Final Report

# Carbon Capture Demo

Novia University of Applied Sciences

Vaasa, Spring 2024


**Team members:**

Isabel Hela Kuchta

Jarne Heylen

Alissa Mzouri

**Supervisor:**

Cynthia Söderbacka


**Degree Program:**

European Project Semester

NOVIA
UNIVERSITY OF APPLIED SCIENCES

# Table of content

# List of figures



# List of tables

# 1 Abstract

The main objective of this project is to find a solution to build a carbon capture demo that will be carried out for the next EPS group.

The research and analysis in this report is carried out by this EPS team to gain a deep understanding of the subject. The team researched various carbon capture technologies based on literature research or review. All the theories were then synthesized to be able to propose a concept for a DIY prototype.

The subsequent EPS group opted against constructing a DIY setup, instead favoring the development of a demonstration model using pre-purchased components. Therefore, halting the construction phase and shifting focus towards theoretical exploration and anticipated outcomes was deemed the most pragmatic approach. Detailed plans were outlined for the progression of the building phase, alongside expectations for test runs, planned procedures, and projected results.

After thorough research, the team identified adsorption as the most suitable technology for our purpose. Synthetic zeolites emerged as particularly promising for post-combustion capture. The decision to utilize a fixed bed reactor was based on its simplicity of configuration. For regeneration, temperature swing adsorption stood out as the most viable option, as it solely relies on zeolite, features a fixed reactor, and facilitates nitrogen purging due to its easy accessibility. Stakeholder preferences also played a significant role in the process selection, favoring solutions compatible with existing processes. Consequently, desorption via temperature increase was chosen for this project.
Finally, all this allowed to propose a plan for the implementation of the demo for the next EPS group.

# 2 Introduction

The thread of climate change is successively growing.

At the 21 Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) the crucial Paris Agreement was adopted by 196 countries. The primary ambition of this agreement is to limit global warming to below 2 ° C compared to preindustrial times (United Nations , 2024).

The climate change is primarily driven by anthropogenic carbon dioxide ($CO_2$) emissions. So, the increasing pressure on decarbonization is concerning all industries.

The target is a net-zero of $CO_2$ emissions.

This creates a need for Carbon Capture and Storage (CCS) (Loughrey, 2024).

For energy intensive industries another factor motivating the reduction of $CO_2$ emissions is the 2005 launched EU Emission Trading System. Its goal is the reduction of greenhouse gases by monitoring the emissions of about 10.000 installations in the EU, Lichtenstein, Iceland, and Norway.

The cap of emissions is defined by a certain amount of emission licenses, which are manly traded between the participants, on the EU carbon market.

By the end of the year, the companies must have one emission allowance per emitted tone of carbon dioxide equivalent ($CO_2eq$) (Directorate-General for Climate Action, 2024).

Correspondingly, the current efforts on improving and developing new methods and materials on carbon capture are enormous.

The number of processes that are designed to capture carbon from industrial sources or even the environment is high. There are for example: Cryogenic capture, Capture by calcium cycle, Capture by absorption, Membrane separation and Capture by adsorption.

The last-named technology, Capture by adsorption, is the target of this report.

A short description of the other processes will lead to deciding on this process, based on the circumstances of this project.

The report will focus on the theoretical background of adsorption. From that, the practical ideas on a DIY prototype will evolve and be implemented. The DIY prototype will be built using the left-over zeolite from an old project that had used the zeolite for drying the air during compression. According to literature findings, zeolite is used in carbon capture by adsorption and the laboratory setup will pose interesting opportunities for test runs. Through comparison with literature the properties can be demonstrated.

# 3 Project description

## 3.1 Background

The capture of carbon dioxide emitted by factories and industrial facilities has become a major concern in the fight against climate change. In many regions, factories emit $CO_2$ into the atmosphere, thereby contributing to the increase in greenhouse gas level. There are industrial facilities actively seeking to utilize the emitted $CO_2$ as a resource rather than letting it escape into the atmosphere. The situation of factories producing $CO_2$ and seeking to use it requires an approach to the capture and effective utilization of this greenhouse gas. This issue raises several important questions, including appropriate capture methods, potential applications of captured $CO_2$, and the environmental and economic implications associated with these initiatives.

In addition to fuel production, captured $CO_2$ can also be used in industrial processes such as the production of construction materials, chemicals, and even in agriculture. For instance, in agriculture, $CO_2$ can be injected into greenhouses to enhance plant growth, thereby increasing yields while reducing reliance on chemical fertilizers.

We are faced with a significant challenge due to $CO_2$ emissions from factories, but we also have the opportunity to turn this challenge into an opportunity by capturing and effectively utilizing this $CO_2$. By adopting advanced capture technologies and exploring new applications for captured $CO_2$.

## 3.2 Mission and vision

The theme program “Climate neutral Vaasa 202X” is the ambitious goal of the city of Vaasa. It is subdivided into three main goals:

" 1. Climate neutral energy consumption and reduction of CO2 emissions.

2. Green transition & Global footprint

3. Finland's most energy smart and energy efficient city" (City of Vaasa 2024, 2024)

The detailed description of the required steps and on measuring achievements get reported to a steering group (City of Vaasa 2024, 2024).
Under the lead of Sören Mattbäck from Novia University of applied sciences, in cooperation with Vaasa University of Applied Sciences(VAMK) and Åbo Akademi University (ÅA), Ab Stormossen Oy and Westenergy Oy, the project of "MAP-UP-P2X-Mapping $CO_2$ Streams in Ostrobothnia: Unlocking potential for P2X Economy" is running between January 2024 until and end of December 2025 (Novia Yrkeshögskolan, 2024).
The region of Ostrobothnia is investigating $CO_2$– and P2X- Technologies, as well as given resources to find new solutions in energy production to replace peat.
The intention is to achieve self-sufficiency and circular economy, to meet the demand from Finland and the EU to keep the global warming beneath 1.5 ° C.
Through SWOT (Strengths, weaknesses, opportunities, threats) and PESTEL (Political-, economic, socio-cultural-, technological-, legal- and ecological/environmental factors) analyzes the currents of material and chemics are to be understood.
The enhanced understanding is to enable the region to find new solutions concerning energy production and waste management (Vaasa University of Applied Sciences, 2024).

The Project "Carbon Capture" aims to build a working Carbon Capture Demo. It is supposed to be just the demo version, not a real plant. This project is part of the EPS spring semester 2024 and will focus on building the reactor for the carbon capture and prepare the demo for the next EPS group who will complete the complex with the compounds needed for the recovery.

Some factories have realized the potential of $CO_2$ as a valuable resource rather than simply a pollution waste. The first step in this process is to effectively capture the $CO_2$ emitted by chimneys and industrial processes.

These technologies aim to isolate $CO_2$ and separate it from other gases emitted by factories before storing it or using it for other purposes.

Once captured, factories can use $CO_2$ in several beneficial ways. One of the most promising uses is in the production of synthetic fuels, such as methanol or synthetic hydrocarbons, thereby reducing net $CO_2$ emissions into the atmosphere.

However, it is important to note that $CO_2$ capture and utilization are not definitive solutions to the problem of climate change. They should be seen as part of a broader strategy to reduce greenhouse gas emissions and transition to renewable and low-carbon energy sources. Additionally, it is crucial to ensure that technologies used for $CO_2$ capture are sustainable and environmentally friendly, avoiding negative impacts on the local environment such as air, water, or soil pollution.

Furthermore, economic considerations must be considered, including the operating costs of capture facilities, $CO_2$ market prices, and financial incentives to encourage businesses to adopt more sustainable practices. It is essential to consider the challenges and implications associated with $CO_2$ capture and utilization. Capture technologies can be costly to implement and may require significant investments in capital and infrastructure.

### 3.3 $CO_2$ Valorization

CO2 valorization is an innovative approach that transforms carbon dioxide, typically considered a pollutant, into a valuable resource. Rather than simply disposing of CO2, this technique retrieves it for something useful.

The CO2 valorization process involves capturing it from emission sources such as factories and power plants, followed by its conversion into valuable products. This conversion can take various forms, including the production of synthetic fuels, industrial chemicals, and innovative construction materials. The major advantage of CO2 valorization is its ability to contribute to greenhouse gas emissions reduction while offering economic opportunities. By transforming CO2 into valuable products, this approach also promotes the transition to a more circular economy, where waste is reused and valorized.

However, there are still challenges to overcome, including cost, efficiency of capture and conversion technologies. Thus, CO2 valorization represents a crucial avenue in the transition to a more sustainable and resilient economy. With continued investments in research and development, it can play a vital role in combating climate change while creating new economic opportunities (Ajay Thapa, 2023).

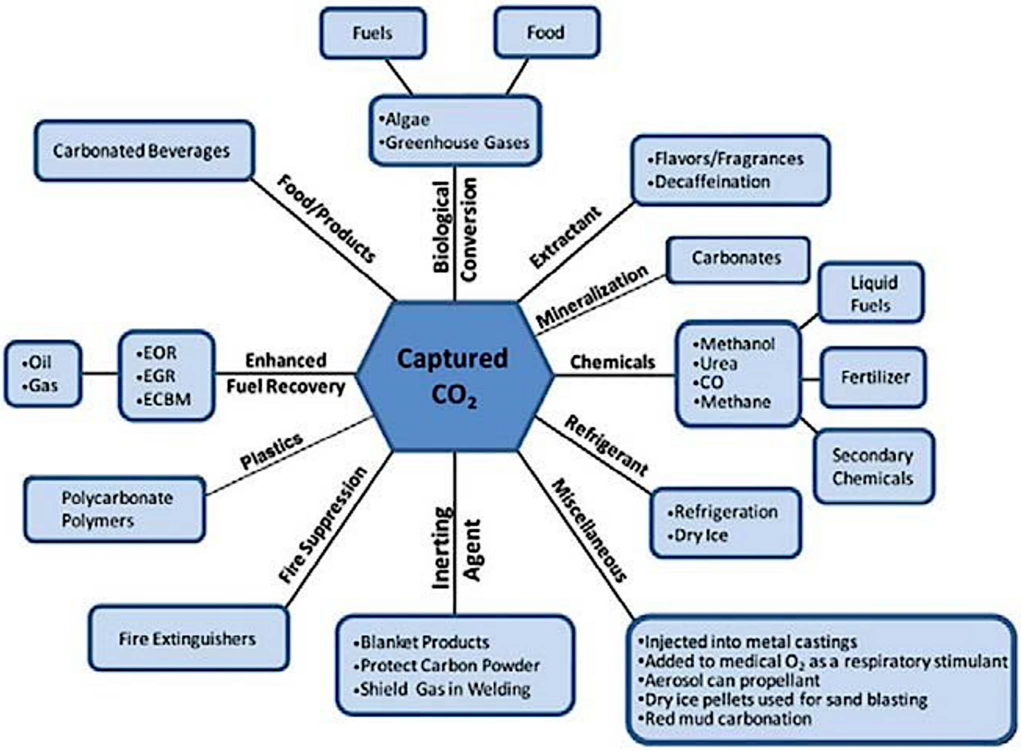



*Figure 1: Utilization of CO2 (ResearchGate GmbH, 2024)*

## 3.4 Scope of the project

Before starting to work on the project there is some preparation required.

The scope of the project must be defined.

In the case of this project, the scope is set by the supervisor of the project, Cynthia Söderbacka.

This project is focused on finding a carbon capture solution that can be implemented in a self-build prototype, to demonstrate the carbon capture phenomenon.

The following visualization was used to show the scope in the overall view.

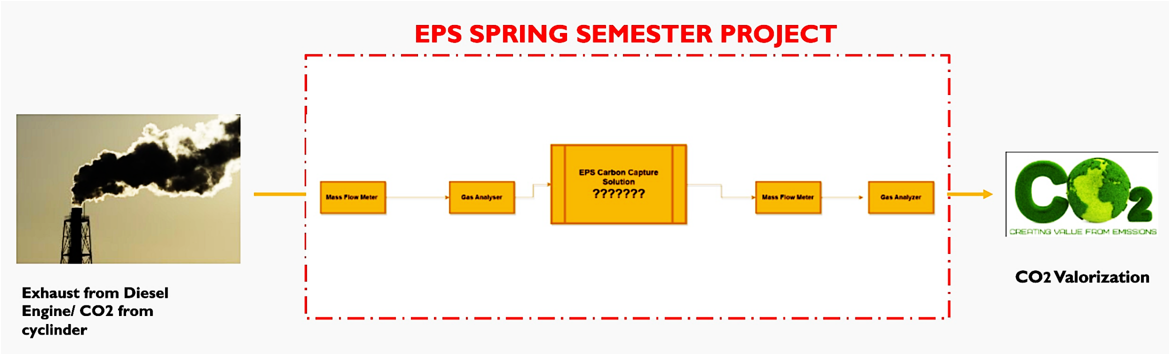



*Figure 2: The overview of the expectations on the EPS Spring Semester and its scope (Söderbacka, 2024)*

A close-up of the scope enables to notice the few boundaries that are set by the scope. This creates freedom in choosing between different processes that can fulfill the expectations on the project.

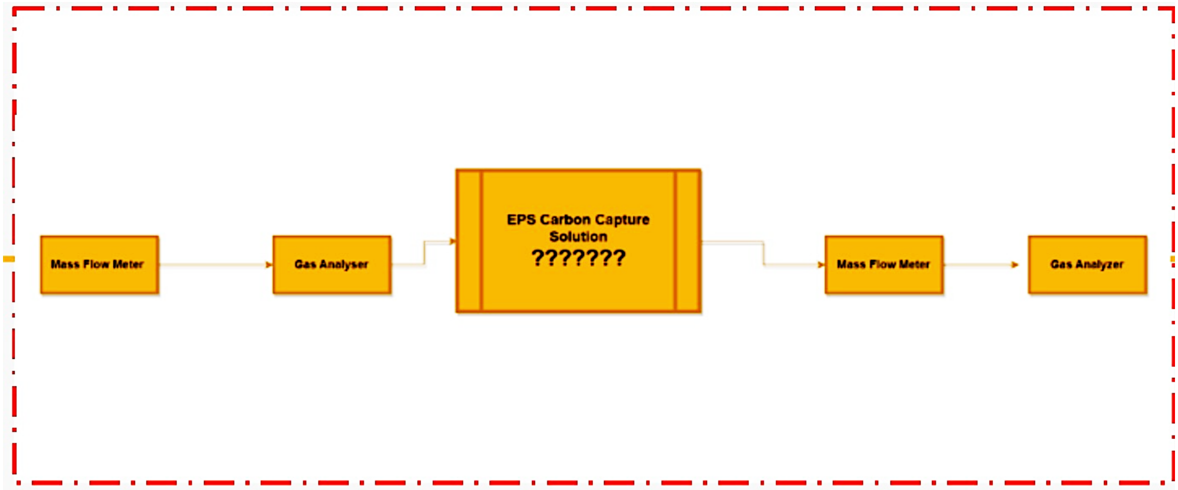



*Figure 3: Close-up of the scope (Söderbacka, 2024)*

# 4 Research

## 4.1 Work methods

The group work method for a project is essential to ensure effective collaboration among team members and the achievement of set goals. Firstly, open communication is fundamental. Members should be able to share their ideas, concerns, and progress regularly and without reservation. This fosters a work environment where everyone feels heard and valued, which can stimulate creativity and innovation. Additionally, clear task and responsibility allocation is crucial to avoid duplications and ensure smooth project progression.

Each team member should have a clear understanding of what is expected of them and the deadlines for their contributions. This allows for the effective utilization of skills and available resources, thereby maximizing team productivity.

Lastly, regular progress evaluation and adjustments along the way are necessary to ensure the project stays on track. This may involve periodic meetings to assess encountered obstacles, readjust plans if needed, and celebrate successes achieved so far. Constructive feedback also allows team members to continually improve and strengthen the cohesion to reach the project's objectives effectively and efficiently.

Firstly, we conducted research individually to become familiar with the subject. Then, we held meetings to discuss and share knowledge. We then conducted further in-depth research on different processes and applications.

## 4.2 Options

There are different methods and approaches to carbon capture depending on the application domain.

Firstly, the method called Cryogenic capture uses very low temperatures to condense and separate carbon dioxide from other gases. $CO_2$ is first compressed to increase its density, then it is cooled to a very low temperature to liquefy it.

This is often done using cryogenic refrigerants such as liquid nitrogen or oxygen. Once C02 is liquefied, it is separated from other gases present in the mixture.

Since liquid $CO_2$ has a higher density than other gases, it can be separated by gravity or other specific separation methods. Then it can be stored in underground reservoirs, used in industrial or commercial processes, or transformed into useful products such as synthetic fuels or construction materials (Chunfeng Song, 2019).

Secondly, the Capture by calcium cycle consists of capturing $CO_2$ using quicklime to produce limestone. The limestone is then heated, which releases the $CO_2$ while producing quicklime. To make this, the $CO_2$ is absorbed by the calcium-based absorbent material, typically in the form of calcium carbonate, at high temperature (500-900 °C), in the presence of carbon dioxide. Then the temperature is increased, releasing the $CO_2$ from the absorbent material as a gas. The regenerated absorbent material can be reused to capture more $CO_2$, while the recovered $CO_2$ can be compressed and stored (Antonio Perejóna, 2016).

Thirdly, capture by absorption is a technique based on the principle of chemical absorption, where a solvent or liquid absorbent is used to selectively absorb the $CO_2$ present in the raw gas. The raw gas containing $CO_2$ is introduced into a contractor, where it encounters absorption solvent. The $CO_2$ then dissolves into the solvent, forming a $CO_2$ rich solution. This solution is separated from the remaining gas. This can be achieved using various techniques such as settling, distillation or adsorption. Once separated, the $CO_2$ can be regenerated from the solvent for reuse or safely stored.

Commonly used solvents in $CO_2$ capture by absorption include amines. These solvents are chosen for their ability to chemically react with $CO_2$, forming water-soluble compounds that can be separated from the rest of the raw gas (Usman Khan, 2023).

Lastly, the method of Membrane separation relies on the use of selective membranes that allow $CO_2$ to pass through while other gases are retained. The emitted gases are compressed to increase their pressure, facilitating their passage through the membranes. Subsequently, they are introduced into a membrane system where $CO_2$ can pass through the membrane pores while other gases, such as nitrogen or methane, are trapped. After that, the $CO_2$ is purified and compressed for storage (Utjok W.R. Siagian, 2019).
Membranes used in this process are typically made from specific polymers or ceramic materials that exhibit high selectivity for $CO_2$. This selectivity makes it possible to obtain high capture yields while minimizing the loss of other gases.

Even though all these processes have their advantages and their drawbacks, the solution for this process is the following one.

### 4.3 Adsorption

The adsorption is the process in which specific atoms or molecules from a fluid get attached to the surface of a solid.

The terminology must be used careful due to the alikeness of the vocabulary.

Adsorbent is the term for the substrate on which the adsorption is performed. The adsorbate is the referring to the atoms and molecules that are to be adsorbed.

To be able to adsorb a maximum of adsorbate, the materials used as adsorbent are highly porous to create as much surface area as possible.

Common materials besides zeolite are activated carbons or polymers with activated sites that cause a high affinity to certain adsorbates.

The prime distinction is to be made to the absorption, where the atoms or molecules get diffused into the substrate or the fluid (LUMITOS, CHEMIE.DE, 2024).

There are two categories of adsorption, the physical and the chemical one.

- **Physisorption**

  In the physisorption the atoms and molecules adhere to a surface because of weak van der Waals forces.

  The chemical structure does not get modified.

  The draw results out of temporary fluctuations in the electron distribution within molecules.

  Usually the process is easily reversible, due to the low binding energy. (LUMITOS, CHEMIE.DE, 2024)

  To release the adsorbed molecules from the surface the binding energy must be applied by increasing the temperature or another external energy source (LUMITOS, CHEMIE.DE, 2024).

- **Chemisorption**

  A stronger chemical bond of the molecules or atoms and the adsorbent surface is formatted in chemisorption.

The formation of a bond like this often involves the share or transfer of electrons between the adsorbate, the atoms or molecules, and the adsorbent. The adsorbate can even be decomposed by those electric changes. Although, it is not necessarily occurring.

Therefore, the adhesion is more stable. Also, it is further specialized in potential associates.

The chemisorption, as well, is principally reversable (LUMITOS, CHEMIE.DE, 2024).

The saturation of atoms and molecules is characteristically for solids.
This symmetry is transgressed at the surface of the solid. There are free bonding electrons, or a weak charge shift present.

Le Chatelier stated that not only the educts and products concentration in a system can influence the equilibrium (5.2.2), but also pressure and temperature changes.
His principle says that a system in state of equilibrium that suffers from a change in one of the previous named dimensions, will shift the equilibrium to minimize the change on the system (Duden Lernattack GmbH, 2024).
The exothermic process of adsorption and its effectiveness is highly dependent on temperature.
Following the Le Chatelier´s principle, the at equilibrium and a constant pressure, the adsorbed amount decreases from the increase of the temperature.
For this reason, most adsorption processes are performed at room temperature (Gabelman, 2017).

## 4.4 Decision on the process

A choice had to be made based on the following advantages and disadvantages, following all these processes.
$CO_2$ capture by cryogenics offers several advantages, including high capture efficiency and high purity of the captured $CO_2$. However, this method can be costly due to the energy required for compressing and cooling the $CO_2$, as well as infrastructure requirements for handling cryogenic temperatures.

$CO_2$ capture by the calcium cycle presents challenges such as high installation and operating costs, potential impacts on facility performance, and the need for proper waste management during the regeneration process. While effective in reducing $CO_2$ emissions, this method also faces challenges such as energy consumption for solvent regeneration and costs associated with installation and operation of capture equipment.

$CO_2$ capture by membrane separations offers several advantages, including its ability to operate at ambient temperature and atmospheric pressure, reducing energy costs compared to other capture methods. Additionally, it can be used in a modular and flexible manner, making it adaptable to different types of industrial installations. However, some disadvantages include high initial costs membrane installation and the complexity of finding membranes for our project.

Therefore, the decision has been made to choose $CO_2$ capture by adsorption. This process can be carried out at different temperatures and pressures depending on the specific properties of the adsorbent material used.
Synthetic zeolites are particularly promising in post-combustion capture due to their high specific surface area, adsorption capacity, thermal stability, and good renewability (Appendix 1).

The fixed bed reactor has also been chosen due to its simple configuration (Appendix 2). Regarding regeneration, the temperature swing adsorption (TSA) seems most interesting as it only uses zeolite, the reactor is fixed, and it is easier to purge with nitrogen ($N_2$) because it is readily available. (Appendix 3).
Concerning the initial project of “MAP-UP-P2X” this is probably the most interesting choice, because it is easy to be implemented in an existing plant.

The decision regarding the process was also influenced by our stakeholders, as it was deemed most interesting for them to utilize a solution that could be easily implemented in the existing process.

The advantages and disadvantages of different processes were assessed. Given the project's focus on sponsors with existing plants, it was concluded that comments favoring the practicality of the adsorption process for implementation in such facilities were significant. Consequently, with the plant already standing and emitting CO2 into the atmosphere, the adsorption process can simply be installed behind it, requiring minimal rearrangement.

As the review says: “The CO2 capture systems based on adsorption offer a promising solution for industrial plants, as they can be easily adjusted and integrated into existing processes with little or no major modifications required.” (Arnob Das a, 2023).

## 4.5 Adsorbent

Zeolite is a type of mineral that has a porous crystalline structure allowing it to selectively absorb and trap certain molecules. Zeolites typically form in volcanic environments and exist in various forms with diverse atomic arrangements. Their physical and chemical properties depend on factors such as chemical composition, crystalline structure, and pore size.

Due to their porous structure and ion-exchange capability, zeolites find wide use in various industrial and environmental applications. There are numerous types of zeolites, each with specific crystalline structures and properties. For example, Zeolite types X and Y are often employed in the petrochemical industry, as well as in ion-exchange processes for water purification and detergents. Another Zeolite mordenite is used as an adsorbent for water purification and as a catalyst in chemical reactions.

In the field of carbon capture, zeolites are being studied for their ability to selectively adsorb $CO_2$ from exhaust gases or industrial sources. Their porous structure and affinity for $CO_2$ make them promising candidates for the development of carbon capture and sequestration technologies. Therefore, based on the table (Appendix 3) and the properties of different zeolites, the most suitable for the demonstration would likely be zeolite X (V. Indira, 2022).

A zeolite will be used because of its characteristics. The first positive and useful aspect of zeolites are that they are a good scientific fit for the chosen process. It consists of all the necessary factors that a material needs to possess.

First of all, the zeolites possess a very well-designed molecule structure that can adsorb a high amount of $CO_2$ molecules at room temperature that will pass through the zeolites. Alkaline counterions that charge-balance the Al-sites in the zeolite's framework create a vast quantity of $CO_2$-philic sites (Anastasios I. Tsiotsias, 2023).

Secondly, zeolites offer the opportunity to choose from different regeneration processes, because it has a high thermal stability. After reaching saturation with $CO_2$, zeolites can be regenerated by desorbing the captured $CO_2$. This is typically done by either reducing the pressure or increasing the temperature, which releases the $CO_2$ from the zeolite pores, allowing it to be captured for storage or further use.

The fact that zeolite can carry out these tasks indicates it is a great material to use in this project.

All these different positive aspects about zeolites give reasons to use this material as the main part of the carbon capture process.

Another reason that in this project zeolites will be used is because in the laboratory there were already zeolites at our disposal. Therefor it becomes first cheaper, more convenient and it is resource-saving solution (Federica Raganati, 2021).

## 4.6 Regeneration

When the feed and the adsorption bed reach equilibrium, the adsorbent must be regenerated. This term refers to the release of the adsorbed adsorbate, to enable the adsorbent to capture, in this case $CO_2$, again.

The regeneration happens through a shift in equilibrium distribution. There are different methods do create this shift:

- Through the contact with a fluid that does just slightly or even does not contain the adsorbate
- By using the higher affinity of a solvent for the adsorbate
- By increasement of the temperature
- Through lowering the pressure

(Gabelman, 2017)

### 4.7 Desorption

The desorption can be achieved by keeping a constant pressure and increasing the temperature. For each partial pressure this leads to a decrease of the adsorbed amount of adsorbate.

The temperature increase needed for a release of adsorbate is relatively low.

The Temperature swing adsorption (TSA) is manly used in processes with the characteristic of a low partial pressure or concentration of the adsorbate in the feed.

But it must be taken into consideration, that the high temperatures can lead to degeneration of the adsorbent.

In industry the use of a Temperature swing adsorption can be difficult because of the exothermic process of adsorption, especially in a large, fixed bed. The large, highly porous beds provide a poor heat transfer. This does extend the time needed for the process (Adsorption Regeneration Desorption, 2024).

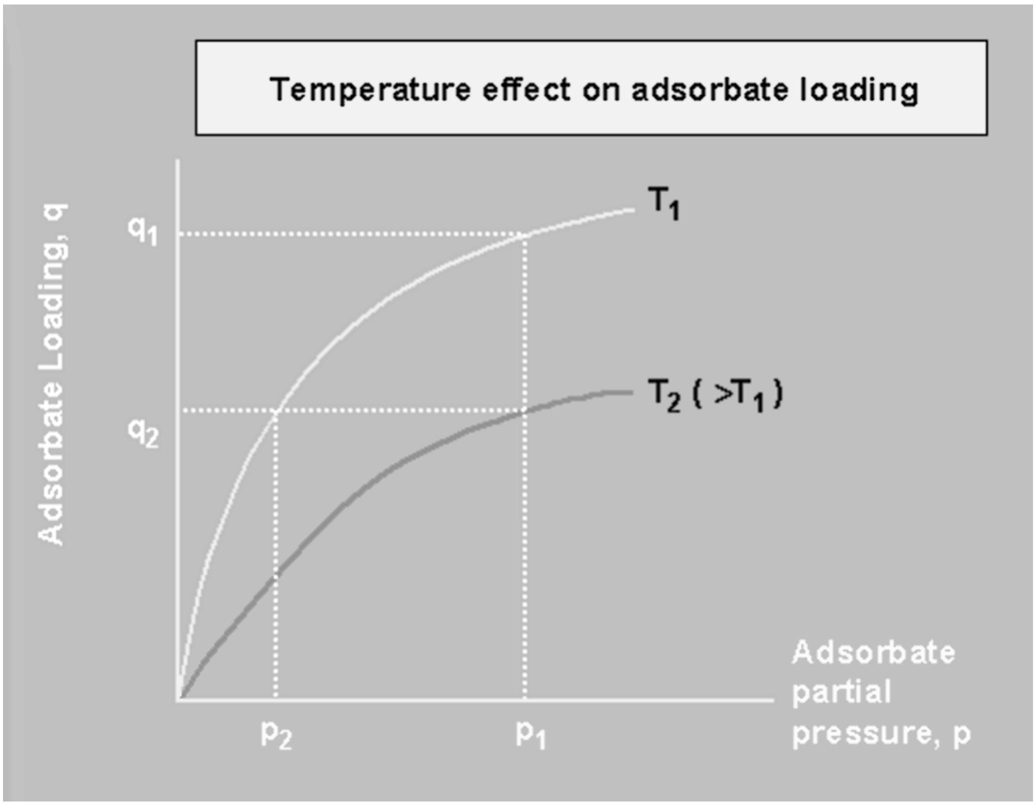



*Figure 4: Visualization of the effect of temperature on adsorption (Adsorption Regeneration Desorption, 2024)*

For this project the decision was made to use the desorption via increasing temperature. This is due to the difficulties of working with plumbing components without proper tools.

The relatively low concentration of $CO_2$ in the flue gas stream of the combustion engine that was measured for this project, was another argument for choosing the TSA.
And the poor head transfer properties seemed less relevant because the bed of the prototype would not be high.

## 4.8 Reactor

The fixed bed reactor is the chosen type of reactor because of its relatively simple setup, which is an important characteristic since the prototype will be self-built and consisting of ordinary construction components.
The operating principle of a fixed bed for carbon capture is relatively simple yet incredibly effective. It's like a cylinder filled with a special material called adsorbent. This material can be activated carbon, zeolites, metal-organic frameworks (MFO) or other porous substances capable of trapping $CO_2$. When gases containing $CO_2$ are emitted from an industrial source, they are directed through this bed of adsorbent material. During this journey through the bed, $CO_2$ molecules are captured and retained on the surface of the adsorbent, while other gaseous components are released through the reactor. This selectivity effectively isolates $CO_2$ from other gases (D.Tondeur, 2002-2004).

Over time, the bed becomes saturated with $CO_2$, much like a sponge becomes saturated with water. To maintain the system´s efficiency, it is necessary to regenerate the bed, meaning to remove the captured CO2. Regeneration can be done through various methods, such as heating the bed to release the CO2 or using chemicals to detach it from the adsorbent. Once regenerated, the bed is ready to be reused to capture more CO2.
In industry these reactors are usually used batchwise and for that reason they are build redundant.

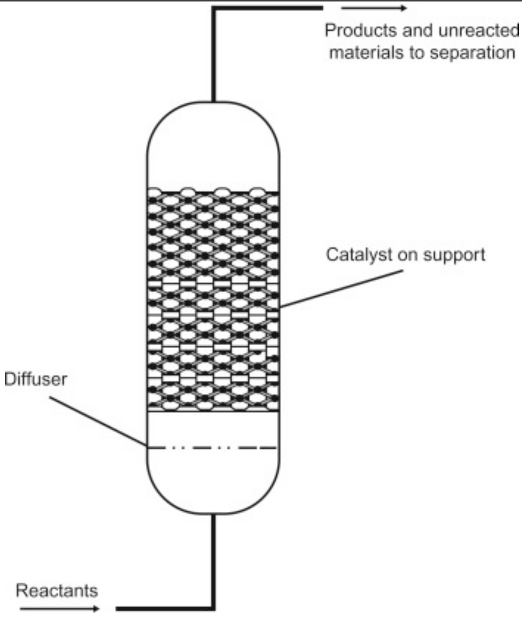



*Figure 5: Fixe Bed Reactor (Worstell, 2014)*

Their main advantage is its simplicity and the inexpensive fabrication compared to other adsorption reactors.

But for industry there are disadvantages in fixed bed reactors. The parts of the bed off the mass transfer zone (MTZ) (5.2.4) cannot participate as long as they are not reached by the MTZ. Upstream they are already saturated, downstream they are not yet in contact with the feed. This leads to an extensive request of adsorbent in the column and a relatively long time for the whole process.

Also, the redundant setup creates challenges in the layout, causing a complex arrangement of valves and pipes.

But for a “DIY” built reactor this is the only one doable. Therefor the decision was made, despite these serious disadvantages (Ikhlas Ghiat, 2021).

# 5 Conception

## 5.1 Laboratory measurements

In order to progress with the project, new milestones have to be made.

The first goal that must be met will be, laboratory measurements. Here for it is necessary that a meeting will be scheduled in the engine lab.

For this project it is necessary that correct measurements find place. If a fault would occur, then this could have a negative output on the price budget of the project. Wrong measuring data can result in wrongly ordered parts of the demo and hereby costs money for a part that has no attribute to the project.

The following paragraph will explain which measurements will be executed.
One of the measurements that will be executed, is the mass flow.
It is the mass of a substance which passes per unit of time. If this factor is known, it will be possible to research a lot of other data that is contained in the flow through calculations.
In the laboratory a gas analyzer test is also going to have to be performed. It serves to display the carbon dioxide percentage in the flow.

## 5.2 Calculations

In case all the measurements were correctly executed, and the data is correct, then the next step in the project can begin.
The calculations will be based on the data that has been collected through the lab measurements. Because the data used in the calculations is straight out of the lab, it becomes possible to calculate the exact outcome that will occur when the demo stand will be build. Hereby it becomes possible to predict what will happen and here for buy the right equipment necessary for the predicted process.

For the calculations, some assumptions will be made.
First, it will be assumed that the feed gas flow behaves like an ideal gas. Therefore, the Dalton´s law of partial pressures can be used.
This law states, that the sum of all partial pressures equals the total pressure:

$$p_{total} = \sum_{i=1}^{k} p_i \qquad (1)$$

But even with these simplifications it won´t be possible to concept the calculations needed to tell the amount adsorbed for every moment of the process, because the complexity of the process.

That's why common models will be used to describe the process.

### 5.2.1 Adsorbent bed

In industry the calculations would have been made in the following order because the flue gas stream would be the crucial value.

First the velocity of the flow from the pressure vessel would have been calculated by:

$$v = \varphi * \sqrt{\frac{2 * p_o}{\rho_{Feed}} + 2 * g * h_v} \tag{2}$$

- $\varphi = velocity\ coefficient$
- $v = velocity\ (in\ \frac{m}{s})$
- $p_o = overpressure\ (in\ Pa, \frac{N}{m^2}\ or\ \frac{kg}{m*s^2})$
- $\rho_{Feed} = \text{density of the feed (in } \frac{kg}{m^3})$
- $h_v = hight\ of\ the\ pressure\ vessel\ (in\ m)$

So next the flow rate would have been divided by the velocity to get the required cross-sectional area:

$$A = \frac{\dot{V}}{v} \tag{3}$$

- $A = \text{cross} - \text{sectional area (in } m^2)$
- $\dot{V} = volumetric\ flow\ rate\ (in\ \frac{m^3}{s})$

With:

$$d = \sqrt{\frac{4 * A}{\pi}} \tag{4}$$

- $d = diameter\ (in\ m)$

the diameter $d$ of the column would have been identified.

Next is the amount of adsorbent required for one cycle of adsorption.

The desired time for an adsorption cycle would have to be set, the time between the introduction of the adsorbate to the adsorbent and the necessary recovery of the adsorption bed.

Therefore, the density of the feed and of the adsorbent bulk must be considered.

The amount of adsorbate per cycle is:

$$m_{adsorbate} = t * \dot{m}_{Feed} * C_{adsorption} \tag{5}$$

- $t = \text{desired time (in s)}$
- $\dot{m}_{Feed} = \text{massflow of the feed stream (in } \frac{kg}{s})$
- $C_{adsorption} = adsorption\ capacity\ (in\ \frac{kg}{kg})$

The amount of adsorbent per cycle is:

$$m_{adsorbent} = \frac{m_{adsorbate}}{C_{adsorption}} \tag{6}$$

So, the height of the adsorbent bed would be described by:

$$h_{bed} = \frac{m_{adsorbent}}{A} \tag{7}$$

- $h_{bed} = \text{ height of the adsorbent bed (in m)}$

The adsorbent capacity at breakthrough:

$$C_b = \frac{adsorbate\ feed\ rate * breakthrouh\ time}{bed\ volume} \tag{8}$$

The shown calculations enable to plan the fixed bed reactor.

### 5.2.2 Equilibrium

During adsorption, initially the rate of adsorption is high, because on the surface of the adsorbent there are many vacant sites. With the increase of occupied sites, the adsorption rate does slow down. At the same time the high concentration of adsorbed adsorbate on the surface increases the desorption rate.

When the rate of adsorption and desorption become equal, the state of equilibrium is reached.

### 5.2.3 Isotherm

The equilibrium can be visualized by an isotherm.

The isotherm is an important concept in thermodynamics. It refers to a curve that describes the state of a system at constant temperature, while other parameters change, like pressure, volume, or density.

Thus, at a certain temperature the adsorbed amount of adsorbate is drawn as a function of the concentration if the adsorbate is a liquid or the partial pressure in case of a gaseous adsorbate.

The diagram displaying the behavior is found under the term of isotherm.

A desired isotherm is a convex shaped one. These show a high adsorption at low partial pressure or concentration.

The unfavorable one is concave. This one is uneconomic since a high partial pressure is required to achieve a significant amount of adsorbed adsorbate per unite weight of adsorbent.

At first sight, the irreversible adsorption seems ideal since a maximum of adsorption is reached at low partial pressure or concentration. But the better the adsorption, the more difficult the desorption is.

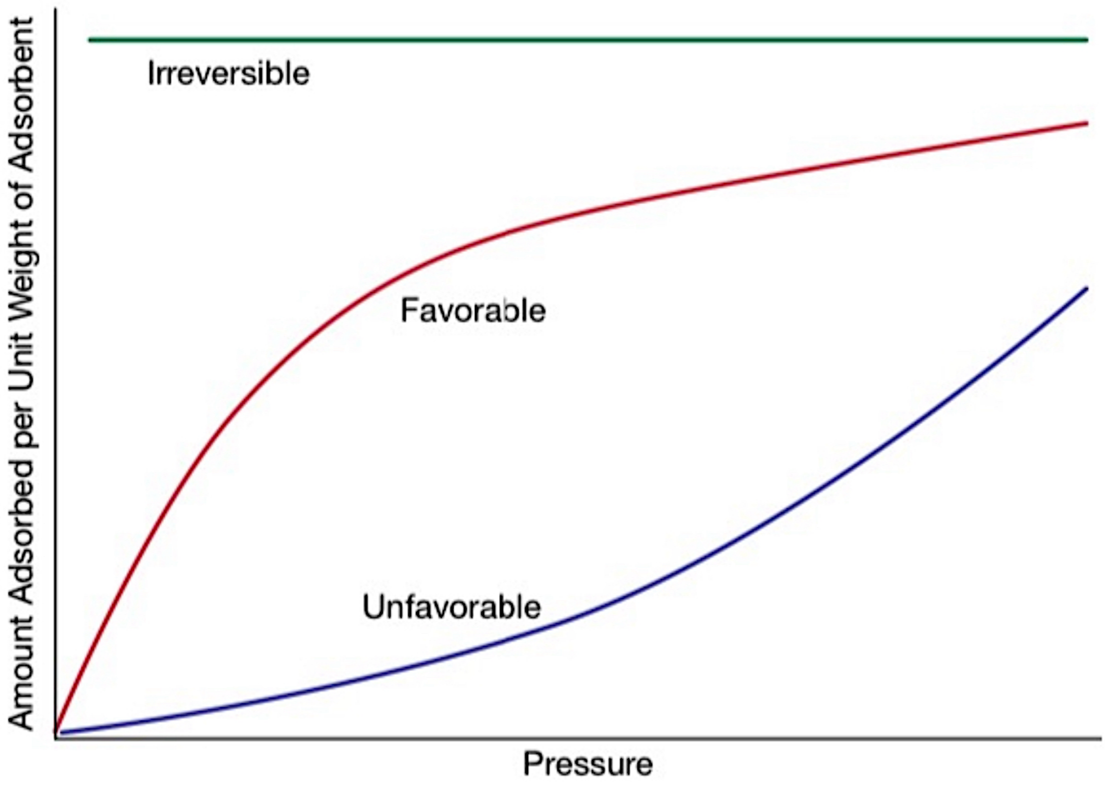



*Figure 6: An example for the different shapes of adsorption isotherms (Gabelman, 2017)*

To draw an isotherm, there are a variety of models. The most common ones are the Langmuir and the Freundlich isotherms (Gabelman, 2017).

- **Langmuir Isotherm**

  The Langmuir Isotherm is based on the assumption that the adsorbate only forms one layer on the surface of the adsorbents flat, homogenous surface. And that the attached molecules do not interact with each other.

  The following formula applies for fluids that only contain one adsorbate:

$$\Theta = \frac{Kp}{Kp + 1} \tag{9}$$

  The fraction of the possible sites that are already occupied is $\Theta$, while $K$ is the adsorption equilibrium constant and $p$ is the patial pressure of the adsorbate or the concentration in case of a liquid.

In the so-called Henry´s law region, the curve does match one's intuition. In this first region the partial pressure is low, and the denominator approaches 1. So, with the increasing partial pressure the number of adsorbed particles increases.

But, as the number of adsorbed particles increases, the available sites on the adsorbent decreases, which makes the further adsorption more unlikely.

So, the increase of the fraction of occupied sides at high partial pressure asymptotically approaches 1.

The described behavior also applies to liquids, the partial pressure being replaced by the concentration (Gabelman, 2017).

- **Freundlich Isotherm**

  The Freundlich Isotherm applies to heterogeneous adsorbents like hydrocarbons on activated carbon.

  In the model:

$$n = kp^{1/m} \tag{10}$$

  While $n$ displays the weight adsorbed per weight of adsobent, the $k$ and $m$ are constants at certain temperatures.

  At low pressure this model does only contain a Henry´s law region, when $m$ equals 1, and it is linear (Gabelman, 2017).

The adsorption isotherms in practice tend to show the amount of adsorbate that is adsorbed per unit weight of adsorbent (Gabelman, 2017).

#### 5.2.4 Breakthrough curve

To be adsorbed the adsorbate must pass the adsorbent, diffusing through the surrounding fluid to get to an unoccupied site where it can attach itself to the surface of the adsorbent. This process is the mass-transfer within adsorption.

In praxis, the venue of the adsorption usually is a column pact with a bed of the adsorbent. Often this column is vertical and contains more than one level, but multiple ones. The mass transfer is driven with the aim to reach the equilibrium, displayed by the previous mentioned Isotherm begins instantly at the introduction of the feed flow, that contains the adsorbate, to the adsorbent in the column.

The regenerated adsorbent takes the adsorbate on along the bed. This leads to decreasing of adsorbate in the fluid, until its ratio almost reaches zero at the outlet of the column. While the feed continues to enter the column, the adsorbent has a decreasing number of unoccupied sites left.

When equilibrium is reached between the concentrations in the feed and the adsorbent, the net mass transfer stops. As soon as this is reached in all parts of the bed, the concentration of the adsorbate in the effluent increases.

This is called the breakthrough.

The breakthrough curve describes the change in the column's effluent over the time. The S-shaped curve takes off at the bottom as soon as there is adsorbate in the effluent. It increases towards the same concentration as in the feed.

The equilibrium time $t_e$ is met when the total adsorbent bed is in equilibrium with the feed, so $\frac{c}{c_0} = 1$.

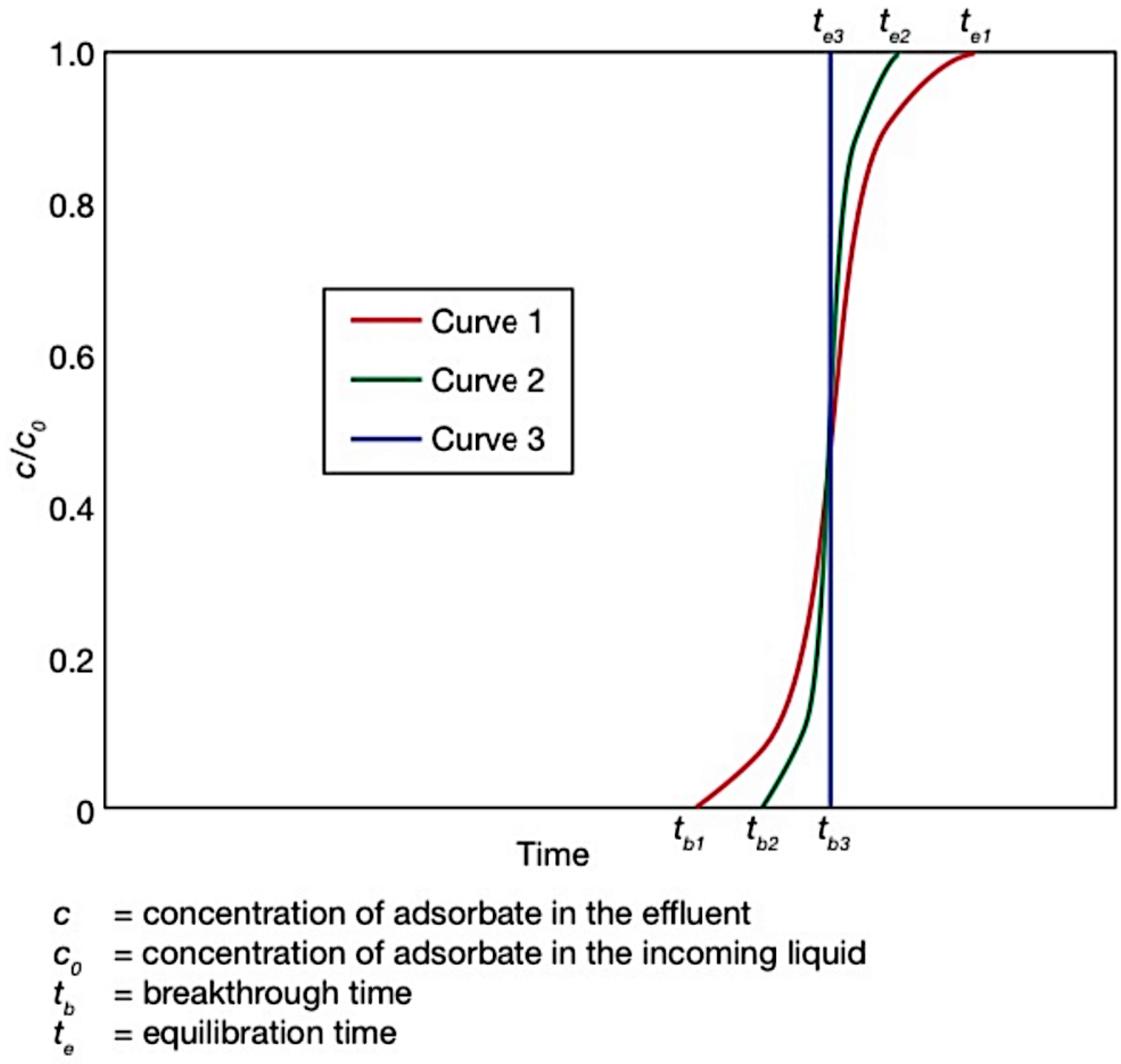



*Figure 7: Example of breakthrough curves (Gabelman, 2017)*

A symmetric S-shaped breakthrough curve does display an ideal adsorption. Its breakthrough time is known as stoichiometric time $t^*$. In a real adsorption´s curve it would occur at the middle of the S-shape.

The adsorbent bed´s portion that is still incomplete or unoccupied by adsorbate can be described by the following Formular:

$$\frac{LUB}{L_T} = 1 - \frac{t_b}{t^*} \tag{11}$$

The acronym $LUB$ stands for the length of the unused bed at breakthrough, $L_T$ is for total bed length, and $t_b$ for the breakthrough time again.

So, in theory the efficiency of the adsorption bed rises with increasing length of it, because the mass-transfer zone would stay the same through the whole column. The unused part would become a smaller fraction of the total bed.

But back mixing and axial dispersion does change the mass-transfer zone in a real column (Gabelman, 2017).

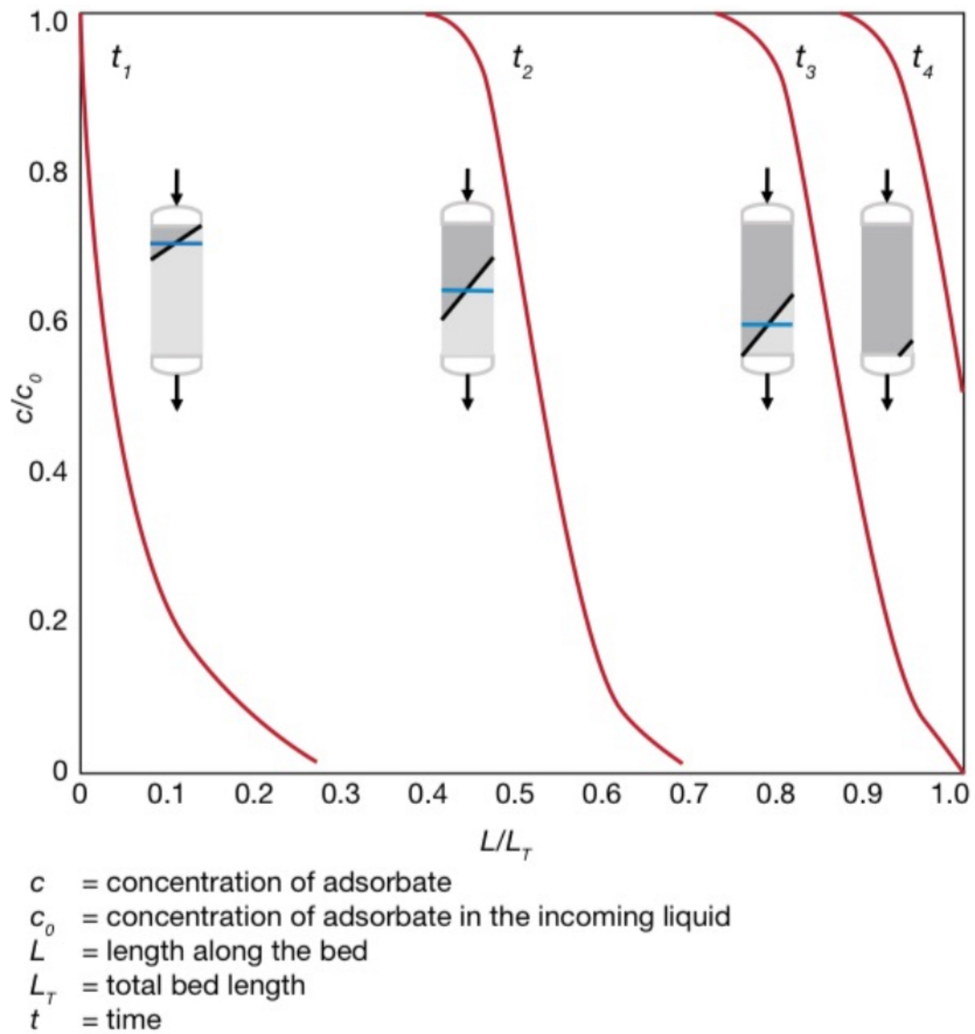



*Figure 8: Visualization of the mass-transfer zone in the column through the black diagonals (Gabelman, 2017)*

The mass-transfer zone is displayed at four different times, along the adsorbent bed in the column. This visualization applies to fixed bed reactors like the one, that has been chosen for this project (Gabelman, 2017).

### 5.3 Schematics

When all the calculations are made, everything that is needed to know from the adsorption physics side is finished. After this, everything must be built.

Before starting to build a demo, always make rough process drawings and equipment schematics first. When this is finished, a clear and neat view of both the process and all the parts necessary to make this process possible and to maintain it.

When this order of planning is pursued the chances of the demo failing because of wrongly implemented physics calculation or faulty equipment will be decreased.

# 6 Execution

## 6.1 Equipment order

After all the calculations are completed, the research can start to find all the right equipment. It is important to note some aspects that need to be pursued. The first aspect is the monetary aspect, always stay under the budget of the project. This can be accomplished by looking for the cheapest but still most suitable components.

Secondly notice that the ordered components often have a long shipping delay. To solve this problem, it will be important to take this into account in the project planning. Here by the shipping delay will not affect the project planning.

In the following paragraph the most important components will be summarized.

Flow meter/controller, this part is responsible for measuring and controlling the flow through the demo stand. This part can be seen as the “brain” of the demo. It will also collect data on its own software program linked to a local PC, where all the data becomes visible and obtainable.

The buffer tank is useful because of its property to store air or liquids and create a storage place. In times when the process is out of balance it can rely and fall back on the buffer tank to provide it with a steady flow because of its storage ability.

Finally, the reactor, the equipment that is at the base of the process. This is the “heart” of the demo. In this part the $CO_2$ will be captured. The reactor is a component that exist out of a few smaller parts, for example a filter and the metal case that holds everything together. This all will work together to become one part of equipment that will filter $CO_2$ out of the flow.

## 6.2 Building phase

Once all the components have been ordered and delivered, the assembly of the demo stand can begin. Do to the earlier made schematics and specifically chosen components, the building phase will be straightforward. All that must be done is following the right instructions and placing the components exactly the way they are displayed on the schematics.

There is always a possibility that something goes wrong, therefore be careful about the following risks.
A component that is been wrongfully designed by the fabricator. The connection between two components can be installed wrong and can result in a flow that is not the same as it was calculated. This could potentially mess up the whole flow and hereby the whole process.
At last, there could also be a fault in the calculations, or that something wasn't considered. This phenomenon can lead to the process behaving differently than was expected.
Throughout the entirety of the project, efforts should be made to minimize these risks whenever possible.

## 6.3 Building process

Before starting the building phase, the expectations had to be lowered. First the goal was to build a working demo stand of a carbon capturing technology. After some setbacks throughout the project, the end goal was changed. For now, the objective is to build a "DIY" prototype to test the used technology.

#### 6.3.1 Schematics

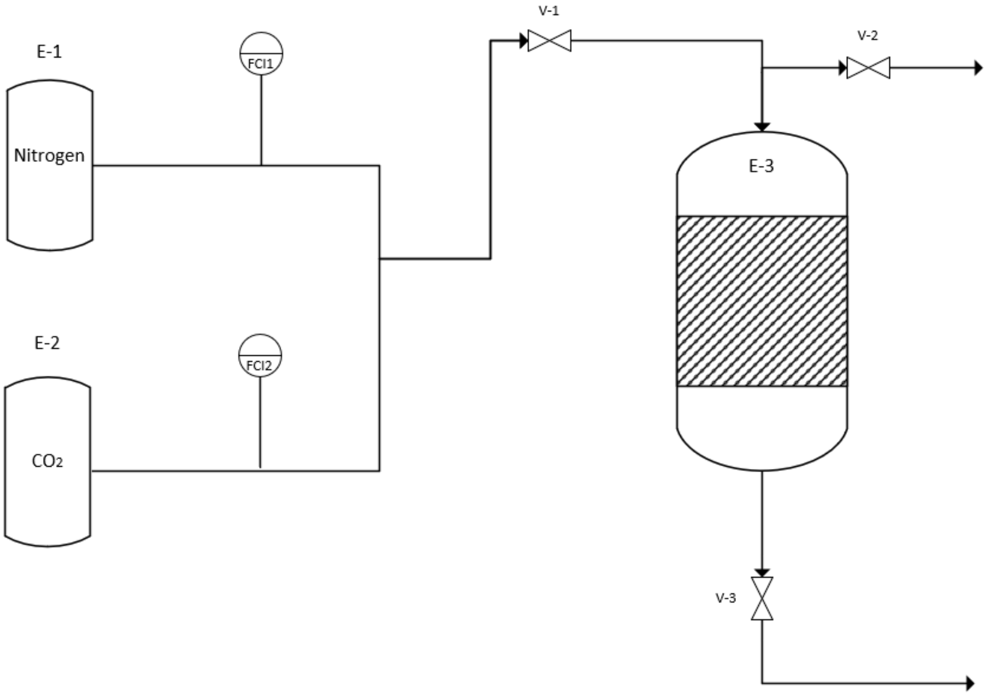



*Figure 9:Process schematics for the prototype (Heylen, 2024)*

Creating a schematic before actual building it is a very important step. This will offer the opportunity to first get rid of a lot of unnecessary mistakes in the process.
Secondly it will produce a clean overview of the whole process and all the necessary parts.
This P&ID schematic creates a clear and simple view of how the DIY build will look like.

#### 6.3.2 Components

The prototype consists of different components. Those are introduced below.

- **Pipelines:** One of the most important parts of the entire build are the coper pipelines. They connect everything together and they also need to be perfectly chosen for the used technology of the carbon capturing demo. This mean that it needs to withstand certain heats, pressures and it cannot let any gasses leak.


*Figure 10: Pipelines*

- **Valves:** Another important component are the valves. They provide the opportunity to control the flow rate through the pipes. It can also be used to block the entire flow.

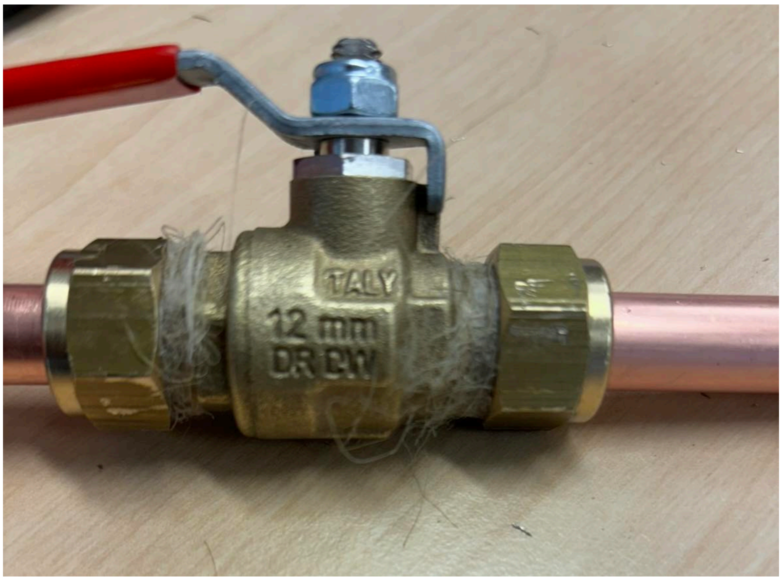



*Figure 11: Valve*

- **Reactor:** The main part of this prototype is the reactor. It serves as the heart of the project. In here it will capture the carbon out of the flow because of the in this project chosen technology.
  The reactor is made from stainless steel, so it would not interfere with the chemical process inside the reactor. Further information about the process inside, can be found in paragraph 4.

*Figure 12: Reactor*

- **Flow Indicator and Controller (FIC):** At last, there are also measurement tools used. This is a very important part of the prototype because it will tell exactly what is happening inside the flow. It gives us a variety on information of data and provides graphs. These graphs are useful to compare the data from this project to already existing demo stands. Herby, it becomes possible to identify if this project has succeeded or not.

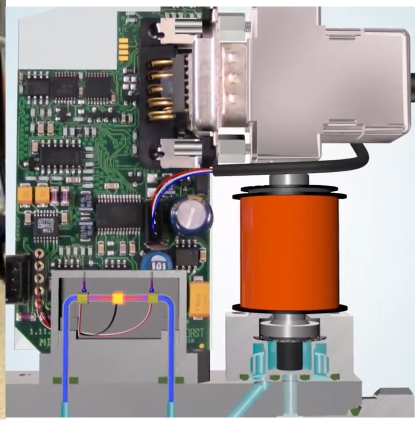



*Figure 13: Practical Flowmeter* *Figure 14: Theoretical Flowmeter*

Working principle of a “FIC”: it is a combination of a measurement device and a control valve. This means that it can measure incoming flow as also control the outgoing flow. This component is useful because it can communicate with a computer. Hereby they can talk to each other and exchange data. By doing this it can create graphs to show what the real time data of the flow is (UK, 2016).

First of all, the flowmeter will be explained.

The flow meter consists of a thin capillary tube with 2 temperature sensors and 1 heating element. The electrical part consists of computing elements that serve as the brain of the FIC.

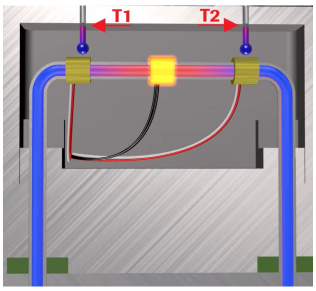



*Figure 15: Theoretical view of the temperature sensors*

Each temperature sensor delivers a certain signal to the “mini” computer in the sensor. In the middle of the two sensors, a heating element has been placed. This part will heat up the flow and therefor create a temperature difference between sensor one and two.

On the other hand, if the flow in the tube is zero, then the two flow meters will have the same value. This will result in the sensors sending the same data to the computing elements and they will know that the flow is zero.

The flowmeter only exists of these few parts (UK, 2016).

In contrast to the flowmeter, the flow controller exists of more complicated parts and principles. The controller will perform the job of regulating the outgoing flow through the data coming from the flowmeter. This means that the controller will collect the sensor data, use mathematical equations on it, and calculate opening percentage of the valve (UK, 2016).

The controller works with the following principle: If a liquid flows through the capillary tube, the first temperature sensor will sense a certain value. The flow then heats up because of the heating element.

After this the temperature of the flow has been changed. The phenomenon will be noticed by the second sensor. The sensor will send his data to the computing elements inside the sensor and (UK, 2016).

For the Flow Indicator and Controller to work it is necessary to have a certain set point. An external computer, PLC or analog port will provide this value and send it to the controller. The controller will then compare the set point value with the measured value and use a PID controller to process the data. After, the PID controller will send a signal to an electromagnetic coil. This coil will provide a force on a magnetic plunger holder that on his turn has a linear effect on the incoming flow in the pipe (UK, 2016).

If the measured flow is lower than the set point value given by an external PC, then the PID controller inside the FIC will send a stronger signal to the electromagnetic coil and that will open the valve a bit more. Hereby the flow increases.

If it is the opposite way, then the PID controller will send a decreased signal to the coil and the opening percentage of the valve will decrease (UK, 2016).

- **3D printed equipment holder:** While building the hole prototype it becomes clear that you need some way of supporting the parts. All the pipes, reactor and valves have to be places correctly and in the right position and place.

To accomplish this challenge, parts must be made that can hold everything together. First, it is important to do research about the material that is going to be used. A couple of factors must be considered. The amount of weight that it needs to be able to hold. Also, the price of the material. And at last, the machineability of the material.

When all of this has been considered, the material can be selected. In this prototype the material of choice is polylactic acid (PLA). Because it is strong, cheap, and easily machinable. All there must be done to create a holder for the equipment is to make a design and then 3D print it. The drawing beneath shows the part that will hold the reactor.

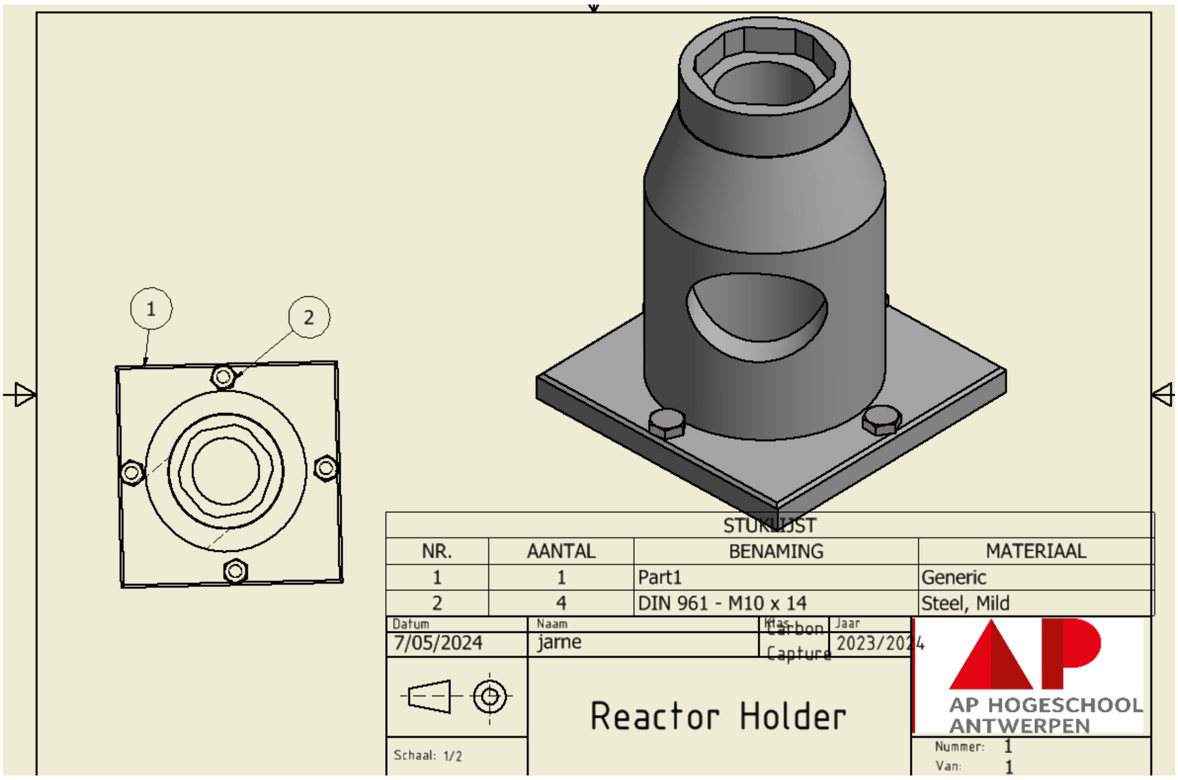



*Figure 16: Inventor design of the reactor holder (Heylen, 2024)*

### 6.3.3 Budget

To achieve all the deliverables in this project, it becomes necessary to contain a certain budget. Therefor it is from highly importance that there are investors included in the project.

The investors in this project created the opportunity for the team to build a working demo stand that holds a value of 5000 €. This means that the materials used in the demo can, as they are expected, be of good quality. Because of this it also means that the stakes and expectations are higher.

As already been told the material choice of the demo is of high importance. Hereby strict research about this topic is a must.

After the material research is completed, the next step can be taken. This will be the process of calculating the amount of material that is necessary. When the whole schematic is known than it becomes possible to achieve this certain calculation. When these calculations are done, then the price of the whole process of building becomes known.

As long as the price of the build is less expensive than the maximum price of the budget it is good. If the price of the materials necessary for the build is close or more expensive than the budget, changes must be made. Meaning that the building process must be changed or that the budget must increase.

For obvious reasons the first thing that will be tried to change is the building process. This consist of some different possibilities. First of all, the budget cut can consist of changing the materials used in the build. The next option could be to make the build a bit more simplistic. Meaning that some parts can be considered as expletive, these items could hereby be removed. The overall build would still work the same way, but it has maybe some fewer extra functionalities. For example, removing a flow meter, in a place that is not realty necessary.

The next possibility is to pitch an idea to the investors and ask for a higher budget. This is not always the best option because they demand strong and correct arguments. This means that they would probably ask some of the same arguments as answered in the paragraph above.

However, the end goals changed during the course of the project. Therefor the use of the budget also changed. The fact that the goals changed from building a working demo stand, to a DIY prototype. Because of this change the budget needed for the DIY is lower than the original needed budget. The total amount of money spend on the prototype is around 500 €.

The high price reduction is because the build is way more simplistic. The fact that the price is lower than before does not mean that the prototype is not as functional. It still consists of high-quality materials and parts.

To conclude all of this, the projects budget consists of 5000 €. Because of the changes with impact on the end goal of the project, the budget will be used differently than expected and the amount of money spend will be a lot lower than first predicted.

# 7 Results

The scope of this project had been adjusted to the circumstances.

The compromise was made on the practical part concerning the building of the prototype. The completing of the building was not possible because of procurement, logistical and organizational difficulties.

The following EPS group would, either way, not have continued the prototype and instead built a demo of purchased components. So, the decision on stopping the building process and focusing on the theory and the expected outcome instead has been the most logical and practical one.

In this part the building phase and how it would have continued will be described.

Also, it does contain the expectations on the test runs, the steps that would have been taken and the results that were predicted.

## 7.1 Prototype

While building the prototype there were some obstacles that had to be overcome. The first part in the process of building the prototype was to search for and buy all the components. To be able to create a prototype as close to the theoretical version of if, it is important to put a lot of time in choosing the correct parts in the store.

There are some factors that are important to know about before buying the materials.

For example, first it was intended to buy a metal reactor. After discussing about the characteristics of metal, the choice tilted more to the side of buying a stainless-steel reactor. This is because it will interfere less with the reactions that are going on inside the reactor.


*Figure 17: different lengths of pipelines*

When all the parts are collected, the actual building of the prototype can start. In this DIY, the pipelines exist of 10 millimeters in diameter.

At first, the copper pipe was 3 meters long. To build the DIY it was necessary to shorten it and divide it into pieces. After cutting the pipes, the sharp corners of the tube and the metal burrs were removed. The sharp edges would have not only created the risk of injuries but also increased the pressure loss.

The process consists also out of valves, flowmeter, and a reactor.

When the pipes are connected to for example a valve, the fitting must be airtight. To make these connections even more tight, Teflon fiber is used. This will help to decrease the leaking of gasses through the screw thread. At last, there is also a liniment used that will help the Teflon fiber to tighten the fittings even more.

In this build Teflon fiber is used instead of Teflon tape. The reason behind this is because Teflon fiber can withstand higher temperatures than the tape. It is always important while shopping for components that you keep in mind that every material and every product has different types of characteristics. That is why its notable to check the limits of every material regarding to the circumstances where it is placed or used in.

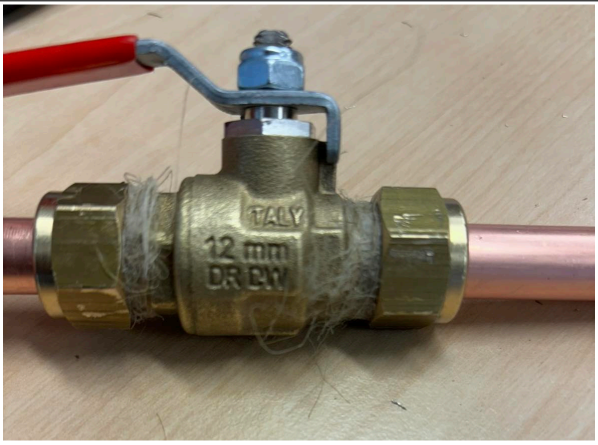



*Figure 18: Valve*

At last, there are also more, and less noble materials used, copper and stainless steel. These materials are used because a specific reaction can occur between two different materials that are connected. When copper is connected to stainless steel, bimetallic corrosion can occur. This is due to the different electrochemical properties of the two metals.
In some certain areas, a galvanic cell can from, causing the less noble metal (in this case, copper) to corrode while the more noble metal (stainless steel) remains protected.
To redeem this problem, three different metals are used. As shown on the picture, the first metal from the top of the reactor is called copper. The second metal is brass. The third metal is stainless steel.

*Figure 19: Reactor*

All of this has been about the building phase that has been done. As said before, the end goal of the project has been changed and the whole demo stand will not be made.
In the next paragraph, it will conclude what can be done by students from next semesters. It will give a summary of all the opportunities and task that can be made from this prototype and the research concluded in this paper.

If a container filled with CO2 and one with nitrogen is connected to the pipes of the DIY, and all the components are correctly installed. It becomes possible to capture the carbon in the reactor.
Inside the reactor there will follow some chemical process that will eventually lead to capturing the CO2 out of the flow.
If this building process has been completed, then the next step can be made. By using a heating/ cooling process, the chemical process can be reversed, and it will generate a restoration process.

At last, there is an option to optimize the flow and control it very precisely. This will happen whenever the flowmeters are correctly integrated into the process. With a local computer it is possible to generate charts and control from inside the computer software what the user wants that the flowmeter will do.
This means that the user has 100 percent control over what will happen to the flow inside the tubes.
The connection between the computer and the flowmeter can happen through a lot of different ways. The most common one is to use an Ethernet cable and an adapter switch to communicate between the different devices.

## 7.2 Expectations on test phase

Since one of the reasons to use zeolite has been, that there was some left, without any data on it, in the laboratory, there was almost no information on its proprieties.

For this reason, assumptions are based on the data of other types of zeolites.

The initial plan was to run some tests with the prototype.

The first would have been, to run the process with a similar fraction of $CO_2$ in the gas mixture, as measured from the combustion engine. That would have been about 11 %.

### 7.2.1 Isotherm comparison

The unknown zeolite would have been pretreated for multiple hours through degassing at 250 ° C.

This preparation is the same treatment used in the paper, which's results serve as comparison to this unknown zeolite.

The researchers from the paper ran their tests on a zeolite called ZSM-5.

The measurements on the adsorption of $CO_2$ were taken at three different temperatures, from 293 K, 308 K to 318 K (Hedi Jedli, 2022).

Also, the parameters for the modeling the Isotherms would have been copied since these are not to be found on an unknown type of zeolite.

*Table 1: Coefficients of ZSM-5 for the isotherms at different temperatures (Hedi Jedli, 2022)*

| Type | | 298 K | 308 K | 318 K |
|---|---|---|---|---|
| Langmuir | $q_m$ | 4.84 | 4.11 | 3.433 |
| | $K_L$ | 0.67 | 0.11 | 0.04 |
| | R | 0.996 | 0.991 | 0.990 |
| Freundlich | $K_F$ | 3.61 | 2.75 | 1.85 |
| | n | 3.7 | 3.4 | 2.5 |
| | R | 0.980 | 0.950 | 0.915 |

At this point, performed on the same reactor, the measurements should appear quite similar.

But by using these same conditions, it would be able to see the performance differences between the professional reactor and the prototype.

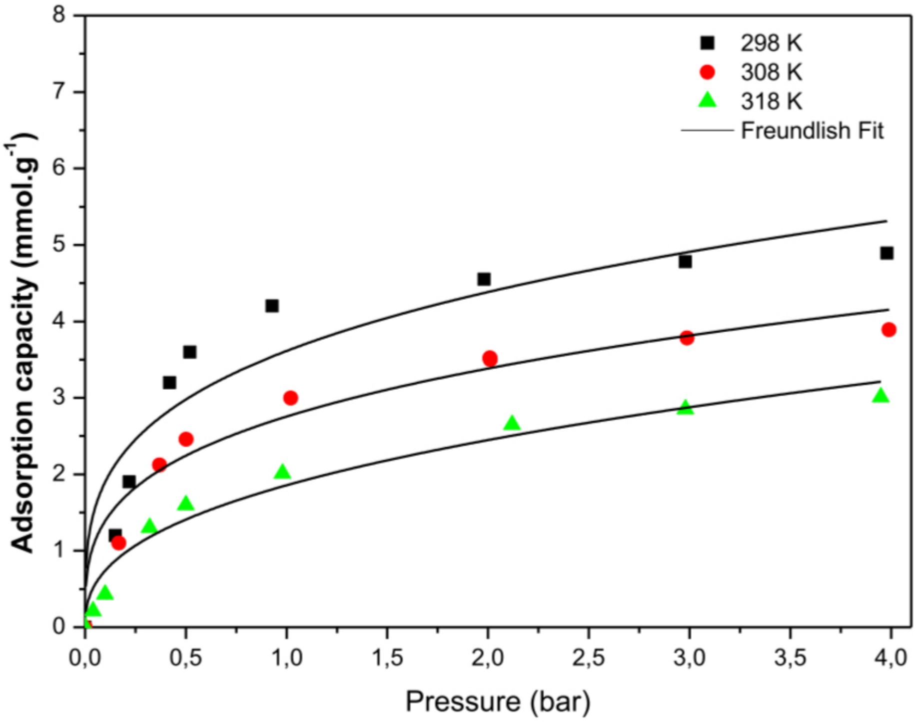



*Figure 20: Results on the adsorption of CO2 on zeolite ZSM-5 compared to the model of the Freundlich-Isotherms (Hedi Jedli, 2022)*

The first thing to notice is that the Langmuir-Isotherm (9) is the better fit for the ZSM-5 zeolite than the Freundlich-Isotherm (10). But for the project´s zeolite it might would look different.

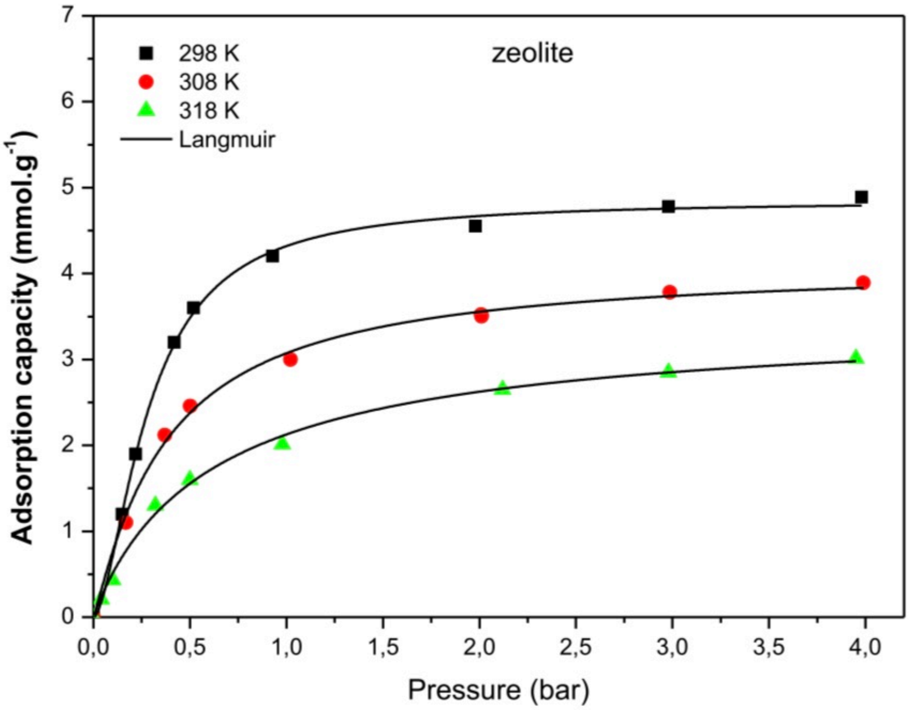



*Figure 21: Results on the adsorption of CO2 on zeolite ZSM-5 compared to the model of the Langmuir-Isotherms (Hedi Jedli, 2022)*

Independent of this, it is questionable if the measurements would look the same or if the small space between the fixed bed and the prototype column would have led to an insufficient contact.

Another possible reason for a lower adsorption capacity could have been the type of zeolite that is used.

For example, it is shown, that zeolites with low Si/Al ratio are the best choice for $CO_2$ adsorption. If the unknown zeolite from the laboratory possesses a higher Si/Al ration this would have led to an inferior performance (Federica Raganati, 2021).

If the post-combustion gas would have been used, a different reason could have caused a lower performance. A presence of $H_2O$ would have been preferably adsorbed from a zeolite that contains little silica. The hydrophobic ZSM-5 contains a higher amount of silica, which leads to a better performance in this scenario.

But without moisture present the low content of silica would have led to a high capacity on $CO_2$ adsorption capacity and high selectivity, at this low-pressure adsorption (Federica Raganati, 2021).

But no matter the question on the change in measured capacity, the prototype would surely perform poor in terms of the breakthrough curve.

#### 7.2.2 Comparison in breakthrough curve

The small space between the construction for the bed and the inner wall of the column provided a bypass for the untreated feed stream.

The adsorbate bypassing would probably exceed any, in industry, tolerable content of adsorbate in the effluent.

So instantly, with the introduction of the feed to the adsorbent there would be a significant amount of adsorbate, what causes the breakthrough curve to not take off from the bottom.

The height to diameter ration is lower for the prototype than for the common fixed bed adsorption columns, so the way for the MTZ would be shorter. This would have led to a shorter cycle of adsorption. So, breakthrough curve would be quite steep.

#### 7.2.3 Pressure losses on the feed side

In the first step the pressures with which the gases come out of the containers and through the flow meters would be measured. This is important to pass first since the steering of the volumetric flow will create a change in pressure. And the data is needed at a specific flow rate.

Also, the literature studies showed that it is common to use atmospheric pressure in the reactor (Anastasios I. Tsiotsias, 2023). To adjust the feed pressure to a level that secures that, the losses through the piping system must be known.

The room temperature is assumed to be approximately 293 K.

The molar mass of the elements the components consist of is to be found in the periodic table of elements (Appendix 4). With the mass of each element the molar mass of the gas streams can be calculated:

$$M_{CO_2} = (12.011 + 2 * 15{,}999)\frac{g}{mol} = 44{,}009\frac{g}{mol}$$

$$M_{N_2} = 2 * 14{,}007\frac{g}{mol} = 28{,}014\frac{g}{mol}$$

Based on this, the density of the gases each can be calculated.

Density depending on the pressure:

$$\rho_{Gas} = \frac{p * M}{R_m * T} \tag{12}$$

- $p = pressure \ (in \ kPa)$
- $M = molar \ mass \ (in \ \frac{g}{mol})$
- $R_m = general \ gas \ constant = 8{,}314 \frac{J}{mol*K}$
- $T = temperature \ (in \ K)$

The purpose of calculating is to enable the calculation of the different pressure losses because of all the installations.

Therefore, the velocity would be calculated by:

$$v = \frac{\dot{V}}{A} = \frac{\dot{V}}{\frac{\pi}{4} * d^2} \tag{13}$$

- $\dot{V} = volumetric \ flow \ rate \ (in \ \frac{m^3}{s})$
- $A = cross - sectional \ area \ of \ the \ pipe \ (in \ m^2)$
- $diameter \ on \ pipe's \ inside \ (in \ m)$

Pressure losses through pipe friction (in compressible media): (Schweizer fn, 2024)

$$\Delta p = p_1 * \left[ 1 - \sqrt{1 - \frac{\lambda * l * \rho_1 * v_1^2}{d * p_1}} \right] \tag{14}$$

- $p_1 = pressure \ at \ beginning \ of \ the \ pipe \ (in \ Pa_{abs})$
- $\lambda = pipe \ friction \ coefficient$
- $l = lenght \ of \ pipe \ (in \ m)$

- $\rho_1 = density\ at\ beginning\ of\ the\ pipe\ (in \frac{kg}{m^3})$
- $v_1 = velocity\ at\ beginning\ of\ the\ pipe\ (in\ \frac{m}{s})$
- $d = diameter\ on\ pipe's\ inside\ (in\ m)$

Pressure losses through installations:

$$\Delta p_\zeta = \frac{\zeta * \rho * v^2}{2} \tag{15}$$

- $\zeta = zeta\ value$
- $\rho = density\ (in \frac{kg}{m^3})$
- $v = velocity\ (in\ \frac{m}{s})$

(Schweizer fn, 2024)

The different values for the coefficients are found in tables online.

Drag coefficients:

- T-piece = 1.5
- Bend 90° =0.4
- Ball valve= 0.08
- Pipe friction coefficient: 0.0015

(Winkelmann Ingenieure-Dienstleistungen, 2024)

The process drawing (Figure 9) shows that on the feed side there are:

- 1x T-piece
- 5x Bend 90°
- 1x Ball valve

#### 7.2.4 Example

There are not the necessary measurements that would have been required to begin the calculations, assumption are made based on various literature.

The density of the gas mix of 89 % $N_2$ and 11 % $CO_2$ at 20 °C and under a pressure of 1.5 bar would be about 1.83934 $\frac{kg}{m^3}$ .

To begin with calculating the adsorbent bed it is to be assumed that the flow rate is 100mL per minute, the height of a 33 kg pressure vessel is about 1,3 m and the hypothetical over pressure is 50 mbar. The velocity coefficient is according to literature about 0.95. Because of the small size of the prototype, the adsorbent will be fast saturated, for this reason the calculation is simplified by assuming a constant pressure.

The velocity:

$$v = 0.95 * \sqrt{\frac{2 * 5000 \frac{kg}{m * s^2}}{1.83934 \frac{kg}{m^3}} + 2 * 9.81 \frac{m}{s^2} * 1.3m} = 70.21 \frac{m}{s}$$

In the next step it is time to consider the prototype. The diameter and the cross-section area are taken from the model that was designed.

The diameter is:

$$d = 0.042m$$

With this the cross-sectional area can be calculated:

$$A = \frac{\pi}{4} * 0.042^2 \approx 0.001385m^2$$

The area is required to calculate the available volume for the adsorbent within the prototype. The available height is measured:

$$h = 0.055m$$

So, the volume would be:

$$V = 0.001385m^2 * 0.055m = 7.6175 * 10^{-5}m^3$$

For calculating the mass of adsorbent that would have fitted in there, the bulk density of the, for previous comparisons used, ZSM-5 be used. It is:

$$\rho_{ZSM-5} \approx 720 \frac{kg}{m^3}$$

The mass would be:

$$m_{adsorbent} = 7.6175 * 10^{-5} m^3 * 720 \frac{kg}{m^3} = 0.054846 kg$$

The mass flow would be:

$$\dot{m}_{Feed} = \dot{V} * \rho_{Feed}$$

$$\dot{m}_{Feed} = \frac{0.0001 m^3}{60 s} * 1.83934 \frac{kg}{m^3} \approx 3{,}066 * 10^{-6} \frac{kg}{s}$$

By using variations of the shown equations (5) and (6), from the part about the Adsorbent bed, the amount of $CO_2$ that can be adsorbed and the time this takes be calculated:

$$m_{adsorbate} = m_{adsorbent} * C_{adsorption}$$

$$m_{adsorbate} = 0.054846 kg * 0.3 \frac{kg_{adsorbate}}{kg_{adsorbent}} = 0.0164538 kg$$

$$t = \frac{m_{adsorbate}}{\dot{m}_{Feed} * C_{adsorption}}$$

$$t = \frac{0.0164538 kg}{3{,}066 * 10^{-6} \frac{kg}{s} * 0.3 \frac{kg_{adsorbate}}{kg_{adsorbent}}} = 17888{,}45 s \approx 4.97 h$$

With the time the test runs could have been planned, the interval of measuring the composition of the effluent could have been set. By that it would have been possible to get enough results to plot a breakthrough curve and compare the actual result with this calculated one.

# 8 About EPS and the Team

## 8.1 EPS

The Team working on this "Carbon Capture Demo" project came together under the guidelines for the "European Project Semester", which request a team to be assembled from at least three different countries.

In this case, not only the origin varies, but it is also a multi-disciplinary team.

The project itself, as well as the supporting courses aim to prepare the students for the globalized work environment most engineers face in their career.

It is a chance to experience the difficulties of a multi-cultural and multi-professional project and an opportunity to do so in a guided environment, where the development of the required competences and knowledge are provided.

## 8.2 The team members

- **Isabel:** My full name is Isabel Hela Kuchta, and I study Environmental-, Power- and Process Engineering at the University of Applied Science in Osnabrück, Germany.

  Before I started studying engineering I have finished my nursing degree. Since then, I have worked part time in a hospital to afford studying.

  Also, I have already lived multiple months in a foreign country before.

  These experiences provided me with an independence, personal responsibility, and a tendency to take a pushing and leading role in the group works I have done the last couple of years.

  I am excited for the project, since the content is close related to the discipline, I am looking for in master´s programs.

- **Alissa:** I am currently a French second year student in Engineering School at ESIReims, specializing in packaging, so I want to become a packaging engineer. I did a two years undergraduate vocational degree in packaging during which I did an internship in a packaging company. I also had the opportunity to do two volunteering abroad as a part of my studies. I developed my interpersonal skills like personal development, by learning to quickly adapt to a new environment, in another language and especially in a job that I absolutely do not know. As you can see, I like to get out of my comfort zone and discover new environments. As well as taking on new challenges while joining a team.

- **Jarne:** I am an automation engineering student from Belgium. I study at the AP University of Applied Sciences. Automatization is something I really love everything that can be optimized is a new challenge and can be perfected. I therefor also hope that once I graduate, I can earn a job in this field. I have done an internship within an electromechanics company where I learned a lot of new things about the difference between school theories and the work field. I am highly interested in this project because it is something that is not near my study field. Therefore, I hope I would be able to learn a lot about carbon capturing and also about process engineering.

## 8.3 The Team role assessments

To build a successful Team that's able to face to upcoming challenges it is important to know the strengths and weaknesses of each member.

The assessments of each one don't say much about the success of the team, but if the results are combined a prediction about the team dynamics can be made. The true potential is in showing possible obstacles can occur inside the team, so they can be avoided by knowing them.

## 8.4 Belbin team roles results

Studying into team effectiveness, during the 1970s, Dr. Meredith Belbin's research was dedicated towards the controlling of team dynamics and discovering possibilities to avoid problems within the team.

Belbin and his team of researchers had assumed, high-intellect teams would be the most successful ones. But their work showed the divers behaving teams turned out to be the thriving one (Belbin, 2024).

The types of behaviors that contribute to a successful team performance were clustered to form the nine "Team Roles".

Through discovering our own Team Roles a better understanding in strengths an allowable weakness is provided to the team. That improves communication and the allocation of tasks. There are three "Social roles": Resource Investigator, Team worker and Coordinator, three "Thinking roles": Plant, Monitor Evaluator and Specialist, and three "Action/Task" roles: Shaper, Implementer and Completer Finisher (Belbin, 2024).

- **Isabel:** My results in the Belbin test were not unexpected to me. But I would have expected, my communication skills would have had more of an impact on my Team worker-Skills. But I already did know that I will have to work on that. That's what I want to focus on improving. At the same time, I will keep an eye on my allowable weaknesses, to more aware of them.

- **Alissa**: According to my results I have the social function because the Belbin test highlights coordinator and resource investigator. I find these results very consistent with my way of behavior that is considered within a work environment. Indeed, during my studies, I had the opportunity many times to work in groups on very different subjects with a very different number and people. These projects allowed me to analyze myself in this group work and thus anticipate the group agreement and effectiveness. I also see what my weaknesses are, and I am aware of them. So now the goal would be to concentrate on these and while using my strengths.

- **Jarne:** After completing the Belbin test, I wasn't surprised. I am aware of my strengths, but I didn't expect my teamwork to be this low. This aspect is now something I'm conscious about and want to improve. I will also try to find a way to improve my other weaknesses but at the same time still use my strengths were necessary.

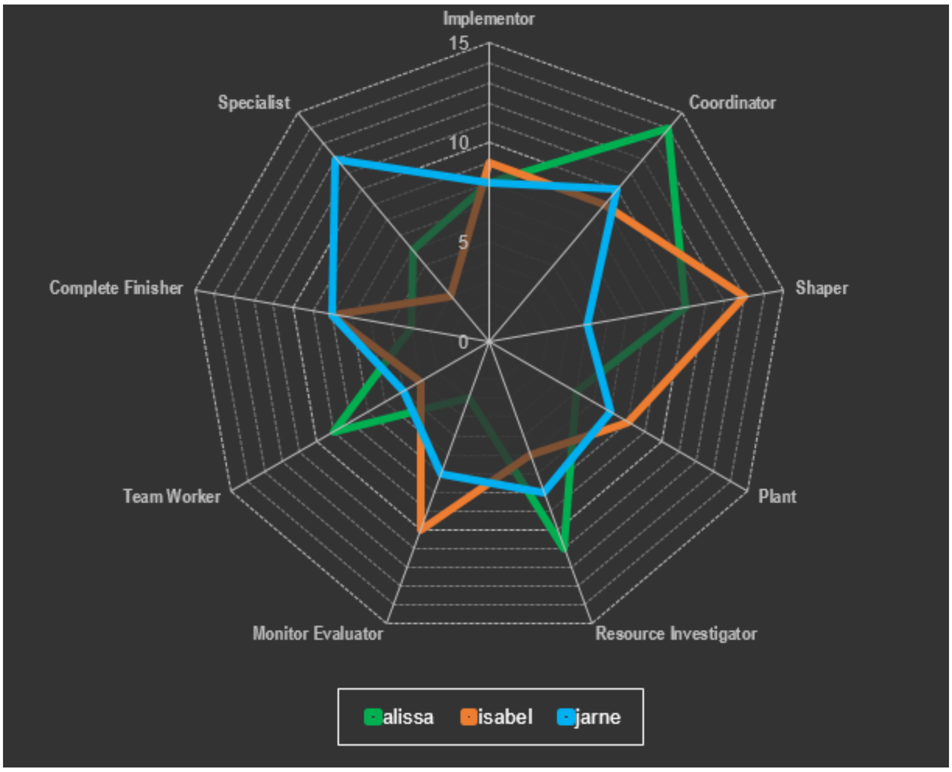



*Figure 22:Belbin Team role results (Authors-own, 2024)*

The overlay of our Belbin results shows that our strengths are divers and at least one of us is always complementing the weaknesses of one of the others. As well as our biggest strengths are all different.

## 8.5 The Leadership test

A factor, common in all industries, is the need of a project manager, when there is a project to accomplish.
Certain leadership skills are asked by a project manager. They must be able to encourage the team spirit, to motivate the team, resolve conflicts while keeping the durable relationship they built. At the same time, they must do the scheduling, make the decisions, use their critical thinking, and solve upcoming problems.

- **Isabel:** My results in the Leadership test match my expectations. I always have been a person who likes planning but therefore has difficulties dealing with uncertainty. In group projects I tent to get in the leading position. But that often leads to the feeling of responsibility and pressure, which can make me want to control everything.
The communication part is where I think to have a lot of experience and knowledge about, since it was an essential part of my previous degree and work live. But that is also why I sometimes apply these expectations on others and if they don't seem to make an effort in good communications, I stop using my communication skills out of frustration. That is something I am still working on.

- **Alissa:** In my opinion, I am a good team player who can always help identify problems and assist members. Moreover, I am a cooperative individual who listens and prevents any potential conflict within the team. This ability has a weakness called indecisiveness, which makes it hard for me to pick a single option to avoid confrontations with the members. So, what emerges from the leadership test seems quite coherent to me with a good ability to communicate which for me matches very well with planning because as with communication, things need to be structured.

- **Jarne:** The results of the leadership test show that I'm above the curve of the typical project manager in 2 different categories named: Leadership and

Creative think' and Problem solving. This could be a positive or negative thing. The positive part could be that I really am good in those subjects. The negative thing could be that I overestimate myself and this could lead to me being overconfident and making bad decisions throughout this project. These facts are something I always must be critical about and don't forget throughout the project. There are two categories where it is almost the same as the typical project manager. There is one aspect where I score lower, and this is in the "Dealing with uncertainty" category. There would probably be a time were an uncertainty will occur in our project and it is important for me to ask for help within my group if I don't know how to manage this situation.

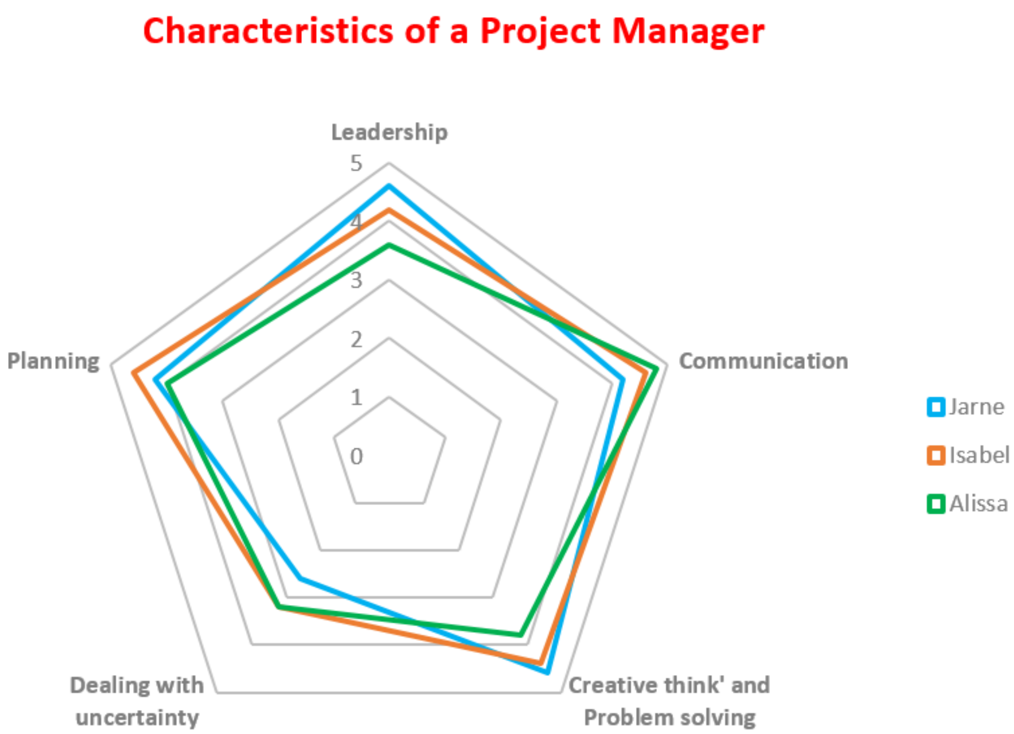



*Figure 23: Leadership test results (Authors-own, 2024)*

Our shapes look similar on the first impression, but the characteristic strengths vary. So, every member of the group provides his specialties.

We should keep a look at our handling of uncertainty, since that's the dimension not one of use has a strength in.

# 9 Intercultural Communication

The increasingly multicultural business environment is presenting new challenges. The communication between employees who are used to different conventions and values will present great challenges unless the individuals are aware of them.

The definition of culture is based on their individual sets of artifacts, norms, values, rituals, ceremonies, heroes, and stories (The Culture Factor, 2024).

## Hofstede's model

Professor Geert Hofstede developed a six-dimensional model, to understand the culture of a county. It is based on its cultural values.

The aim is to improve communication and cooperation in a multicultural team (The Cultur Factor, 2024).


*Figure 24: Hofstede's Dimensions (Slide Bazaar, 2024)*

As the diagram (Figure 25: Country Comparison of the team members**Fehler! Verweisquelle konnte nicht gefunden werden.**) shows, in most of the dimensions Belgium and France are close to each other. Only concerning the dimensions of Motivation towards Achievement and Success and Indulgence Belgium is clearly scoring higher than France.

In two of the dimensions, Individulism and Long Term Orientation, all three of them are at the same level.

These simmilarities can be an advantage for the team, because there is no need to compromiese on the well known working customs, since all partitipants share the tendency to a pragmatic approach as well as the high scores on Individualism.

So everyone profits from explicite responsibility assignments and the ability to work on those sepratly.

Empathie is requiered in other dimensions such as Power Motivation towards Achievement and Success, Indulgence and Uncertainty Avoidance where the major differences accure.

Through the display of the differences missunderstandings can be avoided by reviewing the divers approches of some of Hofstede's Dimensions.

While the discrepancy in Power Distance doesn't seem to influence this teamwork as much as the others.

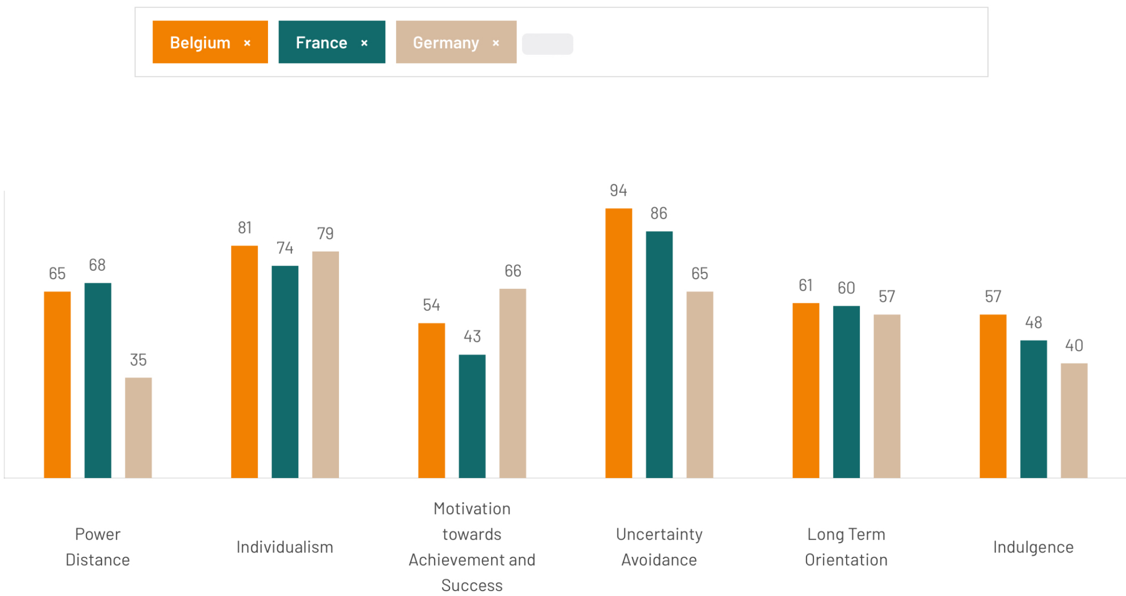



*Figure 25: Country Comparison of the team members (The Culture Factor / Groupe, 2024)*

Even though it is heavily used, there are some critics in quality and quantity of Hofstede's research (Weil, 2024).

Though in this group the results are persived mainly as correct:

- **Isabel:** Reading the description of the different dimensions I see myself well represented as a German. Even though I immediately got examples in my mind, of other Germans know, who wouldn't feel represented by these results.

- **Alissa:** Individualism is prevalent in France, driven by a strong desire for autonomy and independence highly valued in the professional world. Additionally, dealing with uncertainty poses a challenge for the French, emphasizing the importance of planning and organization. My leadership test underscored similar traits in my project work.

- **Jarne:** When I compare my data to the general data of Belgium, I can conclude that it is quite accurate. Overall, I do agree with the statement of Belgium in comparison to my individual data.

# 10 Communication

The key in every interhuman interaction is the communication. It is essential for a functioning team.

Good communication or the lack of it can be the determining variable between a successful and a failing project.

The communication and collaboration within the team was manly based on Microsoft TEAMS and WhatsApp.

One TEAMs group was dedicated to the communication with the tutor, another one on the sharing of external documents, like recourses that seemed interesting as well as collecting the shared ONE DRIVE documents like the reports.

Via WhatsApp the daily communication as well as meetings were arranged since the messages appeared more reliable on the mobile devices.

## 10.1 Stakeholders

During a career in engineering there are numerus acquaintances made.

All this people can be resources that are potentially able to impact the projects that follow. Though they must be attentively managed.

Therefore, the process of Stakeholder Analysis has been generated.

In the first one of three steps, the Stakeholders must be identified. Anybody who affects the project, whether they have power over it or not, can be considered a stakeholder (Mind Tools Ltd 2024, 2024).

The next step is about the prioritization of the Stakeholders based on the amount of power and interest they have in the project (Mind Tools Ltd 2024, 2024).

The visualization of Power/Interest Grid can be used to get a clear picture of our Stakeholders.

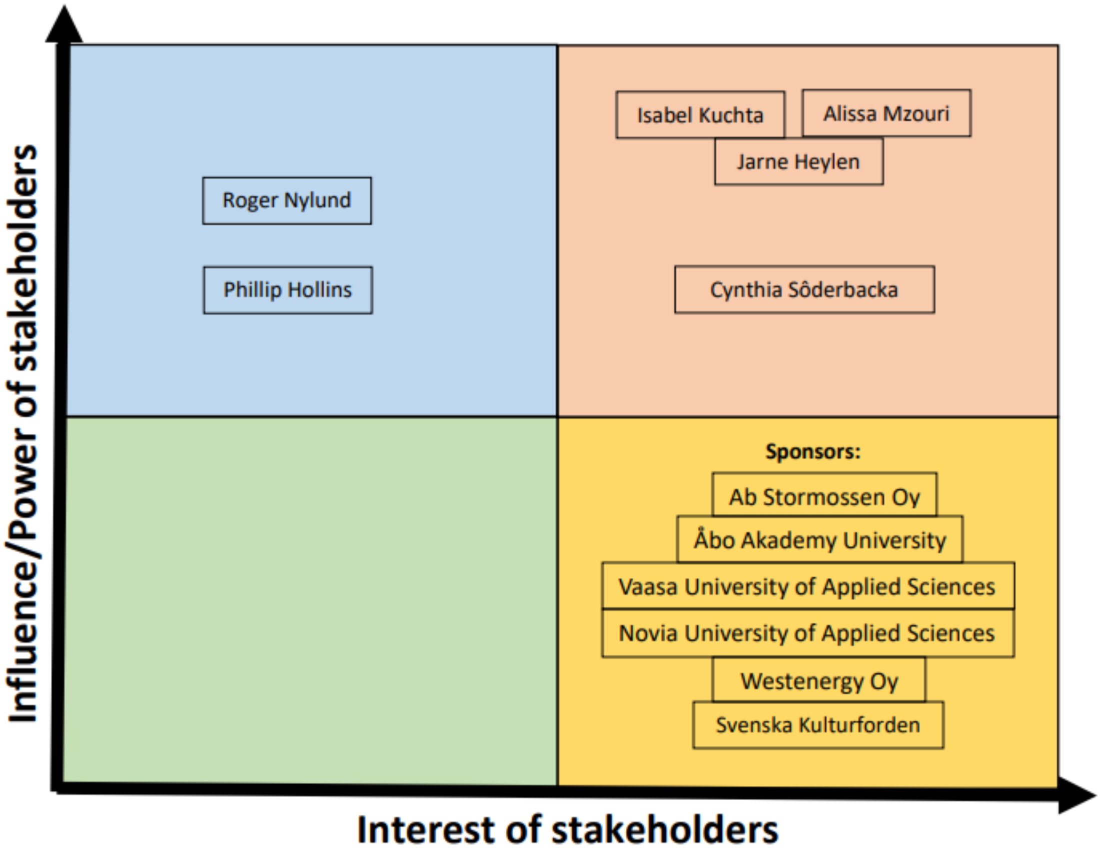



*Figure: 26 Stakeholders Matrix (Authors-own, 2024)*

Through the Stakeholder Matrix it gets obvious, even though the project has been initiated by Novia UAS, the participants of the project "MAP-UP-P2X - Mapping $CO_2$ Streams in Ostrobothnia: Unlocking potential for P2X Economy", Novia University of Applied Sciences, Vaasa University of Applied Sciences, Åbo Akademy University, Ab Stormossen Oy, Westenergy Oy and the SVENSKA KULTURFORDEN through Mikael Ehrs.

They provide the financial frame the project relies on, but the influence/power is estimated lower than for other stakeholders because they act in the background. But their interest is high.

With their classes in the beginning of the semester the influence of Roger Nylund and Philip Hollins was immense because they formed this project partners to teams. Also, they provided the teams with knowledge on managing themselves as well as their projects. Whilst the interest in the project details and technicalities are estimated low.

The highest influence/power and highest interest for this project are the team members and their supervisor Cynthia Söderbacka. The supervisor defines the project scope and guides the team through their experience. Also, the supervisor is providing organizational support. Therefore, the highest influence/power and the highest interest are held by the supervisor.

But since the executive role is held by the team members, they are ranked higher in the influence/power of the outcome. Therefore, the priority should be on the team members and their supervisor.

And in the last step the key stakeholders are to be understood.

It is essential to know the best way to communicate and engage them.

To get to know them ask about their view, opinion, and expectations. (Mind Tools Ltd 2024, 2024)

The stakeholders are the participants of the project "MAP-UP-P2X - Mapping $CO_2$ Streams in Ostrobothnia: Unlocking potential for P2X Economy":

- Novia University of Applied Sciences
- Vaasa University of Applied Sciences
- Åbo Akademy University
- Ab Stormossen Oy
- Westenergy Oy

The SVENSKA KULTURFORDEN through Mikael Ehrs with the "Project funds-Agricultural Project; students Saving Agriculture" funds this Carbon Capture EPS project.

In the Stakeholder Register these information are collected and summarized.

NOVIA
UNIVERSITY OF APPLIED SCIENCES

STAKEHOLDER REGISTER TEMPLATE

| | | | |
|---|---|---|---|
| PROJECT NAME | Carbon Capture | BEGIN DATE | 07/02/2024 |
| CLIENT | Novia UAS | END DATE | 17/05/2024 |
| PROJECT DESCRIPTION | There are plants in the region that are producing C02 and want to utilize it therefore it has to be captured | | |

STAKEHOLDER REGISTER

OVERVIEW

| ID | STAKEHOLDER | Contact | ROLE | CATEGORY | INTEREST | INFLUENCE | EXPECTATIONS |
|---|---|---|---|---|---|---|---|
| 1 | Isabel Kuchta | Phone: +33651154848<br>Email: alissa.mzouri@edu.novia.fi | Project Manager | Internal | High | High | In charge of planning and executing the project |
| 2 | Alissa Mzouri | Phone: +33651154848<br>Email: alissa.mzouri@edu.novia.fi | Co-Manager | Internal | High | High | Researching support/feedback + homogenize the work |
| 3 | Jarne Heylen | Phone: +33651154848<br>Email: alissa.mzouri@edu.novia.fi | Technical Chief | Internal | High | High | Research and implement the demo |
| 4 | Cynthia Söderbacka | Phone: +358443417969<br>Email: cynthia.soderbacka@novia.fi | Supervisor | Internal | High | High | Help with the management of the project |
| 7 | Roger Nylund | Phone: +358505272281<br>Email: roger.nylund@novia.fi | Writting format Supervisor | Internal | Medium | Medium | Support writing, feedback and stakeholder's manager |
| 6 | Phillip Hollins | Phone: +358469215722<br>Email: philip.hollins@novia.fi | Writting format Supervisor | Internal | Medium | Medium | Support writing, feedback |
| 7 | Novia UAS | Phone: +358442155139<br>Email: novium@novia.fi | Support Institution | Internal | Medium | Low | Do formalities and provide access to university tools |
| 8 | Sponsors | | Support the project | External | Medium | Medium | Help with the budget |

*Figure 27: Stakeholder Register (Authors-own, 2024)*

## 10.2 Team Charter

To assure everybody is clear about the exact subject of the communication, the Team Charter is created.

*Table 2: Team Charter (Authors-own, 2024)*

**PROJECT CHARTER**

| 1. General Project Information | | |
|---|---|---|
| **Project Name:** | Carbon Capture | |
| **Team Leaders:** | Isabel Kuchta | |
| **Sponsors:** | Novia UAS | |
| **Date:** | 07.02.2024-17.05.2024 | |
| **2. Project Team** | | |
| **Name** | **Title** | **Responsabilities** |
| Isabel Kuchta | Project Manager | In charge of planning and executing the project |
| Jarne Heylen | Technical Chief | Research and implement the demo |
| Alissa Mzouri | Co-Manager + Design Chief | Researching support/feedback + homogenize the work |
| Cynthia Söderbacka | Supervisor | Help with the management of the project |
| Novia UAS | Support Institution | Do formalities and provide access to university tools |
| Roger Nylund | Supervisor | Support writing, feedback and stakeholder's manager |
| Philip Hollins | Writing format supervisor | Support writing, feedback and stakeholder's manager |
| **3. Project Scope Statement** | | |
| **Purpose Of The Project** | | |
| The aim of this project is to build a working Carbon Capture Demo. | | |
| **Objectives** | | |
| • Research existing processes | | |
| • Design/make a plan of the demo | | |
| • Build the demo by sticking to our budget | | |
| • Accomplish the report by sticking our deadline. | | |
| **Deliverables** | | |
| • Only a demo version | | |
| • Focused on the theoretical part and not commercialized product | | |
| **Scope** | | |
| This project includes the building of the demo with a budget of 5000€ . It’s not supposed to be used on a real plant. | | |

The assigned responsibilities serve as a clarification of competences each one inheritances, it makes it easy to know who to ask and contact in case of a question or a problem. It accelerates the process.

# 11 Work Breakdown Structure (WBS)

A Work Breakdown Structure is a tool in project management to decompose a project into manageable and concrete steps of procedure.

It divides the given scope into its required Deliverables, the Sub-deliverables, and the necessary tasks to accomplish the (Sub-) Deliverables.

There is software to build the digital WBS, but a creative analog approach can offer more divers ideas on it.

It is recommended to start with a brainstorming session on sticky notes, instead of using a software right away. Each team member starts with writing down what comes to their mind, without thinking twice. And then everyone can take some inspiration from what the others wrote. Another chance follows, to write down new thoughts.

Collectively the groups are now able to create a physical WBS on the wall and everyone's ideas will be considered.

As a result, a constructive discussion is initiated about the steps that needs to be taken, in order to fulfill the expectations and the succeed with the project.

Lastly, this analog WBS will be converted to a digital version and can serve as a base for the time schedule.

## WORK BREAKDOWN STRUCTURE TREE DIAGRAM TEMPLATE

| PROJECT TITLE | Carbon Capture | COMPANY NAME | |
|---|---|---|---|

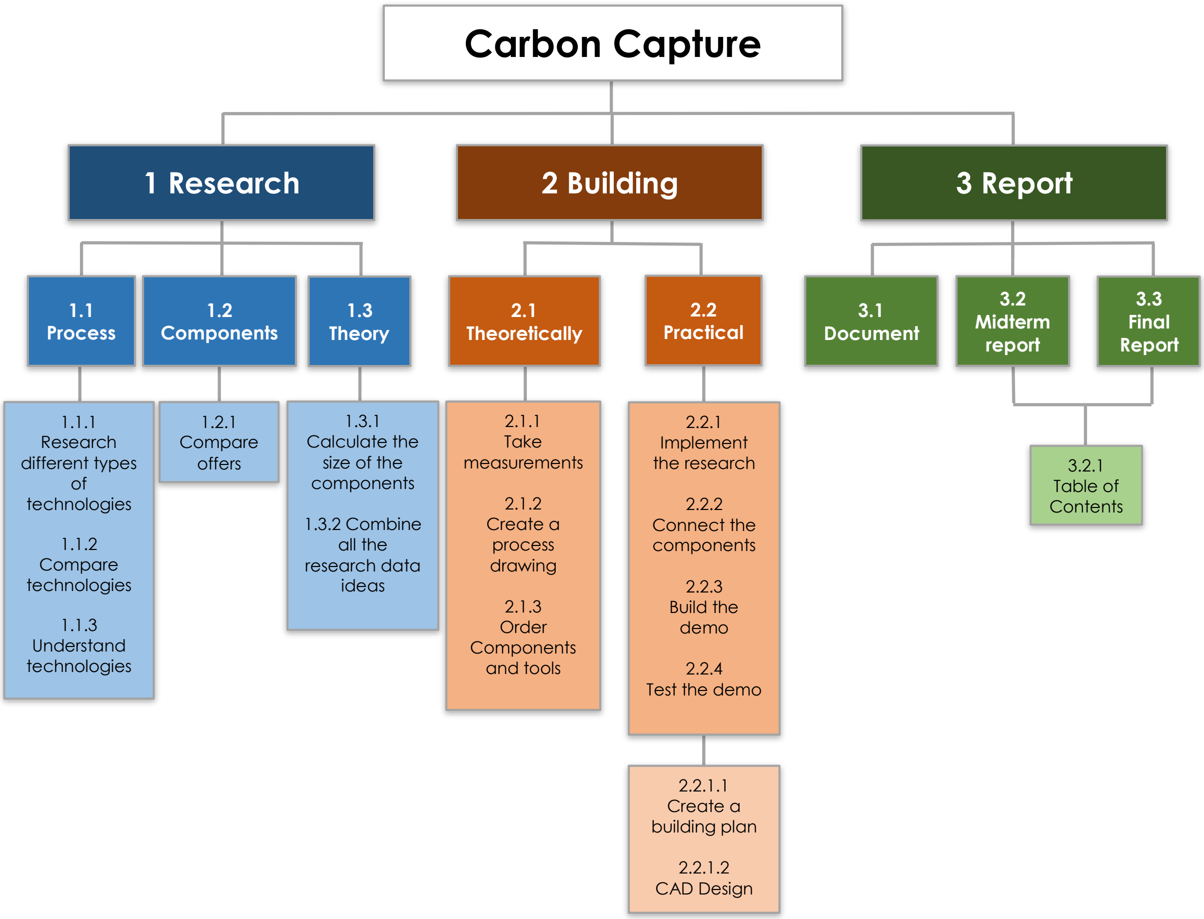



*Figure 28: Work Breakdown Structure (Authors-own, 2024)*

The first level does contain the main Deliverables the Carbon-Capture-Demo-Project requires. The first Deliverable is the Research, which will be a major part of this project. So, it is a mostly theoretical work, to create a ground for following EPS Groups and their practical realization of the Carbon Capture Demo.

The second Deliverable is the building, that is focused the planning and realizing a "DIY" prototype. This part will provide a deeper understanding of the considerations that have to be made when a plant is built from scratch.

The third Deliverable is the report. It is not only the collection of the generated understanding and knowledge, but also a preparation to hand-over the project to the next Groupe.
On the second level the Sub-deliverables are displayed, which concretize the Deliverables. Underneath that, the Tasks that are needed to be completed in order to fulfill the Deliverables, are displayed.

# 12 Schedule

As opposed to WBS the Scheduling contains a timeframe and a clear assignment of each task.

The assigned responsibilities are essential for the objectives to be fulfilled.
The estimated timeframe provides the schedule with a more concrete idea, what must be done and what can be done simultaneously so the deadline will be met.
The deliverables and tasks can be taken from the WBS. Out of these it is obvious how the elements of the schedule are connected and dependent on each other (Hollins P. , 2024).

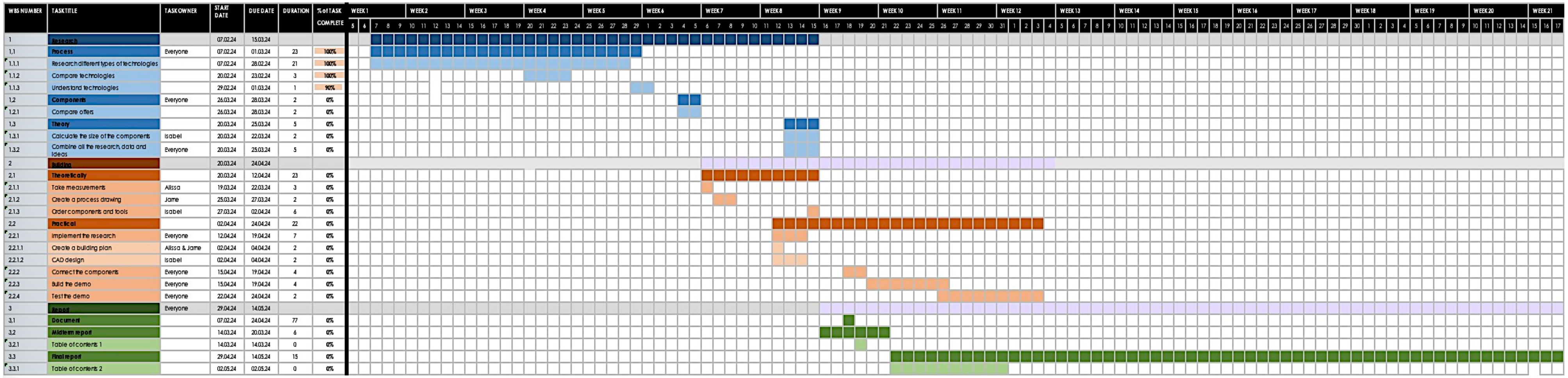



*Figure 29: Gantt Chart WBS overview (Authors-own, 2024)*

An excel template for a Gantt chart has been used for the scheduling.

The colors used refer to the same deliverables and tasks on the WBS to make the schedule clearly laid out.

| WBS NUMBER | TASK TITLE | TASK OWNER | START DATE | DUE DATE | DURATION | % of TASK COMPLETE |
|---|---|---|---|---|---|---|
| 1 | Research | | 07.02.24 | 15.03.24 | | |
| 1,1 | **Process** | Everyone | 07.02.24 | 01.03.24 | 23 | 100% |
| 1.1.1 | Research different types of technologies | | 07.02.24 | 28.02.24 | 21 | 100% |
| 1.1.2 | Compare technologies | | 20.02.24 | 23.02.24 | 3 | 100% |
| 1.1.3 | Understand technologies | | 29.02.24 | 01.03.24 | 1 | 90% |
| 1,2 | **Components** | Everyone | 26.03.24 | 28.03.24 | 2 | 0% |
| 1.2.1 | Compare offers | | 26.03.24 | 28.03.24 | 2 | 0% |
| 1,3 | **Theory** | | 20.03.24 | 25.03.24 | 5 | 0% |
| 1.3.1 | Calculate the size of the components | Isabel | 20.03.24 | 22.03.24 | 2 | 0% |
| 1.3.2 | Combine all the research, data and ideas | Everyone | 20.03.24 | 25.03.24 | 5 | 0% |
| 2 | Building | | 20.03.24 | 24.04.24 | | |
| 2,1 | **Theoretically** | | 20.03.24 | 12.04.24 | 23 | 0% |
| 2.1.1 | Take measurements | Alissa | 19.03.24 | 22.03.24 | 3 | 0% |
| 2.1.2 | Create a process drawing | Jarne | 25.03.24 | 27.03.24 | 2 | 0% |
| 2.1.3 | Order components and tools | Isabel | 27.03.24 | 02.04.24 | 6 | 0% |
| 2,2 | **Practical** | | 02.04.24 | 24.04.24 | 22 | 0% |
| 2.2.1 | Implement the research | Everyone | 12.04.24 | 19.04.24 | 7 | 0% |
| 2.2.1.1 | Create a building plan | Alissa & Jarne | 02.04.24 | 04.04.24 | 2 | 0% |
| 2.2.1.2 | CAD design | Isabel | 02.04.24 | 04.04.24 | 2 | 0% |
| 2.2.2 | Connect the components | Everyone | 15.04.24 | 19.04.24 | 4 | 0% |
| 2.2.3 | Build the demo | Everyone | 15.04.24 | 19.04.24 | 4 | 0% |
| 2.2.4 | Test the demo | Everyone | 22.04.24 | 24.04.24 | 2 | 0% |
| 3 | Report | Everyone | 29.04.24 | 14.05.24 | | |
| 3,1 | **Document** | | 07.02.24 | 24.04.24 | 77 | 0% |
| 3,2 | **Midterm report** | | 14.03.24 | 20.03.24 | 6 | 0% |
| 3.2.1 | Table of contents 1 | | 14.03.24 | 14.03.24 | 0 | 0% |
| 3.3 | **Final report** | | 29.04.24 | 14.05.24 | 15 | 0% |
| 3.3.1 | Table of contents 2 | | 02.05.24 | 02.05.24 | 0 | 0% |

*Figure 30: Gantt Chart WBS close up (Authors-own, 2024)*

The timeframe for the tasks is just a rough estimation, since to that date the details of the project had not been clarified.

But still it delivers the urgency of the decisions by showing what is dependent on the clarification and can already be done without it.

## Risk Management

The intention of the risk management is that even though not all complications can be avoided, to be prepared when they occur.

To identify all possible events, that could influence the project negatively is essential.

The severity and the likelihood must be estimated to assess the risk.

There is a stepwise methodology recommended to manage risks:

1. Identify – ideate the range of project `what-if´ event/risks
2. Measure – quantity using Risk Assessment Matrix
3. Manage – complete using Risk Assessment Register
4. Monitor – review risks and update on going as project proceeds
5. Report – communicate outcomes to relevant stakeholders

(IBM, 2024)

Following this methodology a Risk Assessment Matrix was developed.

| | | Severity | | | |
|---|---|---|---|---|---|
| | | NEGLIGIBLE<br>small/unimportant; not likely to have a major effect on the operation of the event / no bodily injury to requiring minor first aid injury | MARGINAL<br>minimal importance; has an effect on the operation of event but will not affect the event outcome / requires medical treatment | CRITICAL<br>serious/important; will affect the operation of the event in a negative way / suffers serious injuries or medical treatment of minors | CATASTROPHIC<br>maximum importance; could result in disaster/death; WILL affect the operation of the event in a negative way / death, dismemberment or serious injury to minors |
| Probability | LOW<br>This risk has rarely been a problem and never occurred at a college event of this nature | LOW (1) | MEDIUM (4) | MEDIUM (6) | HIGH (10) |
| | MEDIUM<br>This risk will MOST LIKELY occur at this event | LOW (2) | MEDIUM (5) | HIGH (8) | EXTREME (11) |
| | HIGH<br>This risk WILL occur at this event, possibly multiple times, and has occurred in the past | MEDIUM (3) | HIGH (7) | HIGH (9) | EXTREME (12) |

*Figure 31: Risk Assessment Matrix (studylib.net, 2024)*

Also, a Risk Assessment Register was created by using the stepwise methodology to manage and proactively prepare the risks of the project.

*Table 3: Risk Assesment Register (Authors-own, 2024)*

**Risk Tracking Template**

**Date of last review:**

| ID | Description of Risk | Impact | Risk Reponse | Risk Level | Risk owner | Notes |
|---|---|---|---|---|---|---|
| 1 | Supplier delay | Pushes launch | Confirm delivery dates by Phase 2 | High | Alissa, Isabel, Jarne | 2 |
| 2 | Wrong research | Fails the hole project | First brainstorm on the to use technology | High | Alissa, Isabel, Jarne | 3 |
| 3 | Wrong planning | Task will not be ready on time | Create a strong planning | High | Alissa, Isabel, Jarne | 1 |
| 4 | Bought the wrong items | Assembly time will take longer + more expensive | Calculate and design eveything first before ordering | High | Alissa, Isabel, Jarne | 3 |
| 5 | Demo principle not working | End goal will not be reached | Research first, then calculations and then building | High | Alissa, Isabel, Jarne | 2 |
| 6 | Out of budget | Can not buy more tools | use the ones we have | Low | Alissa, Isabel, Jarne | 3 |

The risk is no longer an undefined worry, instead it is described, the impact of it is outlined and a suitable response is planned.

The problems that should be prevented through sufficient planning are no longer a thread to the project. If they occur a next step is prepared and the responsible persons are named, so they can immediately act.

# 13 Project Quality Management

The Quality Management is a continues improvement cycle that is divided into quarters. The first quarter is about the identification of the aims and problems. It is followed by the one about the potential solutions that must be considered and tested. The third contains the study of the outcome of tested ones. In the last quarter the most promising solution gets implemented.

Standards are tested and analyzed solutions or guidelines that provide individuals with a sense of safety, reliability and quality, and the society with a base for more suitable regulations (ASQ, 2024).


*Figure 32: ISO 9000 Quality Management Principles (ASQ, 2024)*

To manage the quality of a project requires of the stakeholders must be identified. How those can be measured should be listed.

To assure the required quality of the deliverables is met, there is a system of project audits is demanded.

Through the monitoring of the quality the standards can be secured. Or if it does not meet the expectations, it can be adjusted (ASQ, 2024).

# 14 Appendix

*Appendix 1*

| adsorbent | advantages | disadvantages |
|---|---|---|
| activated carbons | wide precursor availability | limited values of $CO_2$ adsorption capacity |
| | low cost | friability |
| | high specific surface area | low selectivity |
| | high thermal stability | |
| | rather good tolerance to moisture | |
| | easy regeneration | |
| carbon nanomaterials | well-defined pore size distribution | complex/expensive synthesis |
| | high specific surface | limited selectivity |
| | high $CO_2$ adsorption capacity | |
| | good chemico-physical stability | |
| | fast adsorption kinetics | |
| | tolerance to moisture | |
| synthetic zeolites | tunable pore size and surface properties | expensive synthesis |
| | high surface area and porosity | low tolerance to moisture/impurities |
| | high $CO_2$ adsorption capacity | low selectivity |
| | high thermal stability | |
| natural zeolites | large availability | low purity as a result of variable chemical composition |
| | low cost | limited separation performances |
| MOFs | tunable pore size and surface properties | complex/expensive synthesis |
| | high surface area and porosity | low tolerance to moisture/impurities |
| | high $CO_2$ adsorption capacity | limited thermal stability |
| amine-functionalized materials | large number of supports | low thermal/oxidative stability (amine degradation) |
| | high $CO_2$ capacity | pore blockage |
| | low production cost | |
| | good regeneration ability | |

(Federica Raganati, 2021)

Appendix 2

| | advantages | disadvantages |
|---|---|---|
| conventional fixed bed | simple configuration | relatively high pressure drop, with respect to all of the other configurations, resulting in a larger energy penalty |
| | plug-flow nature, which increases the achievable working adsorption capacity | poor heat transfer coefficients; i.e., heat fronts limit the working adsorption capacity |
| | more suited for pressure swing processes | relatively high pressure drop limits the gas velocities, thus increasing the footprint |
| structured fixed bed | reduced heat/mass transfer limitations and pressure drop with respect to conventional fixed beds | low effective sorbent bulk density; i.e., the inert support monolith occupies a large fraction of the reactor volume |
| | relatively lower pressure drop, with respect to conventional fixed beds; i.e., faster gas flows can be employed, thus resulting in a smaller footprints | |
| moving bed | counter-current mode increases the working adsorption capacity | relatively lower heat transfer coefficients, with respect to fluidized beds |
| | simple steady-state operation achievable by means of the solid circulation through the different sections | counter-current mode limits the gas velocity to avoid fluidization of the sorbent particles moving downward, thus resulting in a larger footprint |
| | more suited for temperature swing processes, in both direct and indirect heating modes | high operational difficulties for pressure swing processes as a result of the interconnected system design |
| conventional fluidized bed | ideal solid mixing, thus leading to excellent mass and heat transfer coefficients with immersed walls | high mixing rate resulting in fast $CO_2$ breakthrough and low working adsorption capacity, thus requiring large sorbent recirculation rates to achieve acceptable $CO_2$ recovery |
| | possibility to use both direct and indirect heating modes | relatively higher flue gas velocities are allowed, with respect to the other configurations, thus resulting in a smaller footprint |
| | simple steady-state operation achievable using only two interconnected reactors with the sorbent circulating between them | sorbent attrition issues |
| | excellent for temperature swing processes as a result of the high heat transfer rates in both direct and indirect heating modes | |
| multi-stage fluidized bed | possible counter-current mode, which increases the working adsorption capacity but preserving the good heat transfer of conventional fluidized beds | increased footprint, with respect to conventional fluidized beds, as a result of the counter-current operation, which somehow limits the gas velocities to keep the sorbent flowing downward |
| | excellent for temperature swing processes as a result of the high heat transfer rates | high operational difficulties for pressure swing processes as a result of the interconnected system design |

(Federica Raganati, 2021)

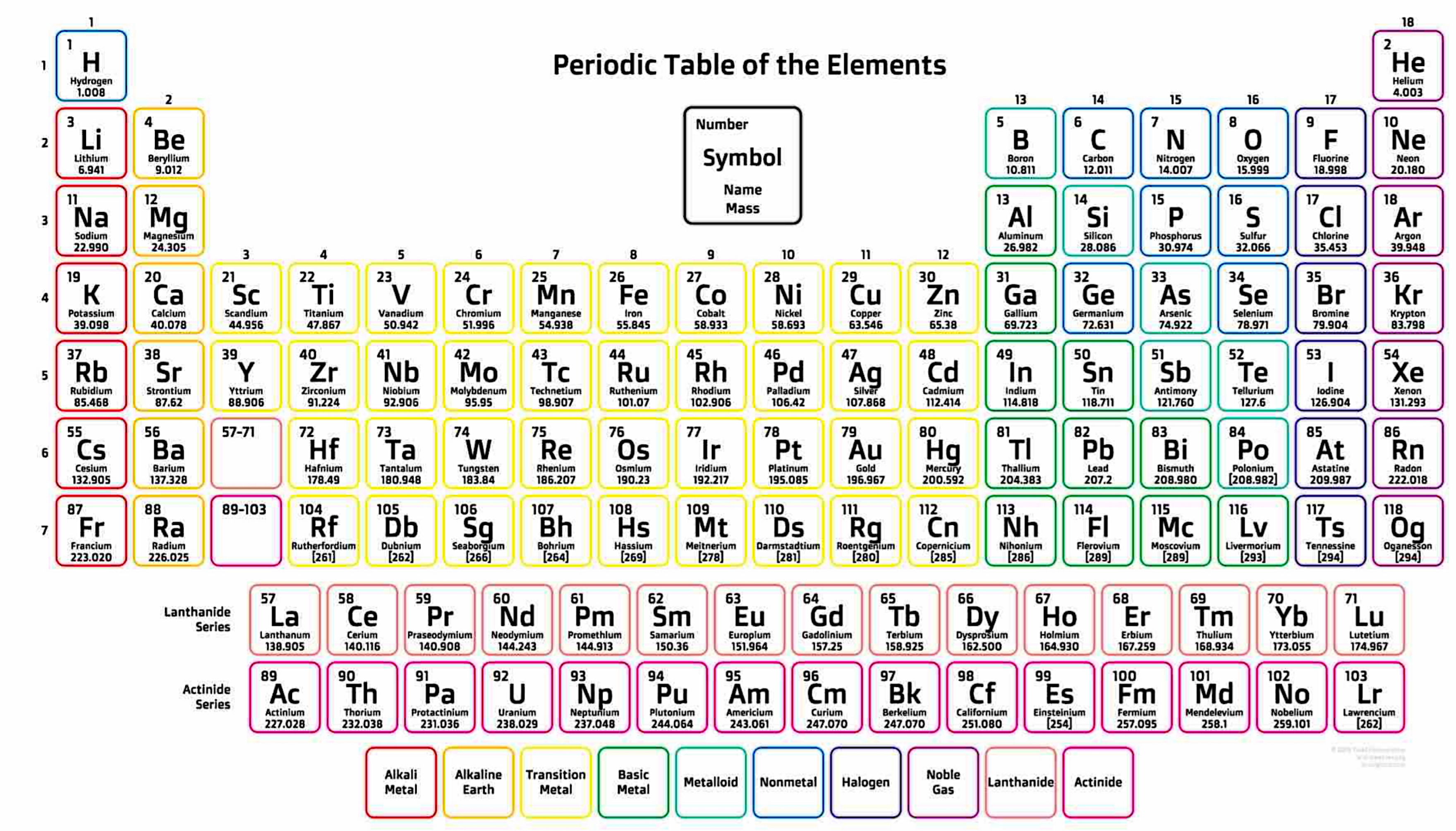
*Appendix 3*

| regeneration mode | adsorbent | reactor | $y_{feed,CO_2}$ | purity (vol %) | recovery (%) | productivity ($g_{CO_2}$ $kg^{-1}_{sorb}$ $h^{-1}$) | energy consumption (MJ $kg^{-1}_{CO_2}$) | reference |
|---|---|---|---|---|---|---|---|---|
| TSA (direct: hot product gas purge) | NaUSY zeolite | fixed | 0.15 | >91 | 55.5−83.6 | 24−41 | 3.40−4.5 | 184 |
| TSA (indirect + $N_2$ purge) | 13X zeolite | fixed | 0.10 | 95.0 | 81.0 | 58 | 3.23 | 182 |
| TSA (indirect) | 13X zeolite | moving | 0.05 | 95.1 | 96.0 | 121 | 2.21 | 163 |
| TSA (indirect + steam purge) | carbon honeycomb monoliths | fixed monolith | 0.14 | 95.6 | 85.4 | 40 | 3.59 | 199 |
| TSA (indirect + vacuum + $CO_2$ purge) | amine-functionalized | multi-stage fluidized | 0.13 | 96.0 | 90.0 | 68 | 2.80 | 170 and 200 |
| VPSA (two stages) | 13X zeolite−activated carbon | fixed | 0.16 | 95.6 | 90.2 | 65 | 2.44 | 201 |
| VPSA (two stages) | 13X zeolite | fixed | 0.15 | 96.5 | 93.4 | 21 | 2.64 | 194 |
| VPSA (two stages) | activated carbon | fixed | 0.10 | 95.3 | 74.4 | 37 | 3.61 | 202 |
| VTSA | 13X zeolite | fixed | 0.15 | 97.3 | 97.7 | 72 | 3.22 | 183 |
| VTSA | 13X zeolite | fixed | 0.15 | 94.4 | 98.5 | 12 | | 192 |

[a]Energy consumption, energy required for sorbent regeneration; productivity, $CO_2$ productivity; purity, $CO_2$ purity; and recovery, $CO_2$ recovery.

(Federica Raganati, 2021)

*Appendix 4*




(ThoughtCo, 2024)

# 15 Bibliography


Adsorption Regeneration Desorption. (2024, May). *Adsorption Regeneration Desorption*. Retrieved from Fixed Bed Adsorpption: http://www.separationprocesses.com/Adsorption/AD_Chp02b2.htm

Ajay Thapa, H. J.-K. (2023, Novembre). Ex-situ biomethanation for CO2 valorization: State of the art, recent advances, challenges, and future prospective. *Biotechnology Advances, Volume 68*. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0734975023001258

Anastasios I. Tsiotsias, A. G. (2023). CO2 Physisorption over an Industrial Molecular Sieve Zeolite: An Experimental and Theoretical Approach. *Materials*, 1-16.

Antonio Perejóna, b. L. (2016). *The Calcium-Looping technology for CO2 capture: On the importantroles of energy integration and sorbent behavior.* Retrieved from https://zaguan.unizar.es/record/63079/files/texto_completo.pdf

Arnob Das a, S. D. (2023, December). Advancements in adsorption based carbon dioxide capture technologies- A comprehensive review. *Heliyon, Volume 9, Issue 12*. Retrieved from https://www.sciencedirect.com/science/article/pii/S240584402309549X

ASQ. (2024, March). *ASQ Excellence Through Quality.* Retrieved from https://asq.org/quality-resources/iso-9000

Authors-own. (2024, Febuary).

*Belbin*. (2024, Feburary). Retrieved from https://www.belbin.com/about/belbin-team-roles

*Belbin*. (2024, Feburary). Retrieved from https://www.belbin.com/about/our-story

Chunfeng Song, Q. L. (2019, March). Cryogenic-based CO2 capture technologies: State-of-the-art developments and current challenges. *Renewable and Sustainable Energy Reviews, Volume 101*. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1364032118307731

City of Vaasa 2024. (2024, April 23). Retrieved from VAASA: Climate neutral energy consumption and reduction of CO2 emissions. Green transition & Global footprint Finland's most energy smart and energy efficient city

D.Tondeur. (2002-2004). *Capture par adsorption de CO2 dans des gaz de centrales thermiques et leur injection en puits de pétrole.* Retrieved from https://inis.iaea.org/collection/NCLCollectionStore/_Public/36/093/36093105.pdf

Directorate-General for Climate Action. (2024, May). *European Commission*. Retrieved from Climate Action - What is the EU ETS: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en?prefLang=de

Duden Lernattack GmbH. (2024, May). *Lern Helfer*. Retrieved from Prinzip des kleinsten Zwangs: https://www.lernhelfer.de/schuelerlexikon/chemie-abitur/artikel/prinzip-des-kleinsten-zwangs-prinzip-von-le-chatelier

Federica Raganati, F. M. (2021). Adsorption of Carbon Dioxide for Post-combustion Capture: A Review. *energy&fuels*, 12845-12868.

Gabelman, A. (2017). Adsorption Basics: Part 1. *CEP*, 48-53.

Hedi Jedli, M. A. (2022). Adsorption of CO2 onto zeolite ZSM-5: Kinetic, equilibrium and thermodynamic studies. *Fuel*, 1-8.

Heylen, J. (2024).

Hollins, P. (2024, March). Project Management for EPS - Closing the Project.

Hollins, P. (2024, March). *YouTube*. Retrieved from https://www.youtube.com/watch?v=COXJtFdpCc4

IBM. (2024, May). *IBM*. Retrieved from What is risk management : https://www.ibm.com/topics/risk-management

NOVIA UNIVERSITY OF APPLIED SCIENCES


Ikhlas Ghiat, T. A.-A. (2021, March). A review of carbon capture and utilisation as a CO2 abatement opportunity within the EWF nexus. *Journal of CO2 Utilization, Volume 45*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2212982020310623

Loughrey, M. (2024, May). *Global CCS Institute.* Retrieved from https://www.globalccsinstitute.com/wp-content/uploads/2023/10/State-of-the-Art-CCS-Technologies-2023_09_Final.pdf

LUMITOS. (2024, April 09). *CHEMIE.DE*. Retrieved from Adsorption: https://www.chemie.de/lexikon/Adsorption.html

LUMITOS. (2024, April 11). *CHEMIE.DE*. Retrieved from Bindungsenergie: https://www.chemie.de/lexikon/Bindungsenergie.html

*Mind Tools Ltd 2024.* (2024, March). Retrieved from https://www.mindtools.com/aol0rms/stakeholder-analysis

Novia Yrkeshögskolan. (2024, April 23). *Novia Yrkeshögskolan*. Retrieved from https://www.novia.fi/fui/vara-projekt/map-up-p2x-mapping-co2-streams-in-ostrobothnia-unlocking-potential-for-p2x-economy

ResearchGate GmbH. (2024, May). *ResearchGate* . Retrieved from https://www.researchgate.net/figure/Variety-of-CO2-utilization-options-that-have-been-discussed-in-the-literature-3_fig1_319196479

Söderbacka, C. (2024, February). Carbon Capture Demo pptx.

Schweizer fn. (2024, May). *Formelsammlung und Berechnungsprogramme Maschienen- und Anlagenbau*. Retrieved from https://www.schweizer-fn.de/stroemung/druckverlust/druckverlust.php

Slide Bazaar. (2024, May). *Hofstede´s Cultural Dimensions Framework.* Retrieved from https://slidebazaar.com/items/hofstedes-cultural-dimensions-framework/

studylib.net. (2024, May). *studylib.net*. Retrieved from https://studylib.net/doc/7239128/the-risk-matrix-and-sample-risk-assessment-tables

The Cultur Factor. (2024, 03 08). *The Cultur Factor*. Retrieved from Intercultural Management: https://www.hofstede-insights.com/intercultural-management

*The Culture Factor*. (n.d.). Retrieved from https://www.hofstede-insights.com/intercultural-management

The Culture Factor / Groupe. (2024, Frebruary). *Hofstede Insights*. Retrieved from https://www.hofstede-insights.com/country-comparison-tool

The Culture Factor. (2024, May). *The Culture Factor*. Retrieved from Organisational Culture: https://www.hofstede-insights.com/organisational-culture

The engineering mindset. (2024, May). *The engineering mindset*. Retrieved from https://theengineeringmindset.com/density-of-gases/#google_vignette

ThoughtCo. (2024, May). *ThoughtCo*. Retrieved from Color Periodic Table of the Elements: Atomic Masses: https://www.thoughtco.com/color-periodic-table-with-atomic-masses-608859

UK, B. (Director). (2016). *EL FLOW select* [Motion Picture]. Retrieved from https://www.youtube.com/watch?v=u0HZVza3DkQ&t=103s

United Nations . (2024, May). *United Nations Climate Change*. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement

Usman Khan, C. O.-A. (2023, September). Assessing absorption-based CO2 capture: Research progress and techno-economic assessment overview. *Carbon Capture Science & Technology, Volume 8*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2772656823000295#:~:text=CO2%20capture%20via%20absorption,2%20from%20the%20gas%20mixture.

Utjok W.R. Siagian, A. R. (2019, July). Membrane-based carbon capture technologies: Membrane gas separation vs. membrane contactor. *Journal of Natural Gas Science and Engineering, Volume 67*. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1875510019301039

V. Indira a c, K. A. (2022, September). A review on recent developments in Zeolite A synthesis for improved carbon dioxide capture: Implications for the water-energy nexus. *Energy Nexus, Volume 7*, 1-12. Retrieved from https://www.sciencedirect.com/science/article/pii/S2772427122000572

V. Indira, K. A. (2022, September). A review on recent developments in Zeolite A synthesis for improved carbon dioxide capture: Implications for the water-energy nexus. *Energy Nexus, Energy Nexus, Volume 7*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2772427122000572#cebibl1

Vaasa University of Applied Sciences. (2024, April 23). *VAMK*. Retrieved from https://www.vamk.fi/hanke/map-up-p2x

Weil, N. (2024, march). *LibreText.* Retrieved from https://socialsci.libretexts.org/Bookshelves/Anthropology/Cultural_Anthropology/Speaking_of_Culture_(Weil)/06%3A_Beliefs%2C_Values%2C_and_Cultural_Universals/6.03%3A_Critique_of_Hofstede's_theory

Winkelmann Ingenieure-Dienstleistungen. (2024, May). *Winkelmann Ingenieure-Dienstleistungen*. Retrieved from https://www.win-ing.de/index.php?option=com_content&view=article&id=15&Itemid=128&lang=de

Worstell, J. (2014). Scaling Fixed-Bed Reactors. Retrieved from https://www.sciencedirect.com/topics/engineering/fixed-bed-reactor