University of Groningen

Faculty of Science and Engineering

Bachelor Thesis

A spatial analysis on geothermal energy in combination with direct air capture technology

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Abstract

This spatial analysis looks into the subsurface to determine where the geothermal temperatures are sufficient for use in Direct Air Capture technologies. It then looks into the combination with district heating as a secondary heat sink for the leftover geothermal energy to put some constraints onto the analysis.
Keywords - direct air capture, geothermal energy, district heating, spatial analysis

Contents

1 Introduction

Greenhouse gases are one of the more significant environmental problems that humanity faces in the current day. These gases have an out-sized impact on climate change by reflecting energy back to earth from the atmosphere. Carbon dioxide is one of the most common GHGs and is therefor a leading cause of climate change.

The dutch government made a climate-agreement with parties in the Netherlands to limit the emission of GHGs, reducing the emission of CO_2 by 49% in 2030 compared to what is was in 1990. By 2050 the goal is to have reduced emissions by 95% leading to an almost neutral emission balance. This reduction should limit the global temperature increase to less than 1.5°C.

One way that can be used to achieve this reduction in emission is the use of negative emission technologies that remove greenhouse gases from the atmosphere with Direct Air Capture being one of these technologies.

2 Theory

2.1 Direct Air Capture (DAC)

Direct Air Capture is a technology that extracts previously emitted CO_2 from the atmosphere. Technologies like this can result in a negative emission balance counteracting climate change.

This study focuses on DAC using a solid adsorbent to bind carbon dioxide molecules. Recovering the sorbent and carbon dioxide requires heating the solution to at least $80 - 100$°C [1]. The model used to calculate the quantity of captured CO_2 uses a regeneration temperature of 105°C [2].

The DAC installation that is used for comparison in this analysis is the Climeworks Mammoth plant, which is currently their largest [3].

2.2 Geothermal Energy

The subsurface consists of many different vertical rock layers with partial to complete coverage of the Netherlands. Utilizing a dataset by TNO-GDN we can get a model for these different layers with their respective depths and temperatures [4]. The depths range from just below the surface for layers from the Neogene period to 5 kilometers for the Limburg group from the Carboniferous. The average temperature gradient of this dataset is calculated to be 31.3°C km^{-1} with a surface temperature of 10.1°C [5].

Extracting energy from the subsurface can be done by a geothermal doublet with two wells, one well injects water into a reservoir and a different well is used to extract water that has by then reached the reservoir temperature. This study will limit itself to a minimum geothermal temperature of 80 to 90°C.

Temperatures of 80 to 90°C are lower than the regeneration temperature for the DAC. A high temperature heat pump can be used to bridge the gap from reservoir to recovery temperature.

Specific models with a heat sink of 110°C have been researched by Penninga and are used in her model [2].

2.3 District Heating

Recovering the sorbent in DAC is expected to require significantly less heat than that a geothermal well is capable of supplying. Pumping the heat back into the reservoir is one option but another is to use the heat for district heating.

District heating uses local waste heat sources to supply customers with a heating demand. This heat can be sourced from industrial processes but another option is to use geothermal energy instead. The primary costs for that kind of district heating are in the exploration and installation of a geothermal doublet after which the price per kwh is comparable to that of electricity [6].

3 Methodology

3.1 The Scenarios

The model from Penninga [2] has two scenarios for the installation of a DAC facility powered by a geothermal well. Both scenarios utilize a pump to extract hot brine from a geothermal reservoir. This flow is divided between a high temperature heat pump and an organic Rankine cycle. The heat pump raises the temperature of the brine to 110°C and the ORC converts the hot brine into electricity to power the DAC.

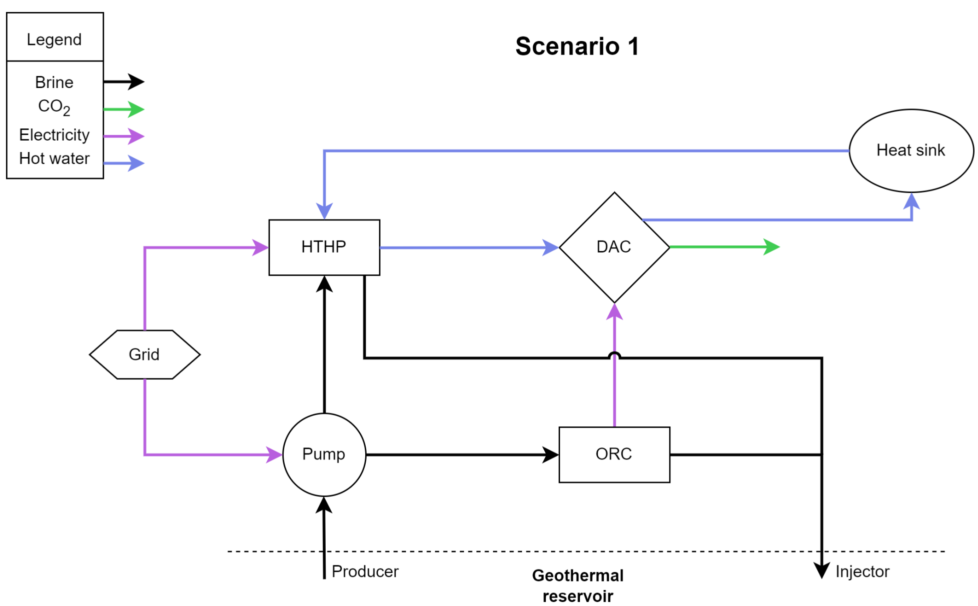


Figure 1: Flow diagram for Scenario 1 [2]

Figure 1 shows the flows of brine, CO_2, electricity and hot water within the configuration of scenario 1. The heat sink in the top right would then be connected to a district heating network to use the waste heat after the adsorbent recovery.

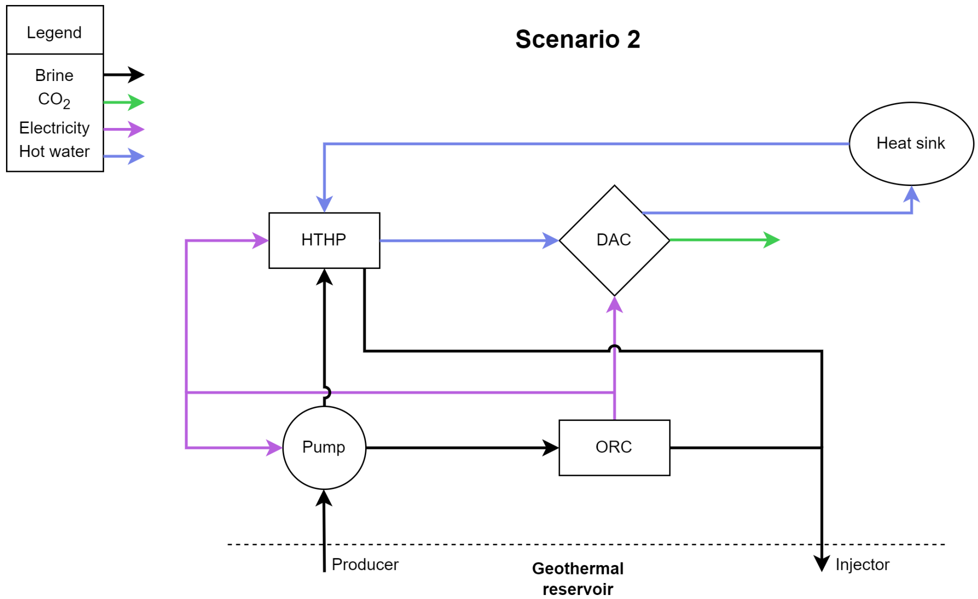


Figure 2: Flow diagram for Scenario 2 [2]

The difference between Figures 1 and 2 is that the second scenario uses the electricity generated by the ORC to also power the geothermal pump and the heat pump. This wouldn't work from the start as the pump would require electricity to start the flow to the ORC but after an amount of time this scenario would be self-sufficient outside of maintenance.

The model by Penninga also made some assumptions on the power requirements of DAC techology. It is estimated to take 300 kWh/t_{CO2} of electrical energy and 1500 kWh/t_{CO2} of thermal energy to recover one tonne of carbon dioxide. The model uses a ratio of $\frac{electricity}{heat} = 0.2$ for the flow of brine to the ORC [2].

3.2 The Model

The geothermal reservoir of this study will have a production temperature of 80 to 90°C. The model assumes that the injection temperature of brine back into the subsurface is 40° lower than the reservoir temperature.

$$T_{inj} = T_{res} - 40 \tag{1}$$

Where these temperatures are in degrees Celsius. The injection temperature is low enough to ensure a significant heat extraction from the reservoir while also limiting the breakthrough time according to literature [7].

The Organic Rankine Cycle converts the hot brine from the pump into electricity and the cooled down brine is then injected back into the reservoir. The equation modeling the produced electrical energy is as follows:

$$P_{ORC} = \dot{m}c_{p,sw}(T_{res} - T_{inj})\eta_{ORC} \tag{2}$$

With $(T_{res} - T_{inj})$=40, the mass flow rate $\dot{m}$ is given in kg s^{-1}, $c_{p,sw}$ is the isobaric specific heat capacity of the brine in J kg^{-1}K^{-1} and η_{ORC} is the efficiency of the ORC. This then generates P_{ORC} in Watts.

The High Temperature heat pump used in this thesis has a Coefficient of Performance (COP) that is determined with a best-fit line by Penninga [2]. The COP is a ratio of the actual heating between the output and input of energy.

$$COP = 10997 - 10977 \cdot T_{lift}^{0.00041} \tag{3}$$

Here T_{lift} is the temperature increase between the input and output flows. In this analysis it is equal to 20 or 30 degrees Celsius depending on the reservoir temperature. The actual heat output of the Heat pump is:

$$Q_{HTHP} = \dot{m}c_{p,sw}(T_{lift}) \tag{4}$$

Combining the heat output and the COP gives the required amount of electricity to lift the temperature of the brine from 80 or 90°C up to 110°C.

$$P_{el} = \frac{\dot{m}c_{p,sw}(T_{lift})}{COP} \tag{5}$$

The DAC is modeled with an input temperature of 110°C and an output temperature of 100°C, corresponding to a temperature drop of 10 degrees Celsius. The heat absorption rate of the DAC then has the following expression.

$$Q_{DAC} = \dot{m}c_{p,w}(T_{DAC,in} - T_{DAC,out}) \tag{6}$$

With $c_{p,w}$ being the specific heat capacity of water as the scenarios in figures 1 and 2 show a closed loop for Hot water going to the DAC. As the DAC doesn't require all of the heat generated by the HTHP a secondary heat sink is installed. It is assumed that this secondary heat sink lowers the temperature from 100°C to 5 degrees above the reservoir temperature.

$$Q_{sink} = \dot{m}c_{p,w}(T_{DAC,out} - T_{sink,out}) \tag{7}$$

The different heat capacities used in this model by Penninga can be found in her thesis as their values aren't relevant in this analysis.

These equations from [2] allow us to model the results for a DAC installation using geothermal energy at a range of mass flow rates from 20 to 100 kg s^{-1} for different reservoir temperatures. The CO_2 capture potential of the DAC and the rest warmth going to the secondary heat sink are graphed here for the different scenarios.

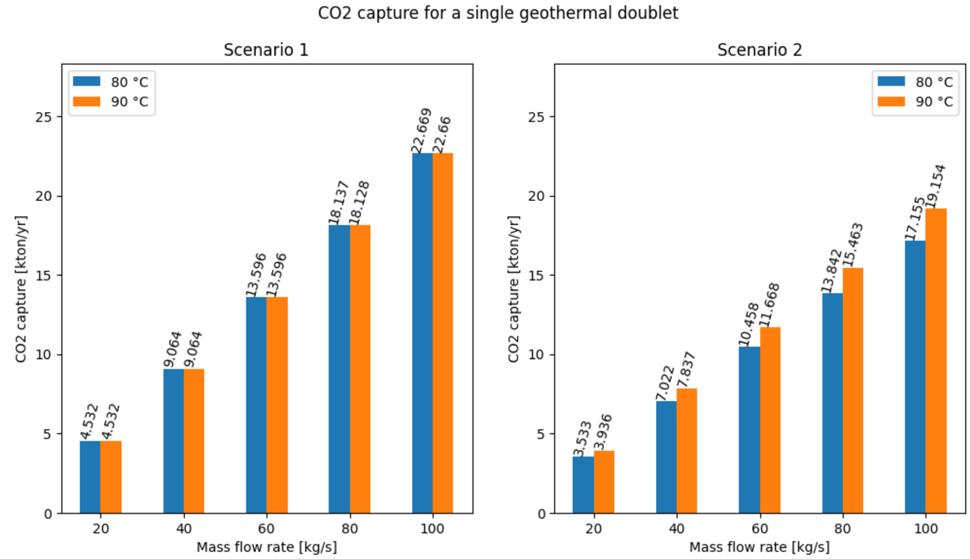


Figure 3: The carbon dioxide capture of a DAC plant in kton yr^{-1}

Figure 3 shows that in scenario 1 the productivity of the DAC is independent of the reservoir temperature and increases linearly with the flow rate as expected. Scenario 2 has about an 11% difference between the two temperatures with a significant drop in comparison to scenario 1, this drop is because the heat pump now also requires electricity from the ORC decreasing the mass flow to the heat pump and DAC.

The rest warmth in figure 4 also increases linearly like the capture potential. The significant difference in output between the different temperatures is a result of equation (7). This is because the temperature drop from $T_{DAC,out} - T_{sink,out}$ is equal to 15°C for a reservoir temperature of 80 degrees but it is only 5°C for a geothermal temperature of 90 Celsius.

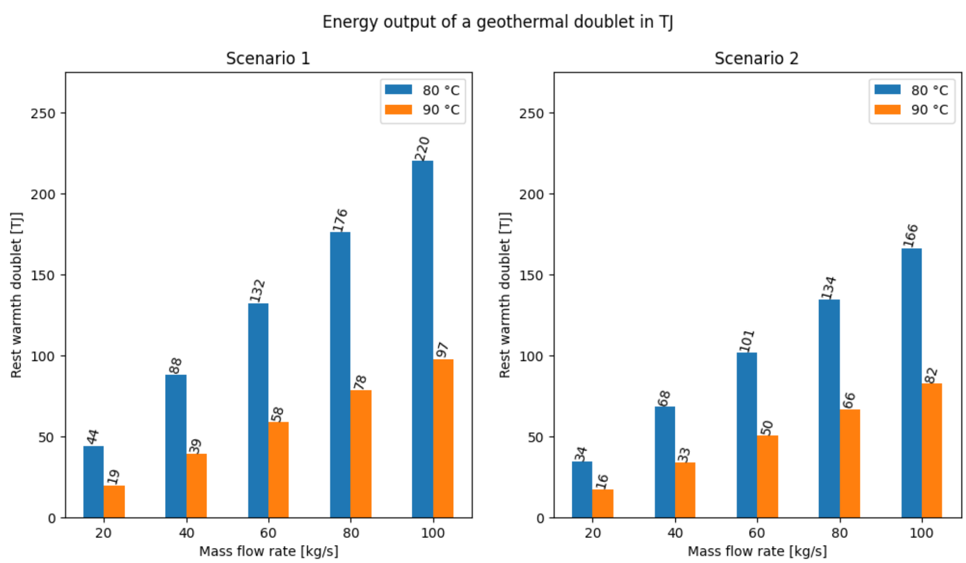
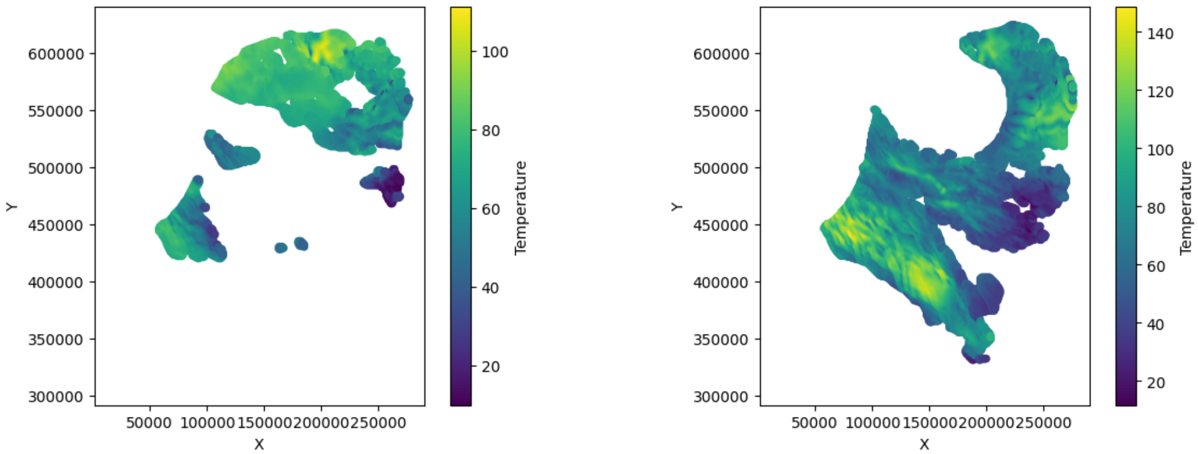


Figure 4: Rest warmth extracted between the DAC and heat pump in TJ yr^{-1}

3.3 Spatial Analysis

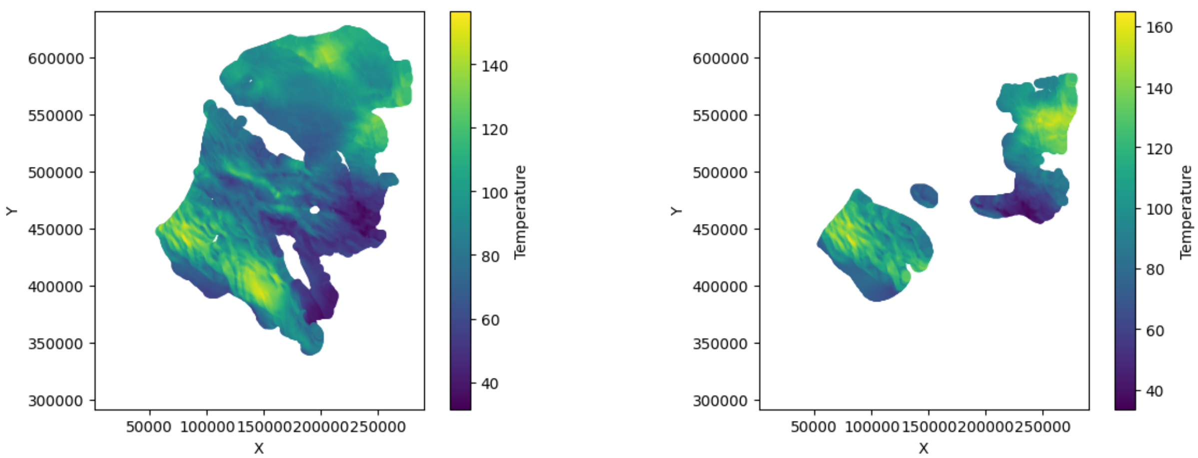
The first step of the spatial analysis is to gather data for the seperate rock layers in the subsurface. In the Netherlands it is TNO and specifically their GDN subdivision that has models predicting temperature and depth for different layers [4].



(a) The Rijnland group

(b) The Germanic Trias groups

Figure 5: Subsurface data for two stratigraphic layers of interest

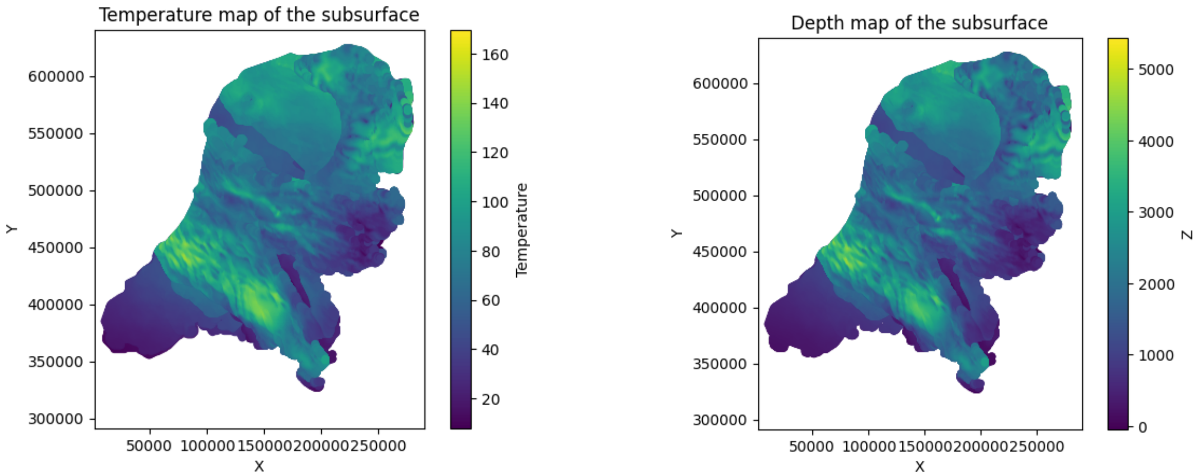


(a) The Rotliegend group

(b) The Limburg groups

Figure 6: Subsurface data for two deeper stratigraphic layers of interest

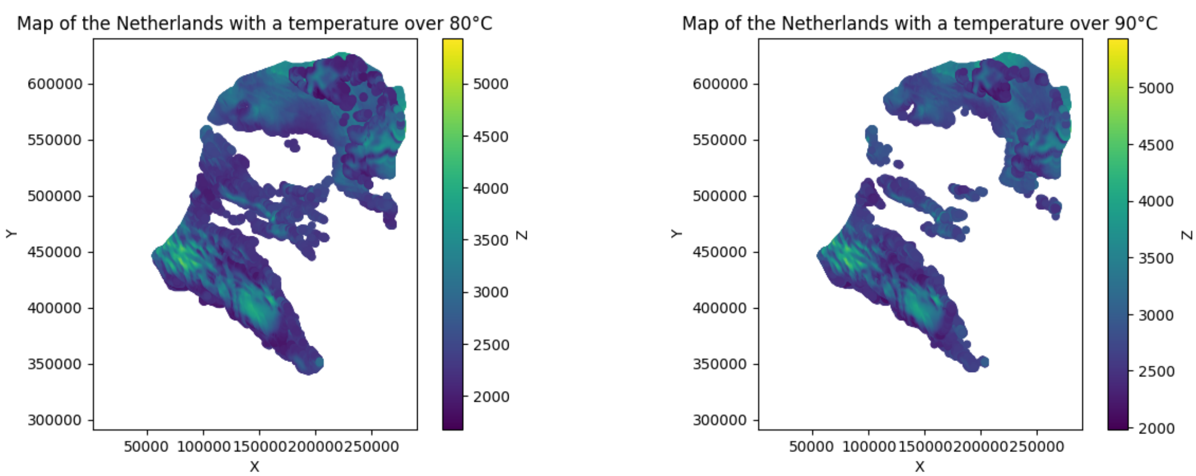
Once we overlap all of the rock layers available through TNO we will get the following linked temperature and depth maps of the Netherlands. The temperatures seen in 7a are achieved at a depth seen in 7b.



(a) Temperature (b) Depth

Figure 7: Combined map of many different rock layers

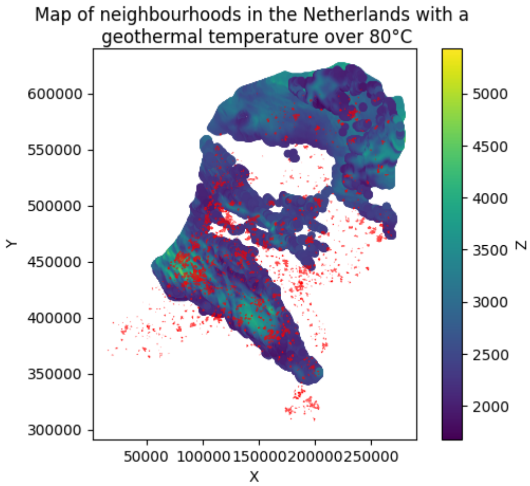
Figure 7 still has large parts of the Netherlands that aren't interesting for this analysis because their temperature is below the reservoir temperature that we are looking for. Once we select all coordinates with a temperature above 80 or 90°C the following depth maps are made. The exact temperature doesn't matter for this research as we assume that the heat pump will always be required for the DAC.



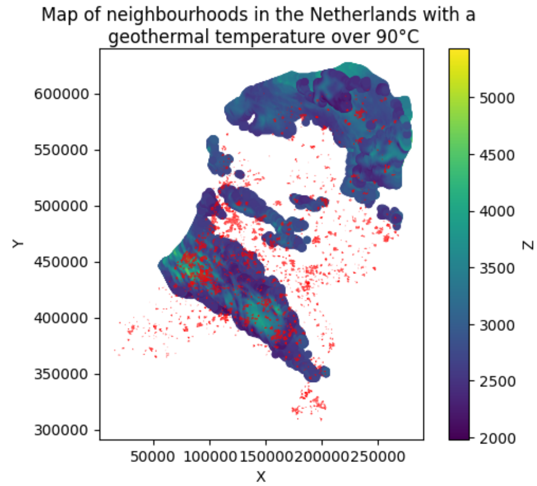
(a) Above 80°C (b) Above 90°C

Figure 8: Depth map for subsurface temperatures above our desired temperatures.

With the maps from figure 8 we now have to decide where we will place our DAC facilities. This analysis uses data on the energy demands of neighbourhoods in the Netherlands from RVO [8]. Overlapping the locations of these neighbourhoods with our temperature maps shows us which of these neighbourhoods would make useful locations for DAC.



(a) Above 80°C



(b) Above 90°C

Figure 9: Map of the overlap between dutch neighbourhoods and the subsurface temperature.

From there we can count how many different neighbourhoods are within our selected area: 3737 for the 80°C area and 2943 for more than 90 degrees. Adding up their energy demand from natural gas gives us the amount of TJ in district heating required, 99814 TJ and 81628 TJ for our reservoir temperatures.

4 Results

This analysis uses three different cases to determine the amount of geothermal doublets we should install. Each case starts in reasoning by replacing gas combustion with district heating as the primary source of household heat. The most straightforward case is replacing the entirety of the demand determined at the end of the spatial analysis with rest warmth.

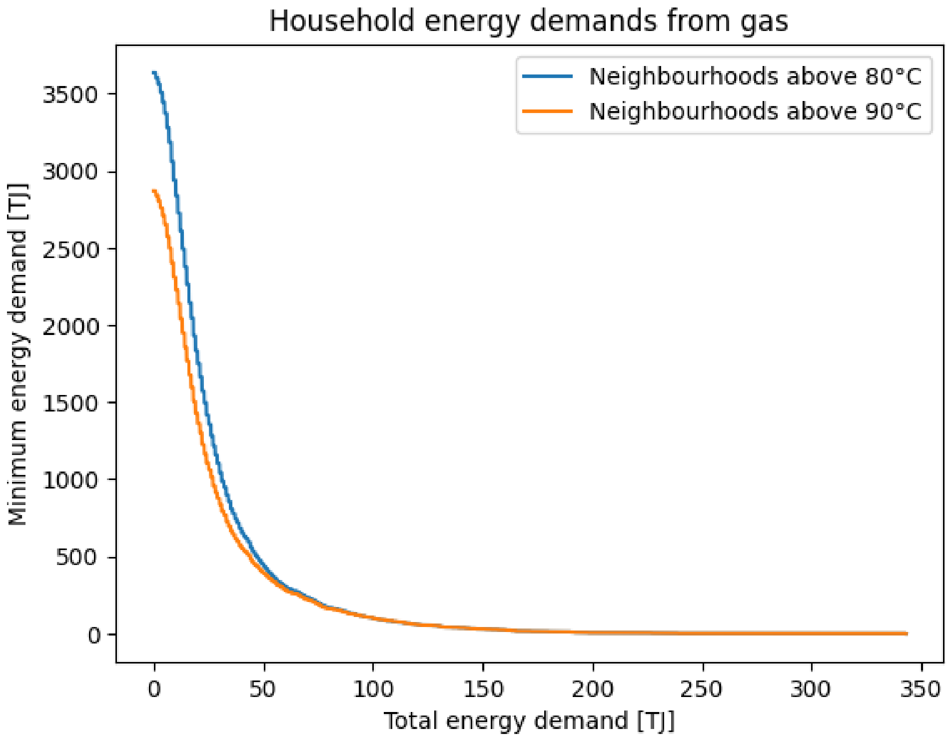


Figure 10: The number of neighbourhoods with a larger energy demand than some cutoff

Figure 10 shows that there a significant amount of the counted neighbourhoods have an energy demand from natural gas between 0 and 50 Terajoules. Comparing that with the rest warmth of a single doublet determined in figure 4 shows us that for a lot of these neighbourhoods a single DAC installation already provides more rest warmth than that they use. The second case places one doublet within each neighbourhood that can use more energy than the extracted rest warmth. The final case expands upon the second case and considers the largest neighbourhoods that require enough heat from gas that multiple doublets can be drilled without providing an excess of rest warmth.

The first case will be labeled as 'CS', the second case as 'LI' and the third case as 'LS'.

4.1 Amount of doublets

The amount of doublets required in the different cases is calculated for mass flow rates from 20 to 100 kg s^{-1}, this is because the rest warmth increases linearly with the flow rate. That means that an inverse relation excists between the number of doublets and mass flow rate, the first case is linearly inverse whereas the second and third cases drop significantly faster because of the minimum energy demand cut-off.

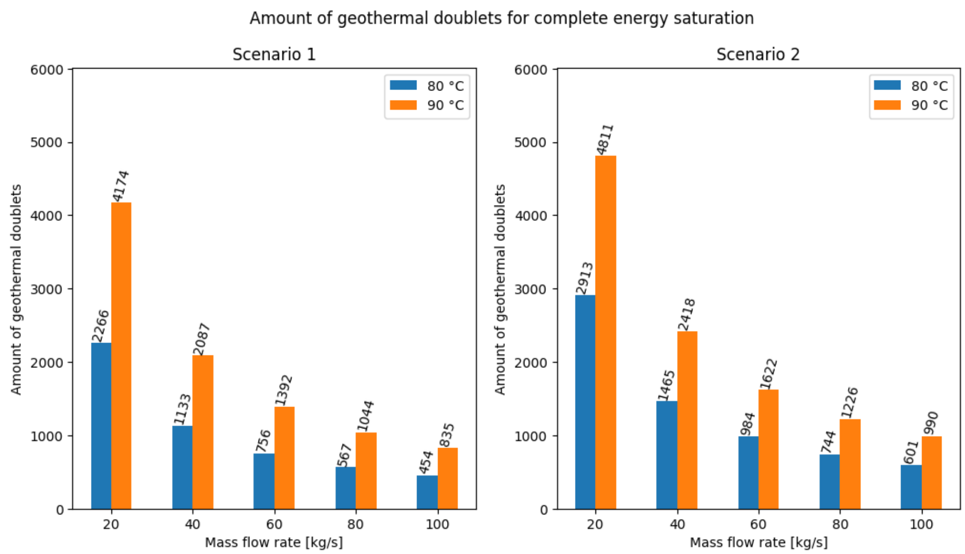


Figure 11: Number of doublets for CS

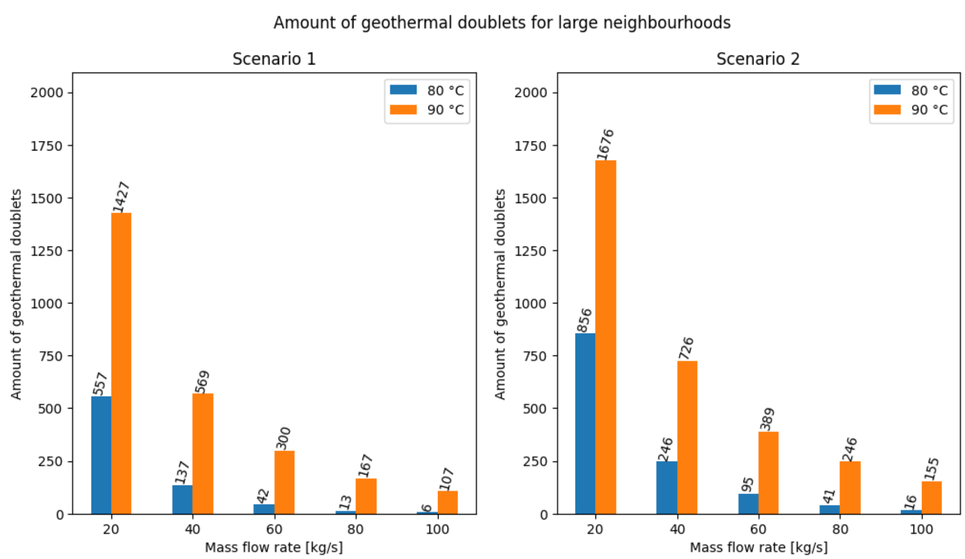


Figure 12: Number of doublets for LI

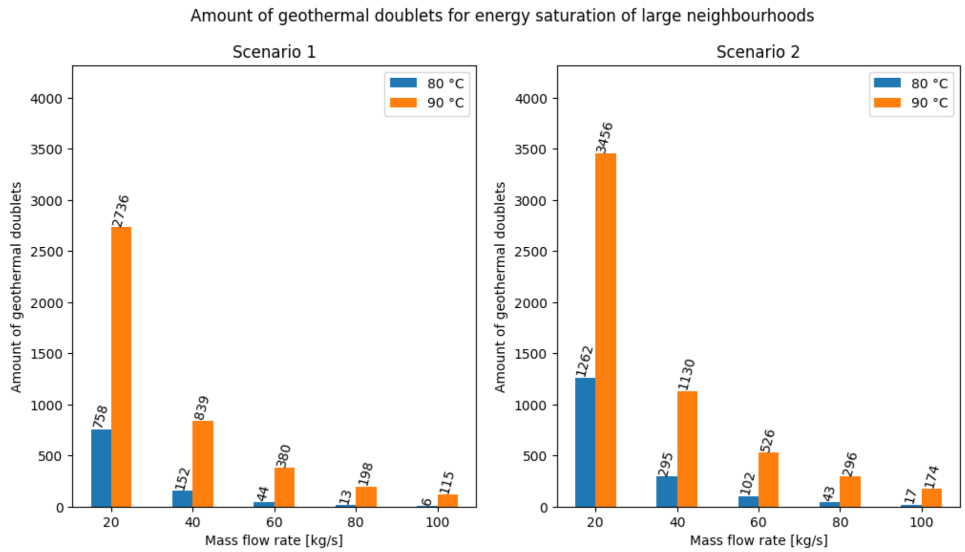


Figure 13: Number of doublets for LS

There is a very significant difference in the amount of doublets between the three cases. Complete saturation of the energy demand requires over 4 thousand doublet drillings throughout the land for a flow rate of 20 kg s^{-1} whereas saturating most of the demand of the largest neighbourhoods requires around 3 thousand doublets and only placing a single doublet in those neighbourhoods requires about 1500 wells. The second and third scenarios do reach a similar number for the largest mass flow rate.

4.2 CO_2 capture

Calculating the carbon dioxide capture per year requires multiplying the results found in figure 3 with the number of doublets determined in the previous section.

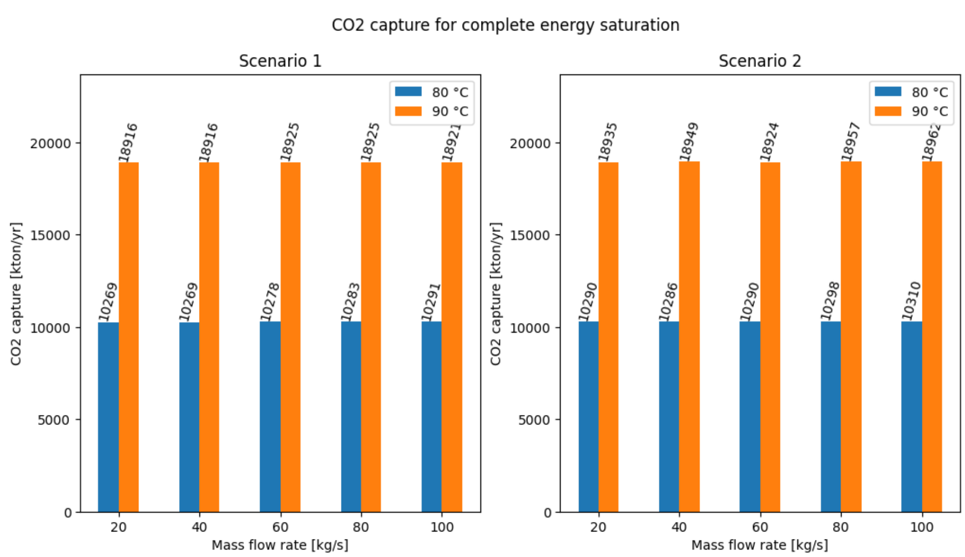


Figure 14: Carbon capture for CS

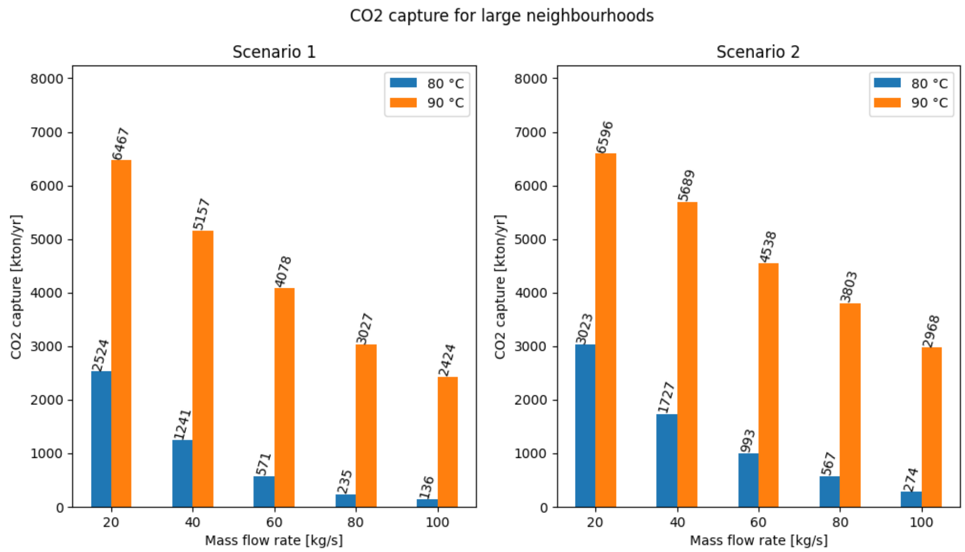


Figure 15: Carbon capture for LI

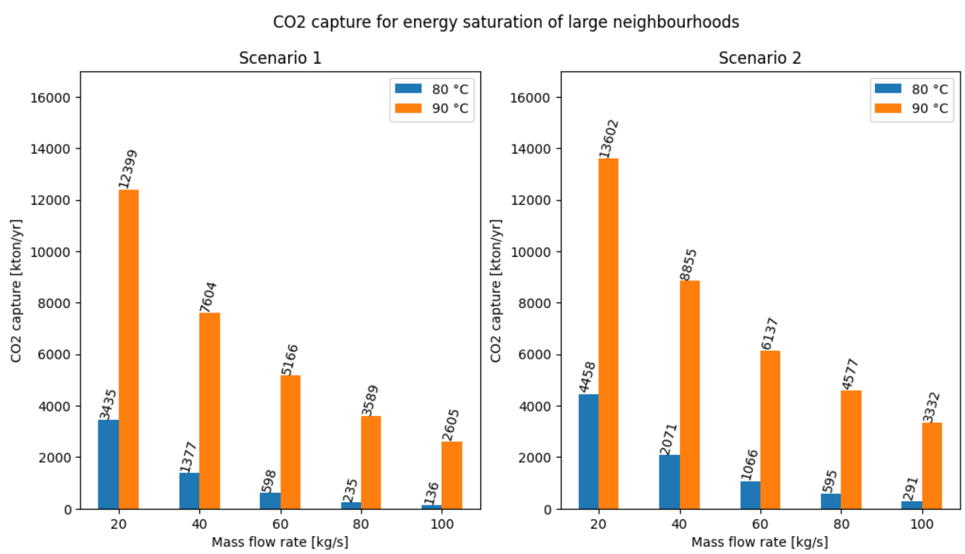


Figure 16: Carbon capture for LS

The flat curve in figure 14 is a result of the dependence on the mass flow rate for the number of doublets and CO_2 capture potential of a single doublet. These relations can be seen in figures 11 and 3, one being linear and the other is a inverse linear relations thus they cancel out.

The second and third cases do have a decrease in the capture potential as the flow rate increases, this is primarily a result of the selection criteria for the cut-off resulting in the amount of doublets decreasing faster than the CO_2 capture from figure 3 can increase.

4.3 CO_2 mitigation

The amount of doublets is decided upon through replacing the energy demand from gas for neighbourhoods with district heating from the rest warmth. This then means that the emissions from the combustion of natural gas would also decrease leading the installation to also have mitigated emissions. These mitigated emissions were determined by dividing the total rest warmth by 50 to get the mass of emitted CO_2 in tonnes [9].

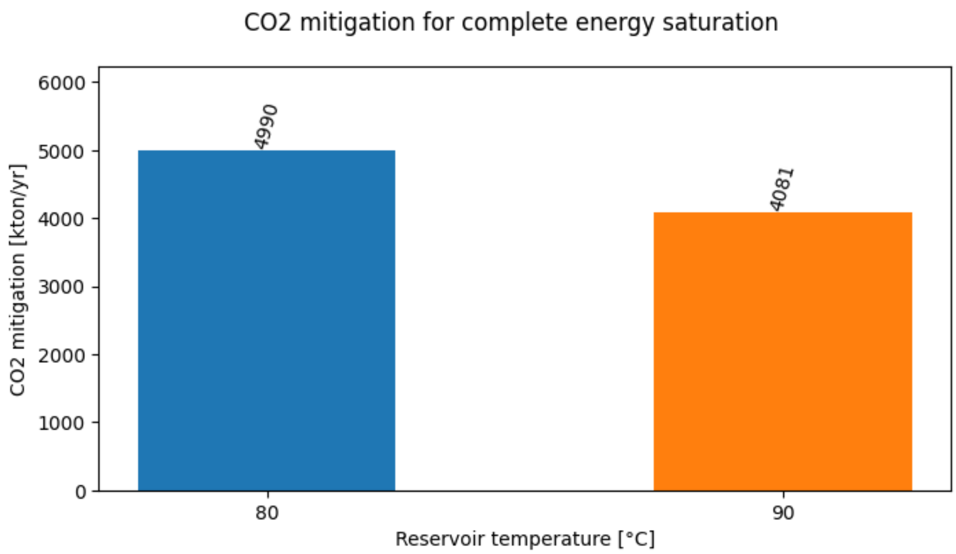


Figure 17: Carbon mitigation for CS

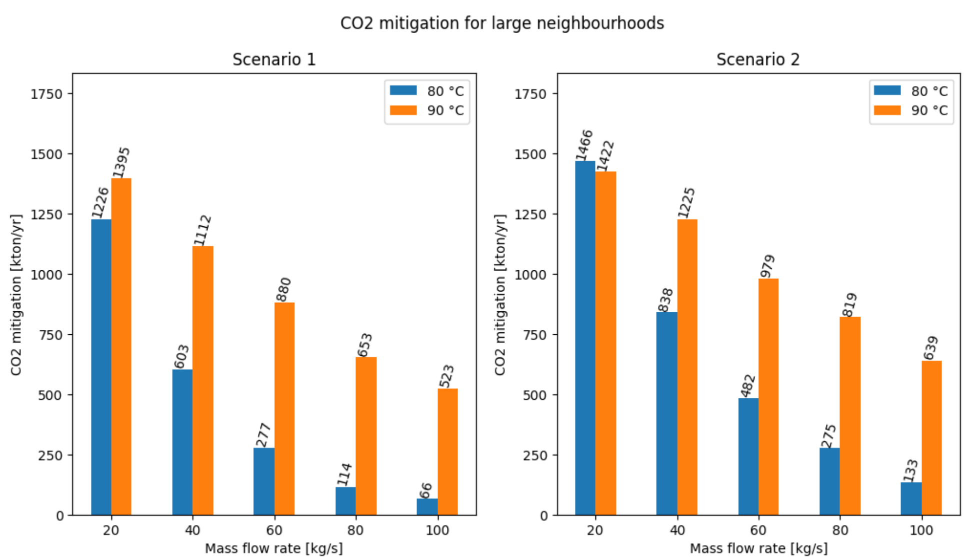


Figure 18: Carbon mitigation for LI

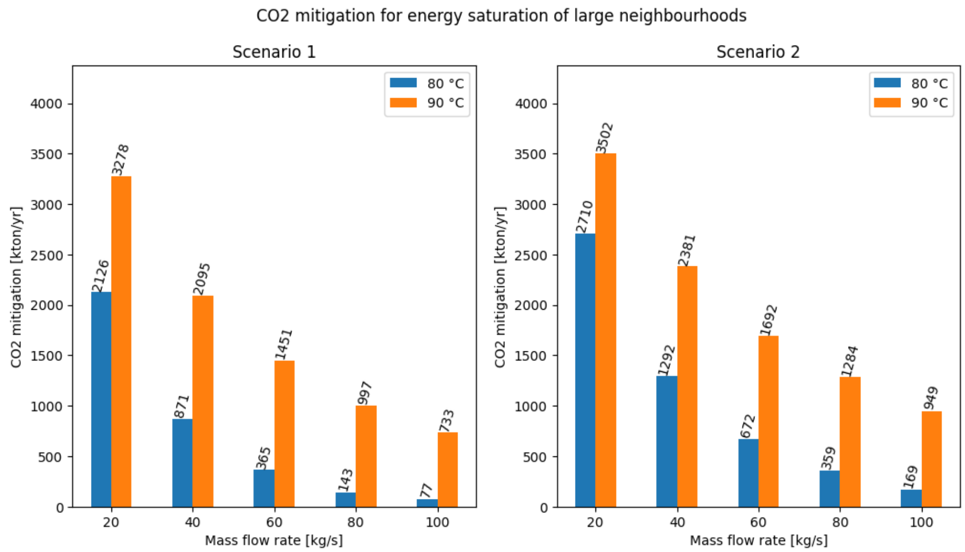


Figure 19: Carbon mitigation for LS

The bar graph in figure 17 only depends on the reservoir temperature as the entire energy demand is satisfied which is constant no matter the scenario or mass flow rate.

5 Discussion

The spatial analysis could be improved in several ways, a more complete stratigraphic dataset could be used to increase the coverage of the Netherlands for the desired geothermal temperatures. Another area where improvements can be made is by considering the porosity and permeability of the rock layers allowing us to make a selection that more closely resembles the real world scenario. Using a method to cluster neighbourhoods into larger groups, likely to be cities, would create a more realistic case for the energy demand and therefor the amount of geothermal doublets in an area.

The model for a single direct air capture facility powered by geothermal energy is a simplified view of a complex system. The equations modeling the above ground behavior make sense although the output temperature of the secondary heat sink, $T_{sink,out}$, is likely too constrained. Within the model a reservoir temperature of 90°C would lead to a temperature drop within the heat sink of 5 degrees Celsius from 100 to 95°C. This means that a higher reservoir temperature would lead to less rest-warmth and that the model actually 'breaks' for reservoir temperatures of 100 degrees or more as the secondary heat sink output temperature would have to be higher than the input temperature.

Connecting the spatial analysis more closely with the model could be achieved by running the model with actual data for the variables instead of the generalised assumptions that are currently used. One downside for this step is the significant increase in computational resources required to run the model with the spatial resolution within the data.

The analysis performed in this thesis seems to be a novel approach so that the results can't be compared to values determined in other studies. Penninga determined that a single DAC plant could provide between 418 and 11497 households with the rest warmth depending on the conditions [2]. A rough estimation where about half the population of the Netherlands is provided with heating from this gives us $10M/10k = 1k$ geothermal doublets. Comparing this to the high flow rate results shows a significant difference to my results thus my selection criteria might have been too harsh.

The carbon dioxide mitigation was determined through replacing the entire gas demand with heating. My calculations assume completely pure Methane CH4 with perfectly efficient combustion. This assumption about efficiency quite clearly doesn't match with real world results so the efficiency is quite likely lower than expected which means that more CH4 needs to undergo combustion leading to more emissions.

This thesis couldn't determine the dimensions of a DAC facility currently in use to help with the spatial viability. Performing a spatial analysis on the surface to determine if there is actually room for the DAC installations near large enough urban centers could show the likelihood that the calculated amount of doublets would actually be drilled. A city like Rotterdam for example could theoretically make use of DAC technology because of the large amount of CO_2 emissions and the demand for heating but finding enough space to build the facility on is likely quite difficult.

A.C. Quinn considered the economic viability of DAC technologies combined with geothermal heating. Her research shows that a larger mass flow rate usually has lower costs per tonne of CO_2 captured and that a higher geothermal temperature has a smaller deficit than a low reservoir temperature. Taking into account that all of her calculations operated under a deficit [10] it is likely not financially viable to build DAC plants on the scales determined in this analysis.

6 Conclusion

Implementing DAC powered by geothermal energy could be a viable negative emission technology to combat climate change in the future. Significant parts of the country have a high enough reservoir temperature that locations for geothermal doublets can be found. Using the remaining warmth for district heating could be applied in several different locations to help finance the system.

A more thorough analysis into the subsurface can be integrated into the model to give a more representative view of the situation. This would be necessary for any actual plans to combine these technologies rather than the academic context of this thesis.

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Appendix

The python code performing all of the initial spatial data processing can be found here: $DT-link$. And the code plotting all of the graphs can be found here: Plotting. The spatial data can be found in this google drive: Spatial data.