Rijksuniversiteit Groningen

Bachelor Thesis

Finding Balance: Emissions- and Cost-Analysis for Direct Air Capture Powered by Low-Temperature Geothermal Energy

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Abstract

Direct Air Capture is one of a class of methods called Negative Emissions Technologies, which will form part of a multifaceted approach to reaching net-zero CO_2 emissions within the next few decades. However, capturing CO_2 in this way is expensive, with current projects costing around €600 per tonne of CO_2 captured, and is also energy and heat intensive. Using geothermal power to provide the energy requirements for Direct Air Capture, and by using leftover heat in a district heating network, can have a significant positive environmental impact, and can greatly reduce the costs involved, especially at higher reservoir temperatures.

Keywords - direct air capture, geothermal energy, district heating, life cycle analysis

Contents

1 Introduction

"It is a mistake to think you can solve any major problems just with potatoes." [1]

At the COP26 meeting in Glasgow in November 2021, 153 countries reaffirmed their committment to the Paris climate agreement with new 2030 emissions targets. Countries responsible for 90% of the world's carbon emissions (including the Netherlands [15]) have made commitments to reduce their emissions to net zero within the next few decades [32]. This will require eliminating 33.44 billion tonnes of carbon emissions annually (compared to 2022's numbers)[28]. This is a major problem, and as such cannot be fully solved by any one approach in isolation (least of all potatoes).

Negative emissions technologies will be an important part of reducing global carbon emissions to net zero[10]. Negative emissions technologies actively remove carbon dioxide from the atmosphere. While capturing and storing carbon dioxide can be done anywhere, the process is most efficient in places where there are very high concentrations of carbon dioxide, such as the chimneys of power plants or steel factories. This is known as Carbon Capture and Storage(CCS), and is differentiated from Direct Air Capture (DAC) in order to highlight the different aims and technical challenges behind the two methods [6].

This thesis builds on previous research conducted by [25], which investigated the technical feasibility of a DAC plant powered by a low-temperature geothermal doublet, and connected to a district heating network in order to make use of hot water left over from the sorbent regeneration stage. Every stage in the process of building and operating such a system has an environmental cost, from manufacturing the different components, to the electricity used to power the heat pumps, to maintenance and the eventual transport and storage of the sequestered carbon. What's more, current DAC plants are very expensive to run, and geothermal doublets are expensive to build, although the heating bills paid by those connected to the district heating network may cover some amount of these expenses. This thesis focuses on the emissions balance of the system as a whole, throughout its lifetime, and attempts to concretise some of the costs involved.

2 Theory

2.1 Life Cycle Analysis (LCA)

A Life Cycle Analysis is a tool used to evaluate the impact of a certain product or process in one or more areas (environmental, financial, resource use, etc.). It is sometimes used to aid with sustainable decision-making, and to determine where processes could be improved. The "gold standard" for an LCA breaks the process down into four steps [4].

1. **Scoping**
   The product or process is defined, as well as the context and boundaries of the analysis.

2. **Inventory Analysis**
   Data is collected on each material, sub-process and byproduct that goes into the final product or process.

3. **Impact Assessment**
   The impact of each material on the context in question is examined.

4. **Interpretation**
   The results of the impact assessment are interpreted and used, for example to choose a preferred process out of several options, or to find improvements in some aspect of the development of a product.

Although a properly-done LCA can be very robust, thorough and consistent across different studies, LCAs are often criticised for requiring a lot of difficult-to-collect data, which takes a lot of time and money [2]. A full LCA is outside the scope of this thesis. Here the focus will be on the collection of data from previous LCAs that have been conducted on different so my research will focus on collecting data on different parts of the system from different LCAs in order to assess the total accumulated emissions (including negative emissions and prevented emissions) for the whole system.

2.2 Direct Air Capture (DAC)

Direct Air Capture is one of several Negative Emissions Technologies (NETs). NETs aim to remove previously emitted CO_2 from the atmosphere, and also include processes like reforestation and improved management of environments like grasslands and coastal wetlands[23]. The concept of DAC as a solution to global warming was first suggested in 1999.

The method of DAC that will be explored here is called solid sorbent DAC. This is a two-stage process, consisting of the collection phase and the regeneration phase[17]. In the collection phase, air is pumped through several filters, which adsorb CO_2 onto their surfaces. Then in the regeneration phase, the filters are heated to a temperature between 80ºC and 120ºC to release the collected CO_2, which is then compressed and removed from the plant. (The model in Penninga [25] assumes a temperature of 105ºC for the regeneration phase)

Currently the largest solid sorbent DAC plant in the world is the ORCA plant in Iceland, built by Climeworks[7]. This plant sequesters 4000 tonnes of CO_2 annually, at a cost of €600 per tonne of sequestered CO_2. The CO_2 collected by Climeworks is mineralised and stored deep underground. However, CO_2 collected by DAC processes is very pure and can be used in a number of industries, from agriculture, to the manufacturing of synthetic fuels, and in food and drink.

2.3 Geothermal Energy

This thesis uses a geothermal doublet with the purpose of generating both heat and electricity. Similar systems in the Netherlands are largely used for greenhouse heating[22].This thesis focuses on low temperature sources, with reservoir temperatures of 60ºC-90ºC, as these temperatures are typical of Dutch geothermal sources. [34] An Organic Rankine Cycle (ORC) is used to generate electricity. An ORC uses the same process as a steam Rankine cycle (commonly used in energy production), however the ORC uses organic fluids with lower boiling points, allowing it to generate electricity from lower-temperature sources[19].

2.4 High Temperature Heat Pump (HTHP)

The reservoir temperatures used in this analysis range from 60ºC to 90ºC[25]. Since the regeneration phase of solid sorbent DAC requires a temperature of 105ºC, the use of a heat pump is required to raise the water temperature. The model in Penninga is based on the HeatBooster by

Heaten[26], as it is one of few commercially available heat pumps that operate within the required temperature range, and therefore this analysis will also use the HeatBooster as an example.

2.5 District Heating

The DAC is expected to only use a small amount of energy from the hot water during the regeneration phase[25]. Therefore there will be a significant amount of waste heat, which could still be useful.

District heating uses heat from local sources, which is then distributed to households and industries via hot water pipes. These local sources include waste heat from industrial processes and power plants, as well as heat from geothermal wells. There are an estimated 6000 total district heating systems in Europe, of which about 240 use geothermal heat as a source.

According to the European Union's GeoDH project, it should be possible to reach 30% of the Dutch population with geothermal district heating.[11] However, the majority of Dutch households still use natural gas for heat, with only 6.4% of households connected to district heating[5]. A major reason for the low adoption of district heating in the Netherlands is that in practice, it is not cheaper (and often slightly more expensive) for the consumer than natural gas[29]. As about half of the costs of installing geothermal district heating come from the drilling of the geothermal wells, it it possible that by also using the geothermal well to power DAC, the district heating could be made slightly cheaper.

3 Methodology

The two scenarios from Penninga[25] were modelled. As shown in Figure 1, Scenario 1 has the geothermal doublet and HTHP drawing electricity from the grid, while Scenario 2 is entirely self-sufficient. In both scenarios it was assumed that grid electricity would be used to operate the district heating network.

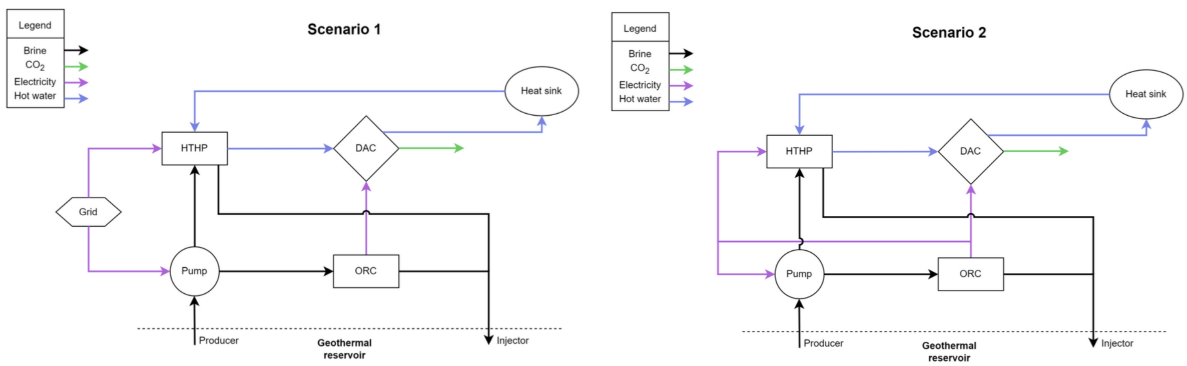

Figure 1: Simplified diagrams showing Scenario 1 (left) and Scenario 2 (right). Image adapted from [25]

As many numbers as possible were drawn from the thesis of Penninga[25]. When choosing LCAs to draw data from, priority was given to those systems that most closely mirrored this model. However, if the data from a less similar scenario was significantly easier to work with, that data was used instead. The current electricity mix of the Netherlands[13][16] was used in all calculations for emissions from electricity, although emissions from electricity production will also have to fall dramatically to meet the target of net-zero emissions by 2050. However, assuming that the current electricity mix will hold for future years makes for a conservative estimate.

	kton CO_2 Captured/Year		Number of Homes Heated	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
mass flow rate=20 kg/s reservoir temperature=60ºC	4.451	2.568	2299	1298
mass flow rate=20 kg/s reservoir temperature=90ºC	4.532	3.936	482	418
mass flow rate=100 kg/s reservoir temperature=60ºC	22.71	12.42	11497	6279
mass flow rate=100 kg/s reservoir temperature=90ºC	22.66	19.15	2414	2036

On the financial side, the biggest factor that was not taken into account was the cost of labor. This is due to most studies being done outside the Netherlands, in countries with different costs of living, worker protections, and thus differing labor costs. Additionally, many studies, especially on the financial aspects of operating a geothermal doublet, are a decade or more old. Accounting for both the differing labor costs between countries as well as inflation requires a greater level of economic knowledge than was possible to attain within the scope of this thesis.

3.1 Geothermal Doublet

The majority of environmental LCAs for a geothermal doublet give their results as a function of the total energy output of the geothermal doublet. This is not very useful for this analysis, as the systems that they deal with use different assumptions for parameters such as mass flow rate, reservoir temperature, etc., than the system modelled in Penninga[25]. It also causes problems when attempting to track the accumulated emissions over time, as there will be a peak in the global warming (GW) impact during the exploration, drilling and installation of the initial equipment for a geothermal doublet, as well as smaller peaks throughout the lifetime of the geothermal doublet due to maintenance. One of the few LCAs that tracks the global warming impact over time is performed by Gkousis et al.[12], on a geothermal doublet in northern Belgium. This is not a perfect comparison, as the plant in Belgium is a deep geothermal plant with a much higher reservoir temperature than that considered in this thesis, however it should serve reasonably well. The GW impact over time for the Belgian geothermal doublet is shown in Figure 2.

The geothermal doublet is modelled as having a lifetime of 30 years. (In reality this lifetime depends on several factors, but taking those into account would make the comparison more difficult.) In Scenario 2, the emissions from the doublet should be lower than in Scenario 1 due to not using grid electricity, but this aspect of the total emissions was difficult to separate out from the total. Years 1 and 2 are assumed to be the exploration and drilling phases of the geothermal doublet, and other elements of the system are assumed to be installed in Year 3, which is the main year the geothermal doublet and ORC are installed.

The installation costs for the geothermal doublet were based on the recent installation in Delft[33]. The electricity costs were calculated based on the table in Appendix A.1 and the electricity consumption laid out in Gkousis et al[12].

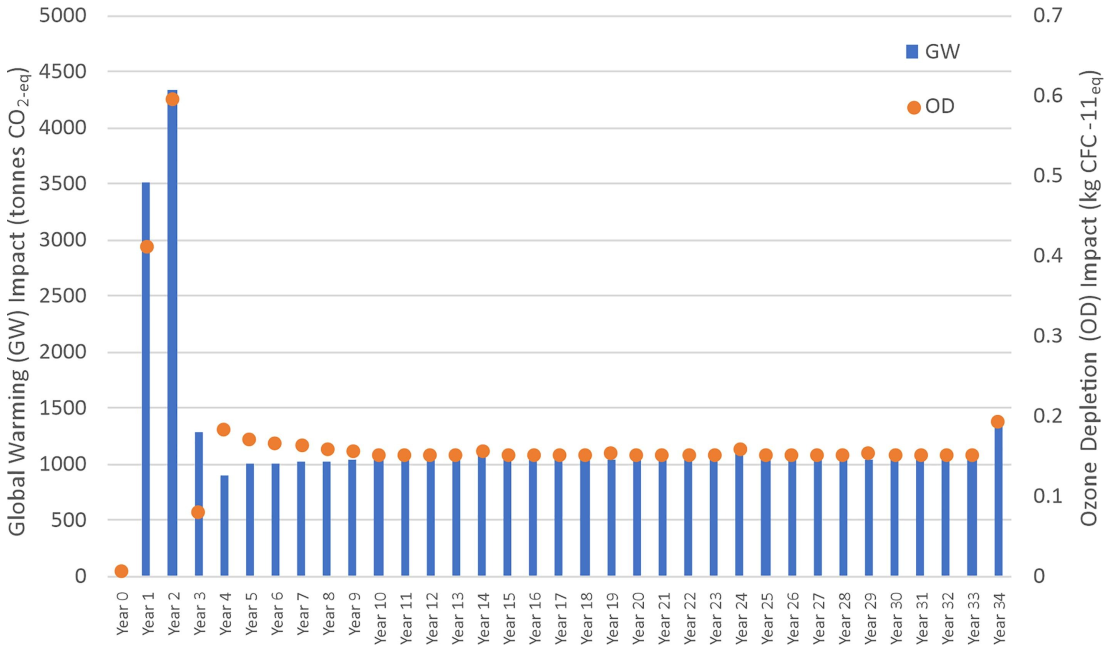

Figure 2: Global Warming Impact of a Geothermal Doublet (image taken from [12])

3.2 HTHP

The HTHP used in this model is based on the HeatBooster HTHP by Heaten[26]. The GW impact of manufacturing this model are not documented (and are currently being investigated by Heaten[18]), but the emissions involved in manufacturing a similar HTHP were documented by Tveit et al.[31] as being 7.74147 tonnes. For several of the modelled scenarios, a second or even third HTHP is required as the total thermal power output exceeded the range advertised by Heaten[26], thus increasing the manufacturing emissions accordingly. The total heat output for each modelled scenario is given in Table 3.2.

	Electricity Demand (MW)	Heat Output (MW)	
	Scenario 1	Scenario 1	Scenario 2
20 kg/s, 60ºC	1.5	5	3
20 kg/s, 90ºC	0.3	2	2
100 kg/s, 60ºC	8	24	13
100 kg/s, 90ºC	1.5	11	9

The HTHP is expected to have a lifespan of 15 years, leading to each unit being replaced once during the lifetime of the geothermal doublet.
The GW impact of replacing the working fluid depends on the output of the HTHP. This, along with the electricity usage of the HTHP in Scenario 1, are calculated in Appendix .

Prices for the Heatbooster are not displayed on Heaten's website, but the company has confirmed that the cost ranges from €400,000 to €800,000 [18], although this price is dependent on the exact configuration of the heat pump. As it was not established what the configuration of the modelled HTHP would be, the highest end of that price range was used in this overview. The cost of the working fluid used in Penninga (R1336mzz(Z)) was not taken into account as it does not yet appear to be in commercial production.

3.3 DAC

The DAC has overall negative emissions, but for each tonne of carbon captured, there are smaller emissions costs from the system, primarily in the need to replace the solvent once a year. The data for the impact of the manufacturing and the sorbent replacement come from Madhu et al.[20], with a scaling factor of 0.9 (as suggested in correspondence with Professor Peter Psarras [27]). This is a much simpler scaling factor than is typically used for similar projects, however the modularity of solid sorbent DAC plants allows the impacts and costs to scale almost linearly. In McQueen et al.(2021)[21] the economic lifespan of the DAC plant is given as 10 years, therefore that was taken as the projected lifespan of the DAC plant in this research. It was therefore assumed that the plant would need to be replaced in its entirety twice during the analysis.

The DAC system in this research, as well as in Penninga, is based on the Orca plant by Climeworks. The ORCA plant reports a cost of about €600 per tonne of CO_2 sequestered[10]. However, research has been done in the US about the possibility of using waste heat from geothermal and nuclear plants[21]. Their models put the price per kiloton at $220, much less than the cost Climeworks reports. These models assume a much higher amount of CO_2 sequestered than this one (around 100 kton CO_2 per year), but using the scaling discussed above, the costs calculated in McQueen et. al. could be scaled to meet the needs of this research.

One way that some income could be generated from DAC is through selling the sequestered CO_2. There are several existing and emerging markets for CO_2, ranging from agricultural applications to culinary uses to the production of synthetic fuels. Potential prices range enormously, from €3/tonne in the creation of fertiliser, as high as €400/tonne in more niche markets[14]. The two most mature potential applications, (and largest potential markets) for captured CO_2 have prices from €3/tonne to €30/tonne, and in this analysis a price of €15/tonne is assumed (as this is the upper end of the price range for fertiliser production.)

3.4 District Heating Network

Data for the installation of the district heating network came from Oliver-Sola et al.[24] Certain components were given to have lifespans of 10-15 years, so to simplify it was assumed that the equivalent of half of the infrastructure would need replacing every 10 years. The electricity use for the district heating network was assumed to be half of the thermal power delivered[9].

The main way that some of the money invested into the project could be recovered is through the heating bills paid by the people who are connected to the district heating network. In the Netherlands, heating bills consist of a fixed yearly fee of €630.73(for the connection, metering service and rent of the heat interface unit), as well as a variable cost that depends on the household's heat usage[29]. In 2023, this variable cost was capped at €47.38 per GJ of heat used[3], and it is this cost that is used to calculate how much money could be recouped through heating bills.

In calculating the cost of installing the district heating network, it was assumed that the cost a consumer would need to pay to switch from gas heating to a district heating network was roughly equivalent to the cost of installing the network. This means that the installation cost is entirely covered by the district heating customers.

3.5 Emissions Balance - Core Assumptions

This is simply a list of the basic assumptions that are used in this thesis, with their sources. More detailed information can be found in Appendix A.

Parameter		Unit	Source
General			
CO_2 emissions from electricity grid	0.172	kg CO_2/kWh	A.1
Geothermal Doublet			
Exploration & drilling phase for geothermal doublet	2	years	[12]
Emissions per year from geothermal doublet	See Figure 2		[12]
Geothermal doublet lifetime	30	years	[12]
High Temperature Heat Pump			
GW impact of HTHP manufacture (per unit)	7.741	tonnes CO_2	[31]
Lifetime of HTHP	15	years	[31]
Maximum heat output of HTHP	8	MW	[26]
Heat Output from HTHP	see Table 3.2		[25]
GW Impact of HTHP refrigerant	100	kg CO_2 / MW	
Electricity demand of HTHP*	See Table 3.2		[25]
Direct Air Capture Plant			
GW Impact of DAC manufacturing (per tonne CO_2 capacity)	1501.121	kg CO_2	[20]
DAC lifetime	10	years	[21]
Amount of CO_2 Sequestered	See Table 3		[25]
Scaling Coefficient for DAC	0.9		[27]
GW Impact of sorbent production	50.576	kg CO_2 / t	[20]
GW Impact of CO_2 compression & storage	46.966	kg CO_2 / t	[20]
District Heating Network			
GW Impact of district heating infrastructure (per household)	1.854	tonnes CO_2	[24]
Heat used per household	11253	kWh/year	[25]
CO_2 emissions from burning gas	0.18	kg CO_2 / kWh	[30]

*Only relevant for Scenario 1

3.6 Cost Analysis - Core Assumptions

As above, this is simply a list of the basic assumptions that are used in this thesis, with their sources. More detailed information can be found in Appendix A.

Parameter		Unit	Source
General			
Electricity price	€0.18	/kWh	[8]
Geothermal Doublet			
Cost of geothermal doublet installation	€20,000,000		[33]
Electricity demand of geothermal doublet*	6300	MWh/year	[12]
Lifetime of geothermal doublet	30	years	[12]
High Temperature Heat Pump			
Cost of HTHP	€800,000		[18]
Lifetime of HTHP	15	years	[31]
Electricity demand of HTHP*	See Table **??**		[25]
Maximum heat output of HTHP	8	MW	[26]
Heat Output from HTHP	see Table 3.2		[25]
Direct Air Capture Plant			
Cost of DAC using waste heat (for 100kton plant)		/ton CO_2	[21]
Amount of CO_2 Sequestered	See Table 3		[25]
Scaling Coefficient for DAC	0.9		[27]
Lifetime of DAC plant	10	years	[21]
Price of CO_2	€15	/tonne	[14]
Direct Air Capture Plant			
Number of households heated	See Table 3		[25]
Heat used per household		kWh/year	[25]
District heating installation cost	€4878.04		[29]
Heating bill: annual fixed cost	€630.73		[29]
Heating bill: maximum variable cost	€47.38	/GJ	[3]

*Only relevant for Scenario 1

4 Results

Each extreme in both mass flow rate and temperature was modelled for both Scenarios 1 and 2. All calculations are linked in appendix A.

4.1 Emissions Balance

As shown in Figure 3, the configuration in Scenario 2 always led to an overall negative amount of released carbon. In Scenario 1, using a high mass flow rate and a low temperature means much more work done by the HTHP and in the district heating network, which creates an insurmountable barrier to be overcome by the emissions removed and saved by other parts of the system.

A better comparison can be made if the scenario with an overall negative impact is ignored, as shown in Figure 4. The largest positive impact is seen in Scenario 2, with a mass flow rate of 100 kg/s and a reservoir temperature of 90ºC.

4.2 Cost Analysis

As expected, in none of the four scenarios presented is it possible for the installation and operation costs of the system to be fully covered by the combination of heating bills and CO_2 prices.

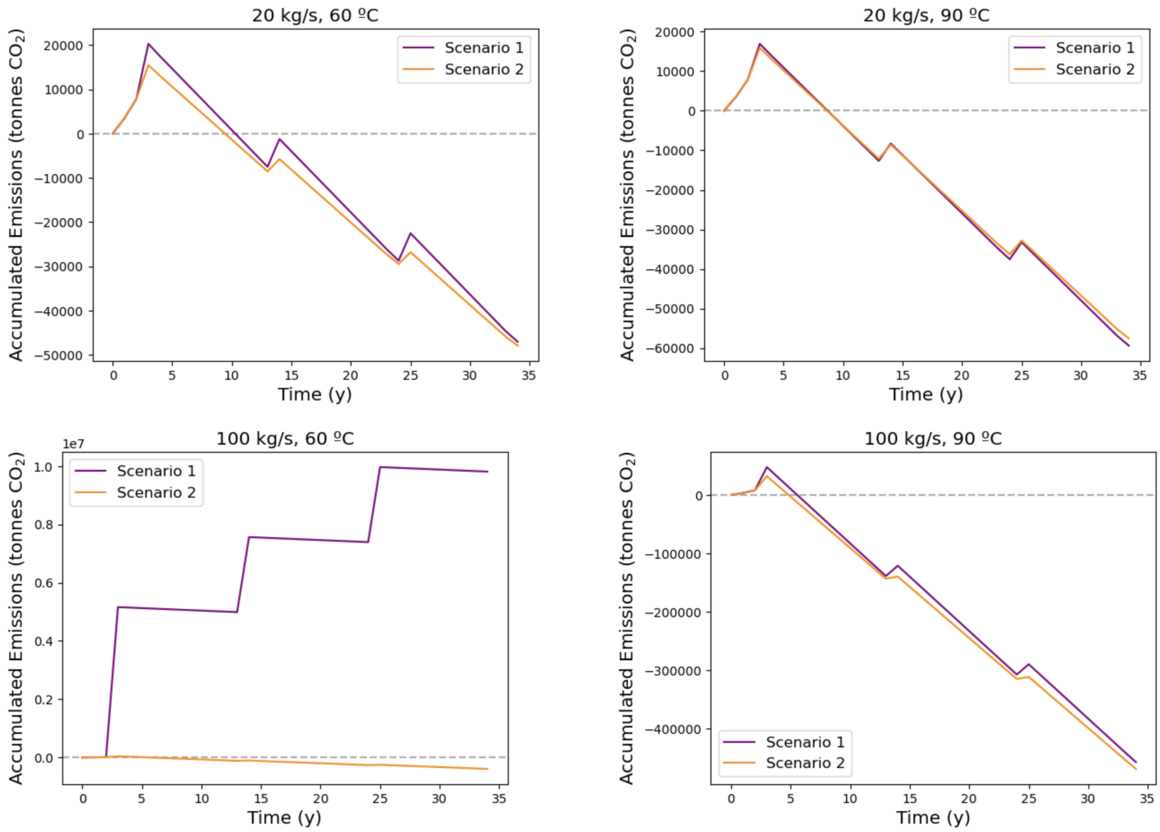

Figure 3: Accumulated Emissions for the system at each extreme of mass flow rate and resevoir temperature

This system would require significant outside investment.

	Scenario 1 (M €)			Scenario 2 (M €)		
	Costs	Income	Deficit	Costs	Income	Deficit
20 kg/s, 60°C	222.3	56.8	165.51	75.6	32.07	43.53
20 kg/s, 90°C	92.56	13.52	79.04	41.29	11.73	29.56
100 kg/s, 60°C	915.83	284.03	631.8	284.42	155.13	129.3
100 kg/s, 90°C	241.93	67.69	174.24	119.09	57.11	61.99

Scenario 2 overall has the lowest costs involved, and thus typically the smallest deficits. The smallest total deficits are also seen when using a low mass-flow rate. Therefore, from the perspective of reducing the amount of investment needed, it may be useful to focus on a system with a low mass flow rate.

However, DAC is currently a large investment. When the cost of the system is compared to the amount of CO_2 sequestered (as in Figure 6), it can be seen that using a higher mass flow rate yields a lower cost per tonne. In fact, most of the modelled scenarios are less expensive than the current Climeworks plant, with two of them being roughly even with the predictions made by McQueen et al.,[21] and the lowest projected price less than half of the estimate from McQueen et al. Therefore, if a project like this were to be approached from the perspective of

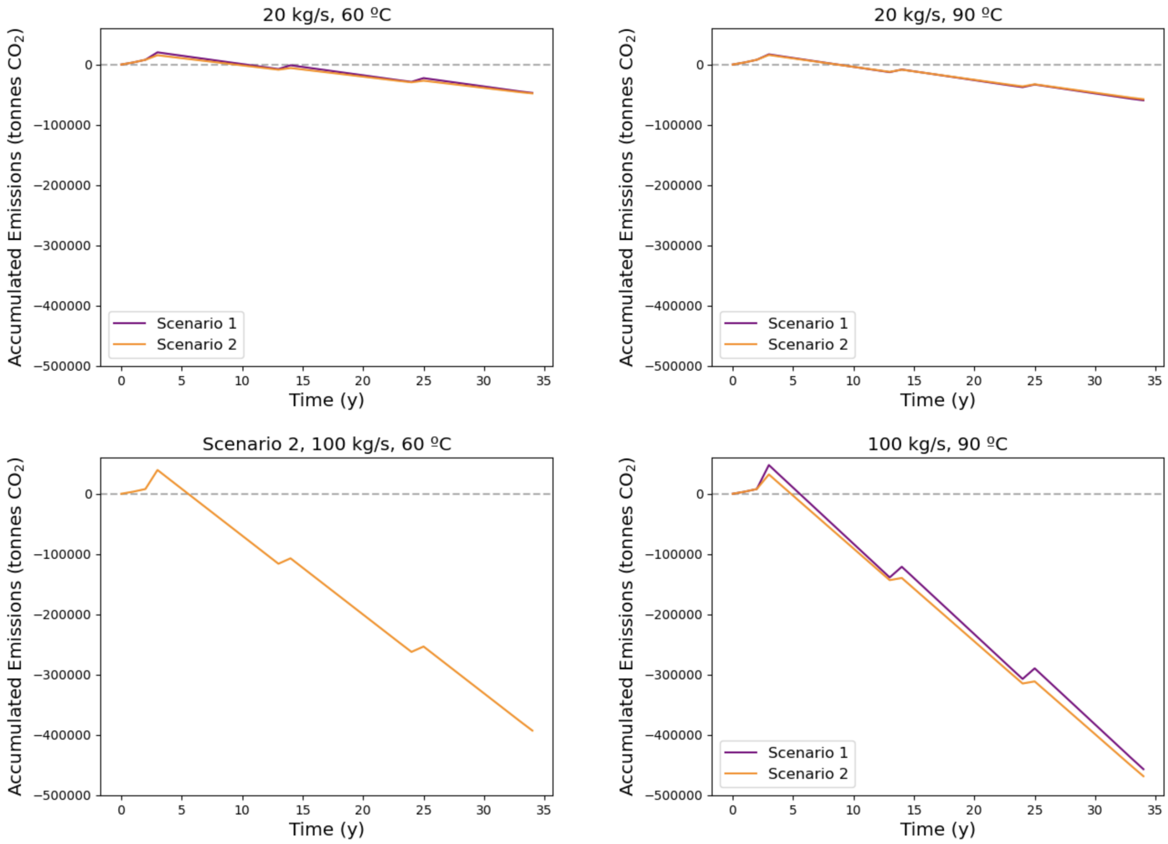

Figure 4: Comparison of positive impact of different scenarios

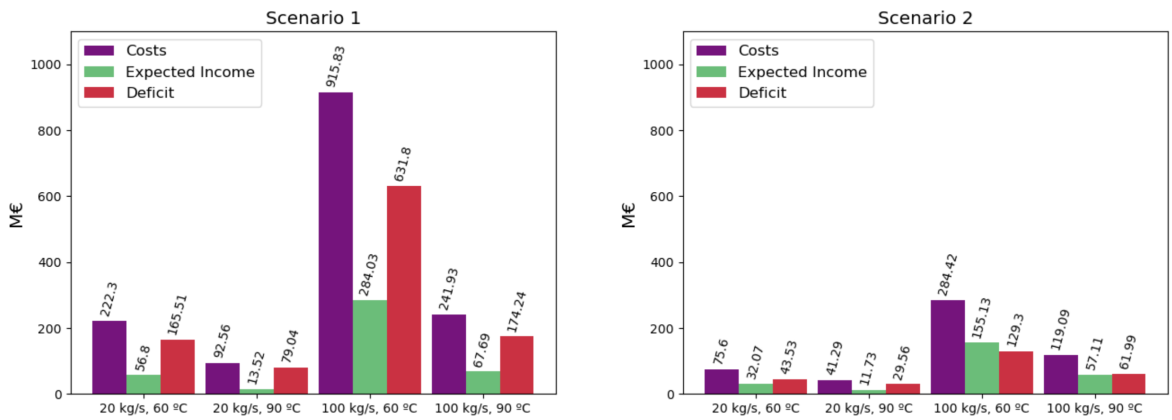

Figure 5: Approximate cost, expected income and deficit comparison for the different scenarios modelled

an investment in DAC, it can be argued that given the current state of DAC, that this system would be a better return on investment than other current DAC systems.

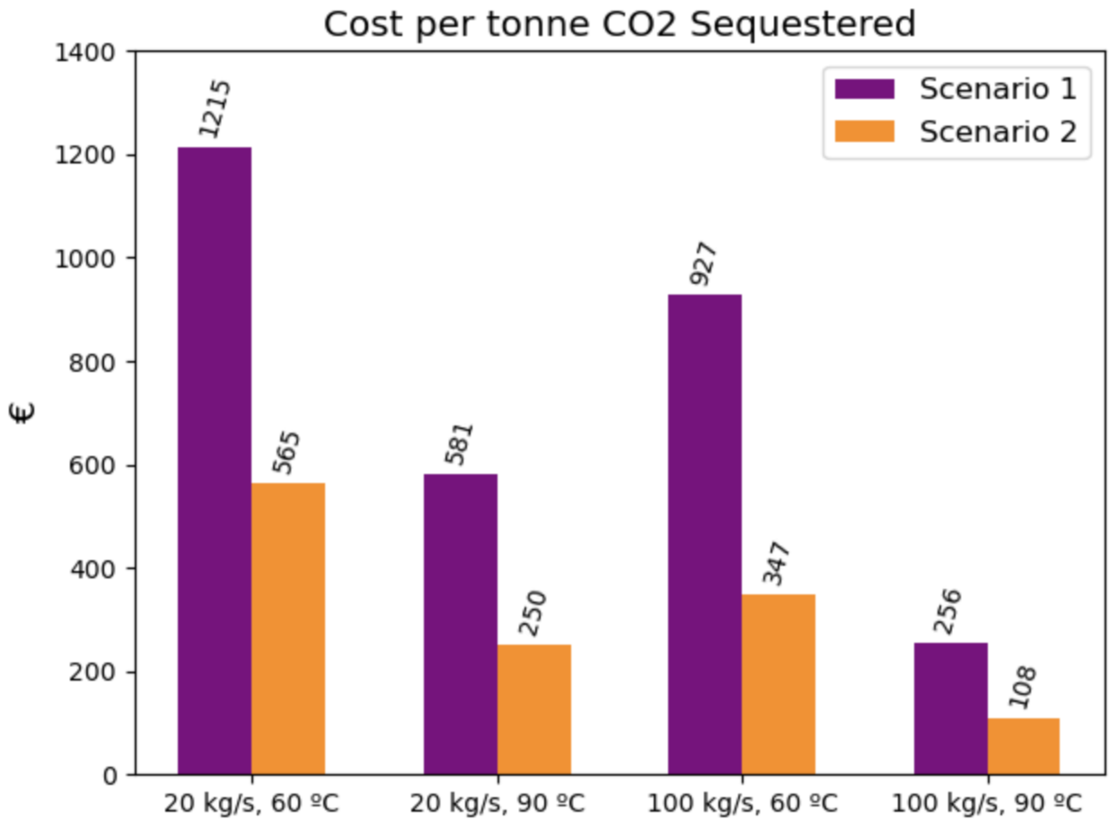

Figure 6: Approximate cost per tonne of CO_2 sequestered (rounded to the nearest euro)

5 Discussion

The cost analysis in this thesis is very rough, and should be looked at as a lower bound for the true cost. A major contributor to the cost of any project is labor, and due to the difficulty of adjusting those costs both for differing labor costs in different countries, and for inflation due to the age of some of the referenced life cycle analyses, was deliberately ignored.

In general, the cost analysis presented in this thesis is incomplete. Certain other assumptions were also made that may be unfounded, such as the assumption that the cost per household of installing a district heating network would be fully covered by the fee charged to households to switch to district heating, and the assumption that powering the district heating network would use half of the supplied heat in electrical power. The analysis presented here also largely ignores the costs involved in the end-of-life handling and disposal of the various parts of the system. A full analysis including properly accounting for things like labor costs, maintenance and end-of-life handling of the various components would have taken more time and a greater expertise than fit within the scope of this research.

A major hurdle in this research was the inaccessibility of data. Some of this was due to requiring data from private companies, who are often loathe to share information about their manufacturing processes (including environmental information) due to the possibility of being copied by others. Companies that primarily supply industry also rarely display their prices publicly, which made estimating costs difficult if there was no response to a request for information.

Scientific papers also don't always publish their data, notes and calculations. This made it much more difficult to find good information, and meant that a lot of numbers (particularly from Penninga [25] and Gkousis et al. [12]) have been simply read from their graphs. This has lead to inaccuracies, although most likely none severe enough to impact the overall trends. In an attempt to lead by example, the full tables and notes used in this thesis are linked in the appendix.

In general, it was difficult to find research on the end-of-life stages of different parts of the system. It's an area that seems to be skipped in a lot of life cycle analyses. Further research into the impacts of the disposal, recycling, or other fates of the different components would make future life cycle analyses much more accurate. It is also very possible that the emissions involved in operating the geothermal doublet are overstated in Scenario 2. It was difficult to separate out the impact of the electricity needed to run the pump.

The impact of the mass flow rate on the lifetime of the geothermal doublet was ignored in order to provide a simpler comparison between the different scenarios. Ignoring this effect likely lead to an overestimation of the net CO_2 removal at higher mass flow rates, and an underestimation of the net CO_2 removal at lower mass flow rates. It is very probable that the longer lifetime of the geothermal doublet at the lower mass flow rate of 20 kg/s would give that scenario a distinct advantage, both in terms of the overall cost, as well as politically, as it would provide a stable, long-term source for both the carbon removal by the DAC and for the district heating network.

This environmental life cycle analysis was very narrow in its scope, focusing only on emissions. When planning a large scale project like this, attention must also be paid to land use, potential air/water/soil contamination, and many other factors. If building a system like this were to be more seriously proposed, research would need to be done into additional environmental effects.

6 Conclusion

In conclusion, the system would most likely over its lifetime have a positive impact on the CO^2 concentration in the surrounding atmosphere, with a higher reservoir temperature causing an increase in the overall carbon reduction. Financially, building this system will definitely require a lot of money from some kind of grant or subsidy, although using a lower mass flow rate and a higher reservoir temperature seems to reduce this amount substantially. If building this system were to be seriously proposed, a more detailed financial analysis would be in order, as well as more research on other environmental impacts besides the total emissions reduction. Further research into other DAC configurations that could further reduce costs may also be useful.

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A Supplementary Information

I'll put all my tables here once they're fixed, but for now here's a link to my spreadsheets: Economic Analysis and emissions balance

A.1 Emissions from Electricity

More detailed tables can be found here.

Total Emissions from Energy [16]	
Unit	
Mt CO_2	169.1

Total Energy Generation by Source [16]							
Unit	Coal	Oil	Natural Gas	Nuclear	Hydro	Renewables	Total
EJ	0.23	1.78	0.98	0.04	*	0.51	3.54

* less than 0.005

Total Electricity Generation by Source [13]								
Unit	Coal	Oil	Natural Gas	Nuclear	Hydro	Renewables	Other	Total
GWh	17408	1533	47843	4156	50	45892	4737	121619

Electricity as Percentage of Energy Use					
Coal	Oil	Natural Gas	Nuclear	Renewables	Total
27.25%	3.52%	17.57%	37.4%	60.91%	12.37%

Total Emissions from Electricity	
Unit	
Mt	20.91434532
kg/kWh	0.1719661017

A.2 Emissions Balance

These tables/notes were too long to effectively include here (even in an abridged form), but they can be found via this link

A.3 Cost Analysis

More detailed tables can be found here

A.3.1 Scenario 1

20kg/s, 60ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€43,538,220.64	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€11,214,613.96	Geothermal Doublet Electricity	€34,057,800.00
CO_2 Prices	€2,043,450.00	HTHP Cost	€1,600,000.00
		HTHP Electricity	€71,004,600.00
		DAC Costs	€3,360,340.00
		District Heating Infrastructure	€22,429,227.92
		District Heating Electricity	€69,850,746.90
Total	€56,796,284.60	Total	€222,302,714.82
Deficit	€165,506,430.22	Cost per tonne CO_2	€1,214.90

20kg/s, 90ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€9,128,065.40	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€2,351,215.28	Geothermal Doublet Electricity	€34,057,800.00
CO_2 Prices	€2,039,400.00	HTHP Cost	€1,600,000.00
		HTHP Electricity	€14,200,920.00
		DAC Costs	€3,353,680.00
		District Heating Infrastructure	€4,702,430.56
		District Heating Electricity	€14,644,654.20
Total	€13,518,680.68	Total	€92,559,484.76
Deficit	€79,040,804.08	Cost per tonne CO_2	€581.35

100kg/s, 60ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€217,728,978.98	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€56,082,825.88	Geothermal Doublet Electricity	€34,057,800.00
CO_2 Prices	€10,219,500.00	HTHP Cost	€4,800,000.00
		HTHP Electricity	€378,691,200.00
		DAC Costs	€16,805,400.00
		District Heating Infrastructure	€112,165,651.76
		District Heating Electricity	€349,314,500.70
Total	€284,031,304.86	Total	€915,834,552.46
Deficit	€631,803,247.60	Cost per tonne CO_2	€927.35

100kg/s, 90ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€45,716,078.56	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€11,775,588.56	Geothermal Doublet Electricity	€34,057,800.00
CO_2 Prices	€10,197,000.00	HTHP Cost	€3,200,000.00
		HTHP Electricity	€71,004,600.00
		DAC Costs	€16,768,400.00
		District Heating Infrastructure	€23,551,177.12
		District Heating Electricity	€73,344,803.40
Total	€67,688,667.12	Total	€241,926,780.52
Deficit	€174,238,113.40	Cost per tonne CO_2	€256.31

A.3.2 Scenario 2

20kg/s, 60ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€24,581,387.73	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€6,331,695.92	HTHP Cost	€1,600,000.00
CO_2 Prices	€1,155,600.00	DAC Costs	€1,900,320.00
		District Heating Infrastructure	€12,663,391.84
		District Heating Electricity	€39,437,263.80
Total	€32,068,683.65	Total	€75,600,975.64
Deficit	€43,532,291.99	Cost per tonne CO_2	€565.06

20kg/s, 90ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€7,916,040.12	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€2,039,020.72	HTHP Cost	€1,600,000.00
CO_2 Prices	€1,771,200.00	DAC Costs	€2,912,640.00
		District Heating Infrastructure	€4,078,041.44
		District Heating Electricity	€12,700,135.80
Total	€11,726,260.84	Total	€41,290,817.24
Deficit	€29,564,556.40	Cost per tonne CO_2	€250.38

100kg/s, 60ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€118,911,042.79	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€30,629,213.16	HTHP Cost	€3,200,000.00
CO_2 Prices	€5,589,000.00	DAC Costs	€9,190,800.00
		District Heating Infrastructure	€61,258,426.32
		District Heating Electricity	€190,775,484.90
Total	€155,129,255.95	Total	€284,424,711.22
Deficit	€129,295,455.27	Cost per tonne CO_2	€347.01

100kg/s, 90ºC			
Income		Expenses	
Description	Total	Description	Total
Heating Bills	€38,557,554.25	Geothermal Doublet Cost	€20,000,000.00
District Heat Installation Fee	€9,931,689.44	HTHP Cost	€3,200,000.00
CO_2 Prices	€8,617,500.00	DAC Costs	€14,171,000.00
		District Heating Infrastructure	€19,863,378.88
		District Heating Electricity	€61,859,991.60
Total	€57,106,743.69	Total	€119,094,370.48
Deficit	€61,987,626.79	Cost per tonne CO_2	€107.90