

The other parts are designed by the team with Solid works. The following components have been designed and produced also with a 3D printer:

1. Housing rotor back top (rose)
2. Housing rotor back bottom (blue)
3. Housing rotor front (Yellow)
4. Axial connected to rotor with thread and bolts (white)
5. Adjustment mechanism generator to rotor axial, (green)
6. exchangeable gears (blue)

The bearings are connected between the two back rotor housings. The bearings make sure that the axial spins without friction. Figure 25 below gives an exploded view of the turbine, the bearings are colored orange.

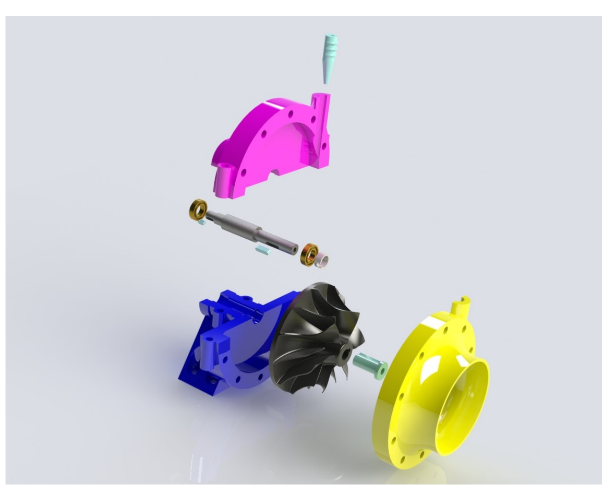


Figure 25: Exploded turbine (own illustration, 2019)

Figure 26 gives an view of the assembled turbine with adjustment mechanism setup.

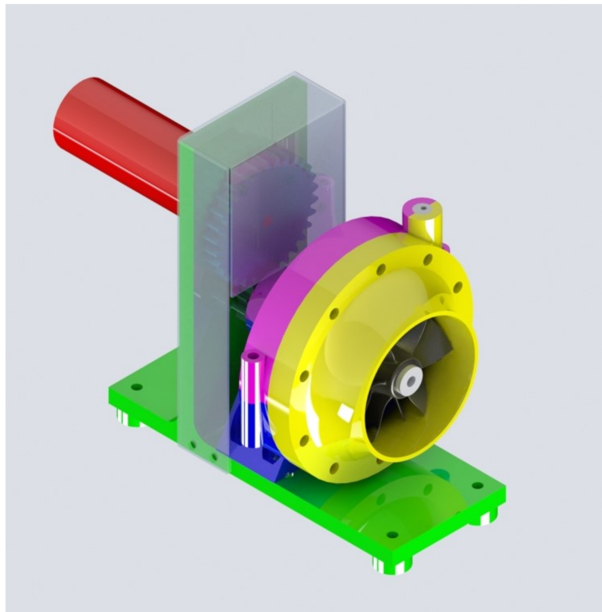


Figure 26: Turbine setup (own illustration, 2019)

4.10 Assembly design

All the components are determined, so the overall placement can be decided on. Figure 27 shows the assembly from above and figure 28 shows a front schematic of the assembly. The aim for the assembly is to get the air flow in one line. The water flow has to follow a circle.

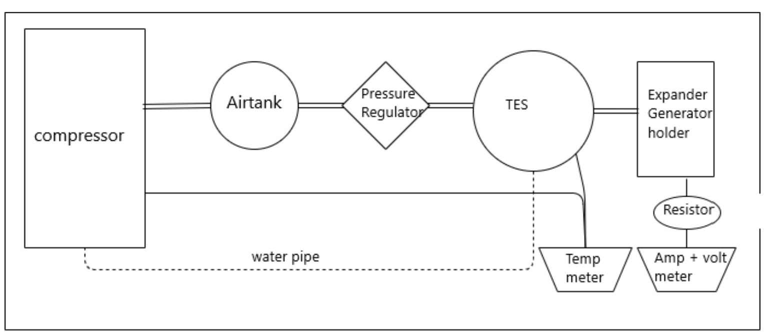


Figure 27: Top view of the overall assembly (own illustration, 2019)

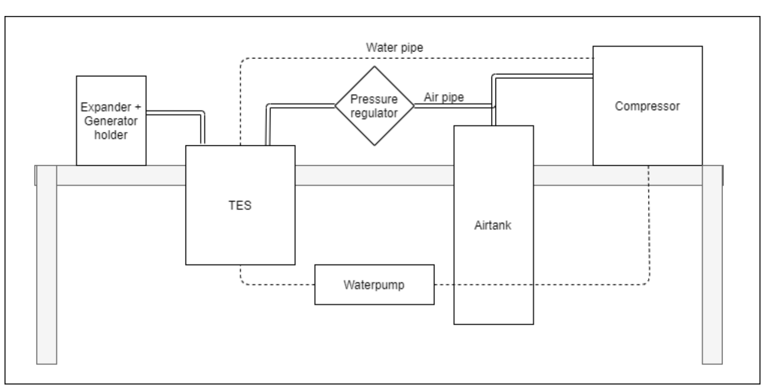


Figure 28: Front view of the overall assembly (own illustration, 2019)

4.11 Efficiency CAES demo

The theoretical efficiency of the system can be calculated. It is assumed that the system needs a charging time of 30 minutes and a return time flow of 25 minutes. To calculate the efficiency of the system the following equations are needed. First, the energy consumption of the compressor. (W_{compr}). This can be determined by multiplying the power of the compressor (P_{comp}) with the time needed to load the CAT ($t_{loadingCAT}$).

$$\begin{aligned} Work_{Compr.} &= P_{Compr.} * t_{loadingCAT} \\ &= [kW] * [s] \\ &= 1.8 * 1800 = 3240kJ \end{aligned} \tag{18}$$

After the energy of the compressor is calculated, also the energy of the CAT ($W_{t.isoth.cat}$) will be determined, this is shown in equation 19.

$$\begin{aligned} W_{t.isoth.CAT} &= m_{AirCAT} * T_{amb} * R * ln(\frac{p_{CAT}}{p_{amb.}}) \\ &= [kg] * [K] * [\frac{kJ}{kg * K}] * ln\frac{[bar]}{[bar]} \\ &= 2,14 * 293,15 * 0,287 * ln(150/1) = 902,1kJ \end{aligned} \tag{19}$$

The energy output of the airmotor will be calculated with equation 20. The amount of energy is calculated through multiplying the power of the airmotor with the time of each cycle:

$$\begin{aligned} W_{AM} &= P_{AM} * t_{cycle} \\ &= [KW] * [s] \\ &= 0,075 * 1350 = 101,25kJ \end{aligned} \tag{20}$$

The efficiency of the compressor (N_{comp}) can be calculated with the previous equations as shown in equation 21.

$$\begin{aligned} N_{comp} &= \frac{W_{t.iso.cat}}{W_{compr}} \\ &= \frac{[kJ]}{[kJ]} \\ &= \frac{902,1}{3240} = 27,8\% \end{aligned} \tag{21}$$

The efficiency of the air motor (N_{am}) can be calculated with the previous equations, as shown in equation 22.

$$\begin{aligned} N_{am} &= \frac{W_{AM}}{W_{t.isoth.CAT}} \\ &= \frac{[kJ]}{[kJ]} \\ &= \frac{101,25}{902,1} = 0,112 = 11,2\% \end{aligned} \tag{22}$$

The complete cycle efficiency of the demo without the TES, as shown in equation 23.

$$\begin{aligned} n_{overall} &= \frac{W_{AM}}{W_{Compr}} \\ &= \frac{[kJ]}{[kJ]} \\ &= \frac{101,25}{3240} = 0,031 = 3,1\% \end{aligned} \tag{23}$$

The complete cycle efficiency of the demo with the TES, as shown in equation 24.

$$\begin{aligned} n_{overall} &= \frac{W_{AM} + Q_{TESout}}{W_{Compr.}} \\ &= \frac{[kJ] + [kJ]}{[kJ]} \\ &= \frac{101,25 + 408,7}{3240} = 15,7\% \end{aligned} \tag{24}$$

4.12 Variables and measurement

The point of building the demo, is to give the students insight of how a CAES system works. That is why it is important to know which variables are adjustable and which values can be measured. If the student adjusts those variables, he can see the effect on the efficiency of the system. The following adjustable variables can be applied for the CAES system.

- The temperature of the cooling water

  The temperature can be influenced by how much cooling water is put into the system. The minimum ammount of cooling water is dictated by how much heat the compressor produces. The water temperature in the system should always remain within safe values, those values will be determined later.

- The pressure in the storage tank

  The pressure can be regulated with a pressure valve. The compressor will most likely have a best efficiency area. The area where the least electricity is used to compress the most air with the highest pressure.

- Pressure inlet of the air turbine

  The inlet pressure can be regulated with the same kind of valve as the pressure in the storage tank. Instead now the pressure running through the turbine is changed. This way students can look for the best efficiency area of the turbine.

- With or without use of a heat exchanger

  In the case of not using a heat exchanger, the water pump is still needed to cool down the compressor. The electricity use of the pump should not be included within the efficiency calculation also, the water should be cooled down before the next run. All of this in prevention of making inaccurate measurements.

To make sure the student could measure certain values of the system, the system needs different sensors and valves to regulate the system. The following sensors could be used in the system:

1. Power meter for usage of the compressor
2. Pressure sensor for airtank
3. Temperature sensor in + out of the heat storage system
4. Power meter for usage of the pump
5. Power meter for the generator

The outcome values of the sensors make it possible for the student to calculate the efficiency of the system, to calculated the effect of an adjustments on the efficiency of the CAES system.

The power usage of the compressor and the pump need to be measured. So the students can calculate how much energy the system used to store the energy in the CAES. With the measured value of generated energy it iss possible to calculate the efficiently of the system.

The calculations can be done with an initial setup for an excel sheet. This excel sheet can be found in the Appendix.

5 Construction

In this chapter the process of assembly and building of the A-CAES model is documented. At first will be explained how the components have been build. The second step is the assembly of the demo.

5.1 Heat exchanger

In the first step of the building phase the heat exchanger for heating up the compressed air will be built. As described in the research the chosen material is copper, due to its thermal conductivity. The copper pipes will be bent in two spirals, the diameter of the inner spiral is 15 cm, the diameter of the outer spiral is 22 cm.

In order to meet the correct diameters a steel plate is cut into the given dimensions of the inner spiral. Then it is bent with the blade roll bending machine into the shape of a pipe and welded together. In the next step the copper pipe is bent around the steel pipe, thirteen rounds are made.

The same procedure is repeated with the outer spiral. At first the steel pipe, with the dimensions of the outer spiral, is welded together. Then the copper pipe is bent around the steel pipe, without separating the copper pipe from the first spiral. See figure 29 and 30.

In the last step 90°connections are welded to the pipe, to enable a proper connection to the lid of the TES casing. The heat exchanger is not attached to the housing by other means.

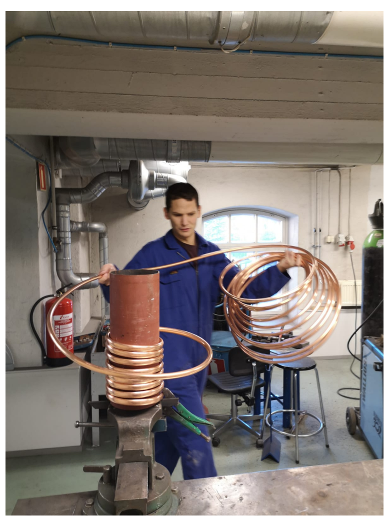


Figure 29: Construction progress of the spirals (own illustration, 2019)

Figure 30: End result spirals (own illustration, 2019)

5.2 Thermal Energy Storage

In the second step the casing of the Thermal Energy Storage (TES) is built, the chosen material is aluminium, with a thickness of 2,5 mm, due to its non-corrosive properties. Firstly, the parts of the casing are cut into the correct dimensions. The rectangular piece for the cylinder jacket, is cut with a punch press, the round parts for the lid, the bottom and the flanch are cut with high-pressure water cutting.

To cut out the inner circle for the flanch, at first holes are drilled with an electric drill around the inner circumference. Afterwards the holes are connected by cutting the aluminum sheet with an angle grinder.

The holes for the draining valve in the bottom and the inlets in the lid are drilled with an electric drill. The draining valve is inserted into the bottom, the heat exchanger and the suction and outlet water pipes are mounted to the lid.

In the last step the pieces are welded together, using the TIG method. All those steps are performed by Vamia Vaasa for the final TES. The pictures below show the building process of the test model.

(a) Welding of Tes (b) Plate Construction

Figure 31: Plate construction (own illustration, 2019)

Figure 32: Drilling of the hole (own illustration, 2019)

5.3 Turbine

The first print of the turbine is conducted with the Ultimaker 3 Extended Dual Extrusion 3D Printer. It uses Volcano PLA 2,85 mm as structural material and Easy Fil, PLA 2,85 mm as support material.

To increase the structural integrity of the turbine rotor is printed again, with the Markforge MarkTwo 3D printer. It uses EXOO ONX as base material, with Carbon Fiber CF-BA 50 inlays, which increases the tear strength of the material.

The axle is made out of metal, by turning it with a lathe. The end result of the turbine is shown in figure 33.

Figure 33: End result turbine (own illustration, 2019)

5.4 Assembly

In this chapter it will be explained, which steps where taken during the assembly of the components.

First the table needs to be assembly ready. This means the holes for the TES and the CAT have to be cut. After that, the connecting parts and holders for the components can be made. Those parts are designed in SolidWorks, made out of steal and are cut and welded in the workshop of Technobothnia. The connecting parts are all painted, to prevent corrosion.

When the table is assembly ready, the components can be placed one by one. After the components are fixed on the table, they can be connected with the pipes. The different fittings are already discussed in the design chapter. The following pictures below show steps of the assembly process.

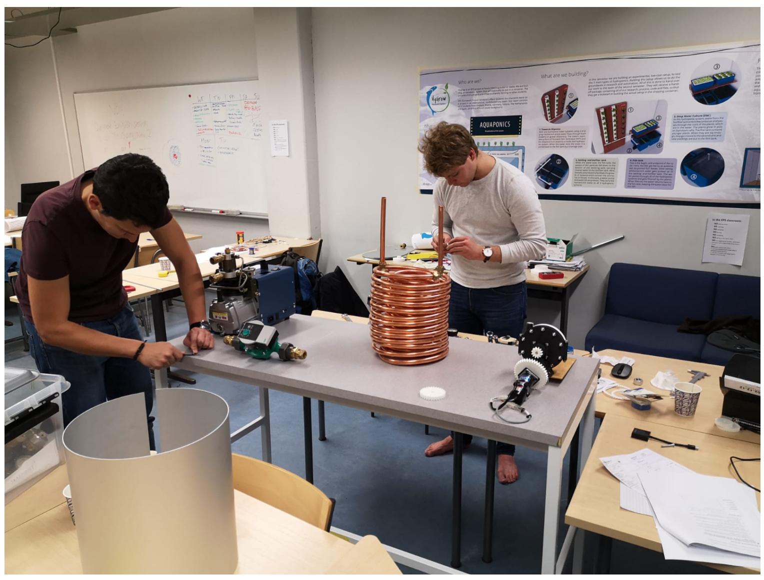


Figure 34: Layout of assembly (own illustration, 2019)

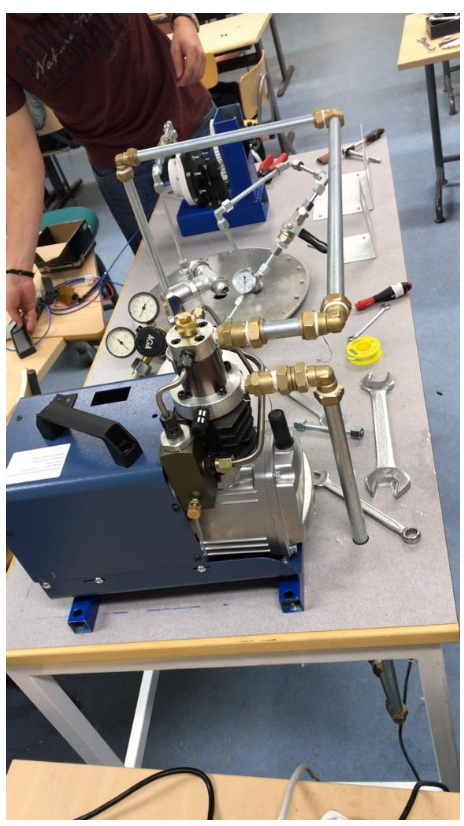


Figure 35: Assembly of the water pipes (own illustration, 2019)

6 Operation procedure

In this chapter will be the procedure steps shown how to run the system. The system can be divided into four phases, three complete runs will be conducted. Phase 1 and 3 have the same sequence, the CAT is charged to a maximum pressure of 150 bars. In phase 2 and 4 the CAT is discharged. In phase 2 the air is reheated in the TES, whereas in phase 4 the TES will be disconnected.

6.1 Phase one and three: Charging of CAT

In this experiment the compressor will pressurize the CAT with 150 bars. A water pump will cool the compressor during the loading time and heat up the TES in this process. During this phase the running time [s], the pressure of the CAT [bar] and the water temperature of the TES [K] will be measured.

Following steps have to be taken:

1. Fill TES with 12,4 liters of water
2. Switch on power
3. Switch on water pump
4. Open valve
5. Switch on power meter and thermometer
6. Switch on compressor
7. Read out values every 30 seconds
8. When pressure of CAT reaches 150 bars switch off compressor
9. Close valve
10. Switch off water pump

The charging phase of the experiment is completed.

6.2 Phase two and four: Discharge of CAT with and without TES

In the second and fourth phase of the experiment the compressed air is expanded through the air turbine. Three complete runs are performed. During this phase the running time [s], the power output of the generator [W], the pressure of the CAT [bar] and the water temperature of the TES [K] will be measured.

The following steps have to be taken:

1. Switch on power meter and thermometer
2. Open the following valves: UNKNOWN
3. Read out values every 30 seconds
4. When power output of generator is zero close valve X
5. Empty TES

The discharge phase of the experiment is completed. When performing phase four the value T of TES can't be recorded. Also step five can be left out.

7 Results

This chapter discusses if the demo performance as was expected. Unfortunately during the construction two problems occur that could not be fixed in time. There is a leakage between the compressor and the CAT. The second error that occur is that the air motor did not arrive on time. That is the reason the first set-up is only with the self build turbine. Due lack of time, the components are all tested separately. This could have been done, by dividing the demo in different phases. See figure 36 for the different phases.

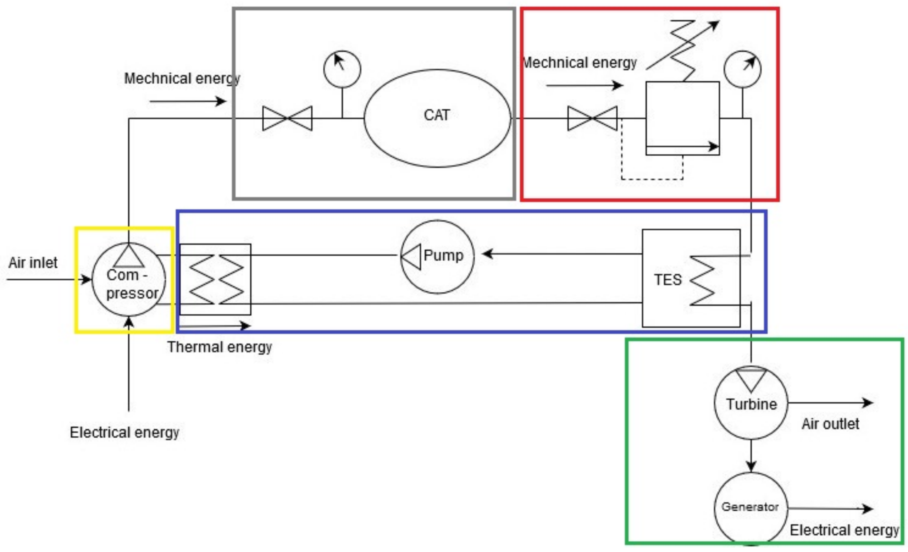


Figure 36: Different phase of the demo (own illustration, 2019)

Compressor (yellow section)

First the compressor, the yellow square is tested. Through different test runs, it is assured the compressor did not has any issues. While controlling the compressor the water flow through the TES can be tested at the same time (blue square).

Water system (blue section)

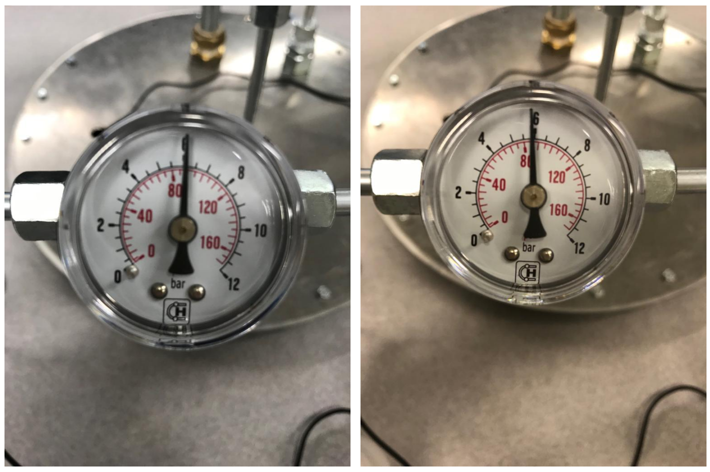
This section is checked by connecting all the components together and filling the TES with water. In the first test, the water pump had to run for 3 hours. No leakage occured, that means that this part is watertight. In the second test, the compressor was turned on for 15 minutes. During this test the water temperature increased and the compressor stayed under the maximum temperature of 80 degrees. This concludes that the water can cool the compressor enough.

CAT (grey section)

With the use of the compressor the CAT is checked, the grey square in figure 36. As stated before there were air leakages, which made it difficult to do a complete test run. After the leakages where fixed, air was compressed in the air tank, to check if the problems were solved. Figure 37 shows the difference in the pressure with a time different of two and a half hours. As can be seen there is almost no pressure release.

Pressure regulator (red section)

With the use of the compressor and by closing the air tank, the pressure regulator can be checked, the red square in figure 36. The compressor increases the pressure in the pipe, the pressure sensor shows a increase of pressure. When opening the valve, the air flows through the selected pressure outlet.



(a) 10:30 (b) 13:00

Figure 37: Pressure in the CAT (own illustration, 2019)

Turbine and generator (green section)

The green section is the part, where the conversion of mechanical energy to electricity takes place. This is tested by using high pressure compressed air net system in Technobotnia. The turbine is connected to the DC motor with the gears. The DC motor is connected to a resistor, with an amp-meter and a volt meter. When the pressured air is let in to the turbine, the turbine starts to scroll and powering the generator. The amount of energy that is regained is shown with the volt and ampere meter.
This concludes that all the phases of the system work individual correct. But the overall efficiency of the system can not be tested yet.

8 Conclusion

The mission of this project was to build an energy storage model, that allows students to gain deeper insights into the principles of the technology. With project management tools a suitable plan of action was formed. In the research was concluded that an Adiabatic-CAES is the most suitable system as a demo. This is because diabatic-CAES is not a closed system and is dependent on fossil fuels. Isothermal-CAES systems are more complex than Adiabatic-CAES and still in development. This means that a lot of components are not available in the given price range.

In the design phase the following components are selected for the demo. For the expander two options were chosen, a Bibus PMO 0450 Radial Piston Engine and a self designed 3D-printed turbine. A turbine is better suited for regaining energy, but not within the given budget and not available in the right size. With the printed 3D model the possible higher efficiency of turbines can be tested. The selected air tank is a professional tested scuba tank with a volume of 12 l, designed to withstand 300 bars. The selected compressor is a water cooled piston compressor. Thermal Energy Storage (TES) is designed and build by the project team because there was not a standardized size suitable for the system. The selected water pump for the TES, is a Wilo Yonos Pico 25. The generator is provided by Technobotnia.

The construction of the turbine is conducted with the Ultimaker 3 Extended Dual Extrusion 3D Printer and the Markforge MarkTwo 3D printer. The TES is produced by the school Vamia Vaasa. All the components were assembled on the table. The system was tested in five different phases. It was concluded that all the phases of the system work individually correct. The overall efficiency of the system, can not be tested because of a leakage between the compressor and the CAT and the air motor, that did not arrive on time.

9 Recommendations

The recommendations can be split in two subjects, how to improve the demo and how to improve the project process. First the project process and second the recommendations for performance of the demo will be discussed.

As stated before the system could not be tested as a complete demo. This happened due to the lack in time management. This project was focused on building a demo, yet the project group in the beginning focused more on the research. This resulted in a delay in starting with the designing and building phase. For project of the Energilagring group in the future, it is recommended to start the construction of designed components before having designed a completed system.

The overall demo is not tested as stated before, but there are still some things known already, that (theoretically) can be improved. In the future, there should be done more research about how to get the thermal energy back in the system to improve the efficiency. In the research was concluded that a turbine is more suitable for regaining energy. Nevertheless, in this demo an air motor is used, because of budget limitations. To improve the performance of the demo, it is a good investment to dig deeper in the different kind of expanders available. Not all the heat of the compressor is captured and stored in the TES. So further research in the capturing the heat of the compressor and giving it back to the air, could be improved for a higher efficiency.

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List of abbreviations

Abbreviation	Meaning
EPS	European Project Semester
CAES	Compressed Air Energy Storage
TES	Thermal Energy Storage
CAT	Compresses Air Tank
VAMK	Vaasan Ammattikorkeakoulu
UAS	University of Applied Sciences
ECTS	European Credit Transfer and Accumulation System
ISO	International Organization of Standardization
PDCA	Plan,Do,Check and Act cycle
BCWP	Budgeted Cost of Work Performed
ACWP	Actual Cost of Work Performed
A-CAES	Adiabatic CAES
D-CAES	Diabatic CAES
NPSH	Net Positive Suction Head
HVAC	Heating, Ventilating and Air-Conditioned systems
VDI	Virtual Desktop Infraestructure
MIG	Metal Inert Gas

Symbols	Description	units
emf	Electromotive force	V
JB	Magnetic flux	Wb
B	Magnetic field	T
R	Resistance	Ω
I	Electric current	A
m_{AirCAT}	Mass of air compressed	Kg
$V_{AirExpander}$	Volume flow through the expander	m^3/s
$v_{amb.Air}$	Specific volume of air	m^3/kg
t_{cycle}	Running time of discharge	s
V_{CAT}	Volume of the CAT	m^3
$Work_{t.isoth.CAT}$	Work stored in the CAT	kJ
T_{amb}	Ambient temperature	K
P_{CAT}	Pressure inside the CAT	bar
P_{amb}	Ambient pressure	bar
R	Gas constant	kJ/kg/K
$T_{CATadiab.}$	Temperature of adiabatic compression	K
$Work_{t.adiab.CAT}$	Work of the adiabatic compression	kJ
k	Isotropic exponent for expansion and compression	-
$Q_{isotcompr.}$	Excess of thermal heat	KJ
$V_{Compr.}$	Volume flow of the compressor	m^3/h
$m_{AirCompr.}$	Air mass flow of the compressor	kg/s
$t_{loadingCAT}$	Duration of one loading cycle	s
$P_{Compr.}$	Power consumption of the compressor	kW
$Work_{Compr.}$	Work of the compressor over the loading cycle	kJ
Q_{TES}	Heat stored in the TES	kJ
$m_{WaterTES}$	Mass of water of TES	Kg
Cp_{water}	Specific heat of water	kJ/kg/K
$T_{max.TES}$	Maximum temperature of TES	K
$T_{initial.TES}$	Initial temperature of TES	K
V_{TES}	Volume of the TES	m^3
$\rho_{WaterTES}$	Density of the water	Kg/m^3
$TAirTESin$	Air temperature at the inlet of the heat exchanger	K
$p_{AirTESin}$	Air pressure at the inlet of the heat exchanger	bar
$\dot{m}$	Air mass rate flow	Kg/s
T_m	Mean temperature of the air	K
D	Diameter of the pipe	m
A_{pipe}	Section of the pipe	m^2
q	Rate flow of air	m^3/s
ρ	Density of air	Kg/m^3
v	Speed of air	m/s
Re	Reynolds number	-
Nu	Nusselt number	-
h	Heat transfer coefficient	$W/m^2/K$
k	Conductivity of the air	W/m/K
A_s	Surface of the pipe	m^2
T_e	Outlet temperature	K
ΔT_{ln}	Logarithmic temperature increase	K
Q	Heat flow transference	W
T_{tf}	Temperature of the water in intervals of one second	K
η_{use}	of storage heat Percentage of useful heat	-
W_{am}	Output energy from the airmotor	kJ
P_{am}	Power of the air motor	KW
N_{compr}	Efficiency of the compressor	-
N_{am}	Efficiency of the air motor	-
$N_{overall}$	Complete cycle efficiency	-

11 Appendix

11.1 List of requirements

The list of requirements is described in the Problem analyse and listed as follows:

1. The complete test cycle takes maximum 3 hours.
2. The system cost maximum € 9000,-.
3. The lifespan of the system is minimum 5 years.
4. The system can have an maximum dimension of 2x2x4,5 meter.
5. The system stays under 85 db.
6. The system has at least two adjustments settings.
7. The system has at least four values what are able to read out.
8. The system has at least an efficiency of 2 % of returning its energy.

11.2 Belbin team roles

Dr Meredith Belbin and his team did research about the diverse mix of behaviours in successful teams. They discovered that there are nine clusters of behaviour these were called team roles. To have a high preforming team you need all the different team roles. However, this doesn't mean that every team requires nine people! Most people will have two or three Team Roles that they are most comfortable with, and this can change over time. Each Team Role has its strengths and weaknesses, and each has equal importance. As stated on the Belbin website. All members of the project made a Belbin test. With the results of the test we can see where are strength lie and what will be risky for our group. First the different team roles will be explained, as they are stated on the Belbin website. After that the results of every team member will be analysed. Finally there is a summary made with all the different team roles present in our team.

- Coordinator = needed to focus on the team objectives, draw out team members and delegate work appropriately
- Shaper = provides the necessary drive to ensure that the team keeps moving and does not lose focus or momentum
- Plant = tend to be highly creative and good at solving problems in unconventional ways
- Monitor = provides a logical eye, making impartial judgements where required and weights up the team's options in a dispassionate way
- Implanter = needed to plan a workable strategy and carry it out as efficiently as possible
- Resource investigator = uses their inquisitive nature to find ideas to bring back to the team
- Team worker = helps the team to gel, using their versatility to identify work required and complete it on behalf of the team
- Finisher = most effectively used at the end of tasks to polish and scrutinise the work for errors, subjecting it to the highest standers of quality control
- Specialist = brings in-depth knowledge of a key area to the team

Team members

For all the team members a graph is made with the results see figure 1 until 5. Out of this graph the top two of team roles of every member is mention, whit his/her strengths and weakness.

	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	1	0	3	2	0	0	2	2
2	0	1	3	1	0	2	2	1
3	0	0	2	0	1	3	3	1
4	1	2	2	2	1	2	0	0
5	0	1	2	2	1	3	0	2
6	0	0	2	2	2	2	2	0
7	3	0	0	0	0	3	2	2
Tot	5	4	14	9	5	15	11	8

think act

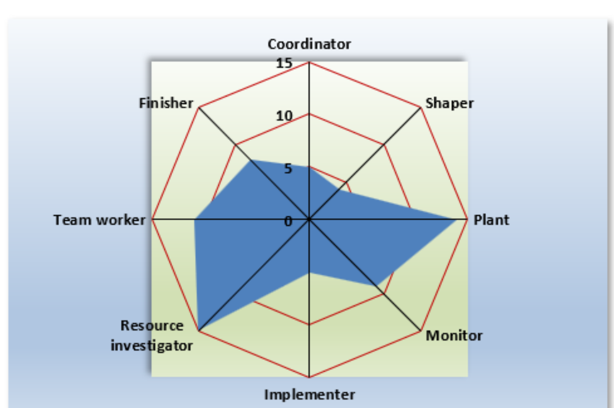
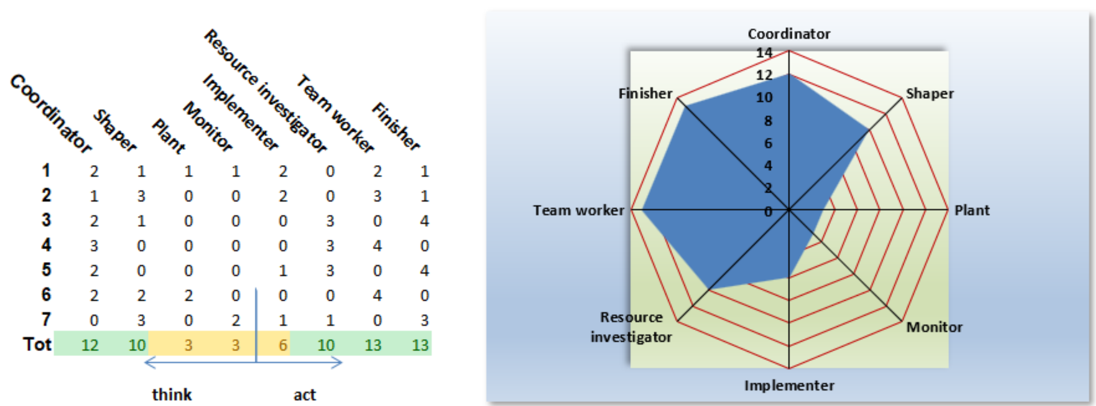


Figure 38: Belbin test Carles

As shown in the figure 38 the two key team roles for Carles are plant and resource investigator. The following strengths and weakness will come with this team roles.

STRENGTHS	WEAKNESS
Creative	Might ignore incidentals
Imaginative	Too preoccupied to communicate
Free thinking	Forgetful
Solves difficult problems	over-optimistic
Outgoing	can lose interest
Develops contacts	

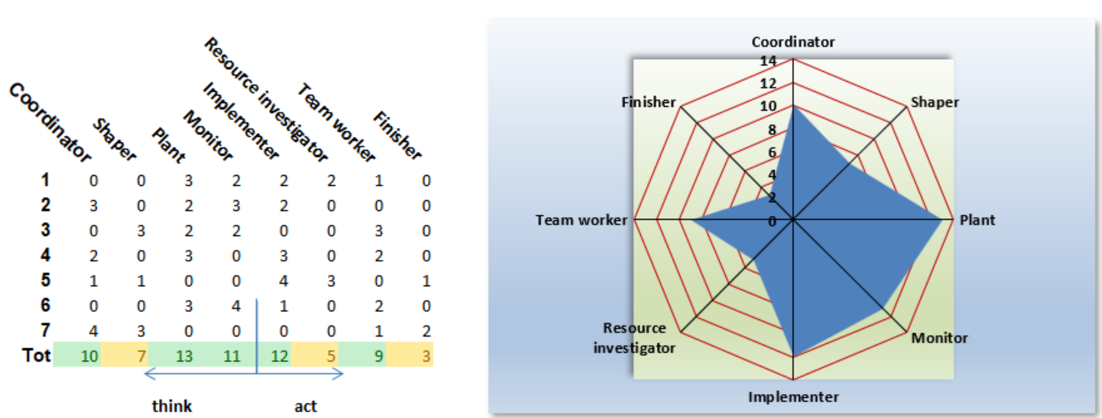


	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	2	1	1	1	2	0	2	1
2	1	3	0	0	2	0	3	1
3	2	1	0	0	0	3	0	4
4	3	0	0	0	0	3	4	0
5	2	0	0	0	1	3	0	4
6	2	2	2	0	0	0	4	0
7	0	3	0	2	1	1	0	3
Tot	12	10	3	3	6	10	13	13

Figure 39: Belbin test Eeke

As shown in the figure 39 the two key team roles for Eeke are team worker and finisher. The following strengths and weakness will come with this team roles.

STRENGTHS	WEAKNESS
Co-operative	Avoiding confrontation
Perceptive	Indecisive in crunch situations
Diplomatic	Worry unduly
Painstaking	Reluctant to delegate
Conscientious	Extreme perfectionism
Polish and perfects	



	Coordinator	Shaper	Plant	Monitor	Implementer	Resource investigator	Team worker	Finisher
1	0	0	3	2	2	2	1	0
2	3	0	2	3	2	0	0	0
3	0	3	2	2	0	0	3	0
4	2	0	3	0	3	0	2	0
5	1	1	0	0	4	3	0	1
6	0	0	3	4	1	0	2	0
7	4	3	0	0	0	0	1	2
Tot	10	7	13	11	12	5	9	3

Figure 40: Belbin test Felix

As shown in the figure 40 the two key team roles for Felix are plant and implementer. The following strengths and weakness will come with this team roles.

STRENGTHS	WEAKNESS
Creative Imaginative Free thinking Solves difficult problems Practical Reliable Efficient	Might ignore incidentals Too preoccupied to communicate Forgetful Inflexible Slow with new possibilities

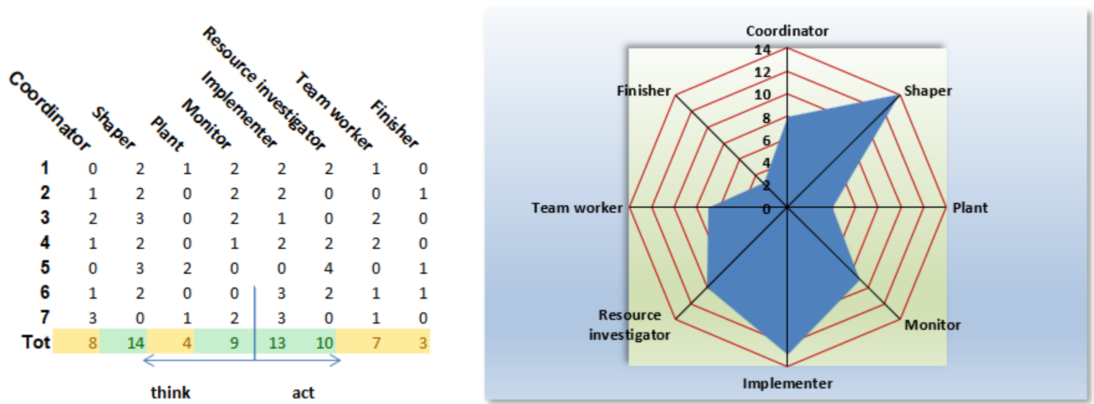


Figure 41: Belbin test Leon

As shown in the figure 41 the two key team roles for Leon are shaper and implementer. The following strengths and weakness will come with this team roles.

STRENGTHS	WEAKNESS
Challenging Dynamic Thrives on pressure Practical Reliable Efficient	Provocation Offend people's feelings inflexible Slow with new possibilities

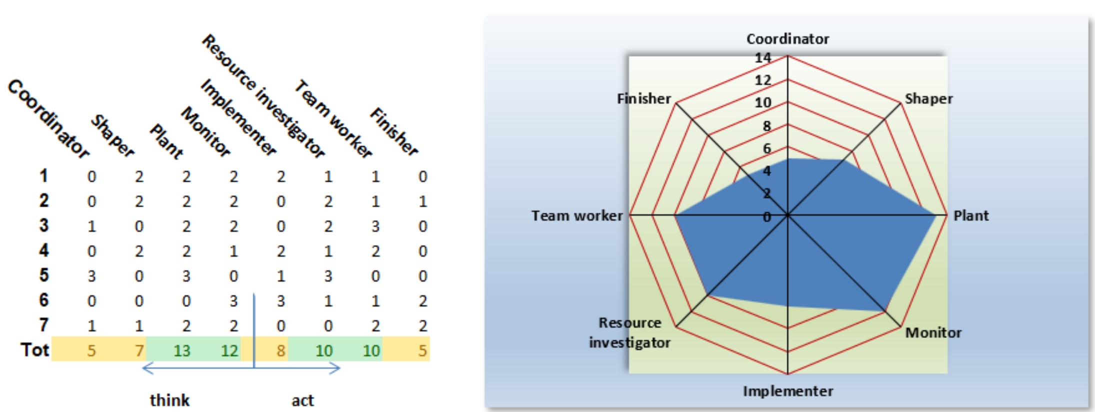


Figure 42: Belbin test Renier

As shown in the figure 42 the two key team roles for Renier are plant and monitor. The following strengths and weakness will come with this team roles.

STRENGTHS	WEAKNESS
Creative Imaginative Free thinking Solves difficult problems Strategic Sees all options and judges accurately	Might ignore incidentals Too preoccupied to communicate Forgetful Lacks the drive and ability to inspire others Overly critical

11.3 Schedule

Objective	Task owner	Check	Deadline week nr.
Research phase			
View on energy storage	eeke	Leon	3
Discion on which type of system for demo	eeke	Leon	1
Research in different CAES system	Leon	Felix	5
Compraring CAES	Leon	Felix	4
Principle explained for different solutions of each components	Leon	Eeke	5
Design system			
Discion of which system (A-CAES)	Leon	Eee	4
Schematics of the system	Leon	Eeke	4
Overview of what has to been calculated?	Carles	Leon	5
Needed formulas (including symbol list)	Felix	Carles	6
Report of assumptions	Renier	Leon	6
Report of know values	Renier	Leon	6
Calculation each component	Felxi	Eeke	7
Component selection	Renier	Leon	7
Component slection with morfologic chart	Leon	Renier	8
3d models of total system	Eeke	Renier	9
Bill of materials	Eeke	Renier	8
Blue print of overall build system	eeke	Renier	9
Adjustmance and measuring system	Eeke	Renier	8
Inform workplace manager of bill materials	Felix	Renier	6
Theoritcaly eficiency calculation	Renier	Leon	7
Order list raport	Eeke	Leon	7
Building phase			
Production plan/schedule	Renier	Leon	7
Production tools	Renier	Felix	7
Test run	Felix	Eeke	10
Data analysing	Eeke	Felix	10
Proof of Principle turbine	Leon	Renier	9
Project management phase			
Define the project	Eeke	Leon	3
Define mission and end result	Eeke	Leon	3
Make a list of reqruiments	Carles	Eeke	4
Objectives	Leon	Eeke	4
Risk management	Leon	Eeke	6
Quality management	Eeke	Leon	6
Human research management	Eeke	Leon	6
Cost management	Felix	Renier	7
Change + communication management	Renier	Leon	6
Schedule of project (Work breakdown structure)	Leon	Eeke	4
Final report phase			
Abstract	Leon	Eeke	11
Introduction	Eeke	Leon	11
Combined documentation	Felix	Renier	10
Reference	Felix	Leon	10
Summary	Renier	Eeke	11
Conclusion	Eeke	Renier	11
Appendix	Leon	Felix	12
Sub-phase			
Spelling corrector	Eeke	Felix	13