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URBAN FOREST.

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Buildings that Capture and Utilise Carbon Dioxide

Martin Wikestad
Master Thesis 2025

Chalmers School of Architecture
Department of Architecture and Civil Engineering

Examiner: Jonas Lundberg
Supervisor: Jonas Lundberg

"We are in a car going way too fast, and there is a bend coming. At this point there is no question that we will hit the guard rail. The question is whether we will roll the car. We will have damage when this is done, so we will have to start acting now to minimize the damage." - Lackner

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ABSTRACT

The built environment is a major contributor to the global CO_2 emissions (United Nations Environment Programme, 2023), making it essential for us to explore new ways of designing our built environment in a way that not only reduces its emissions but also actively participates in the reduction of greenhouse gases in our atmosphere. This thesis investigates the potential of buildings to function as carbon sinks by integrating Carbon Capture into architectural design. By treating facades as active components in carbon sequestration, the study envisions buildings as part of an "urban forest" that removes CO_2 from the atmosphere, much like trees in a natural ecosystem.

The thesis builds upon existing carbon capture technologies, developed by Dr Klaus Lackner (2009) at Columbia University, and explores their potential architectural integration through a design-driven case study where filters serve a dual purpose of offering shade to reduce solar heat gain while simultaneously capturing CO_2. In an effort to address one of the major challenges of carbon capture, what to do with the captured CO_2, this thesis also explores, beyond sequestration, how the captured CO_2 can be repurposed within the building itself, creating a closed-loop system. The thesis uses data from non building devices to calculate the magnitude and possibility of integrating carbon capture on a buildings facade.

Drawing on data from Lackner (2009), this thesis develops a design proposal located on a site in Gothenburg showing that the building's closed-loop system can sequester and reuse more CO_2 than is emitted during its construction. With this thesis design and in the given context, the proposed design could capture and utilize approximately 200 tonnes of CO_2 annually.

Keywords: Carbon capture, climate-positive architecture, regenerative design, built environment, CO_2 sequestration

Figure 01: *Image by author (2022). Industrial buildings in Gothenburgs harbor.*

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Thank you Jonas for the ever so helpful supervision and for continuously pushing me to dare to explore.

And thanks to those who have helped, inspired, guided me with this thesis.

INDEX

DESIGN PROPOSAL

Figure 02: *Image by author (2025). Visualisation of the design proposals balconies.*

Figure 03: *Image by author (2025). Map of Gothenburg in scale 1:20 000. The site for this thesis is marked in black.*

SITE

In selecting a site for this thesis project, careful consideration has been given to the urban structure, existing infrastructure, and the potential for integrating carbon capture technologies into a dense urban environment. The choice of Första Långgatan in Gothenburg is based on its strategic location within the city's industrial and commercial history, as well as its ongoing role in urban development. Första Långgatan presents a unique opportunity to test architecture's ability to actively participate in atmospheric carbon removal.

Första Långgatan has long served as a central corridor for trade, production, and cultural exchange. Today, it is undergoing a transformation where historical buildings, industrial heritage, and new development projects coexist. This district, located in the city center, presents a unique opportunity to explore the integration of carbon capture in future architectural interventions.

A key factor in selecting this site is its proximity to ongoing construction and renovation projects. The area is undergoing active urban development, with planning initiatives emphasizing mixed-use spaces, sustainable housing, and improvements to public areas. The presence of existing buildings in varying states of use provides a spectrum of possibilities for retrofitting, adaptation, and experimental applications of carbon-absorbing materials. These conditions create an interesting framework for investigating how architecture can contribute to urban resilience in addressing climate challenges.

Första Långgatan's historical significance and its contemporary transformation make it a reflection of the broader changes occurring in Gothenburg and other European cities. By situating the thesis within this context, the project not only engages with the site's immediate conditions but also contributes to the ongoing discourse on how architecture can play a crucial role in reducing the environmental impact of urban development (UN-Habitat, 2021).

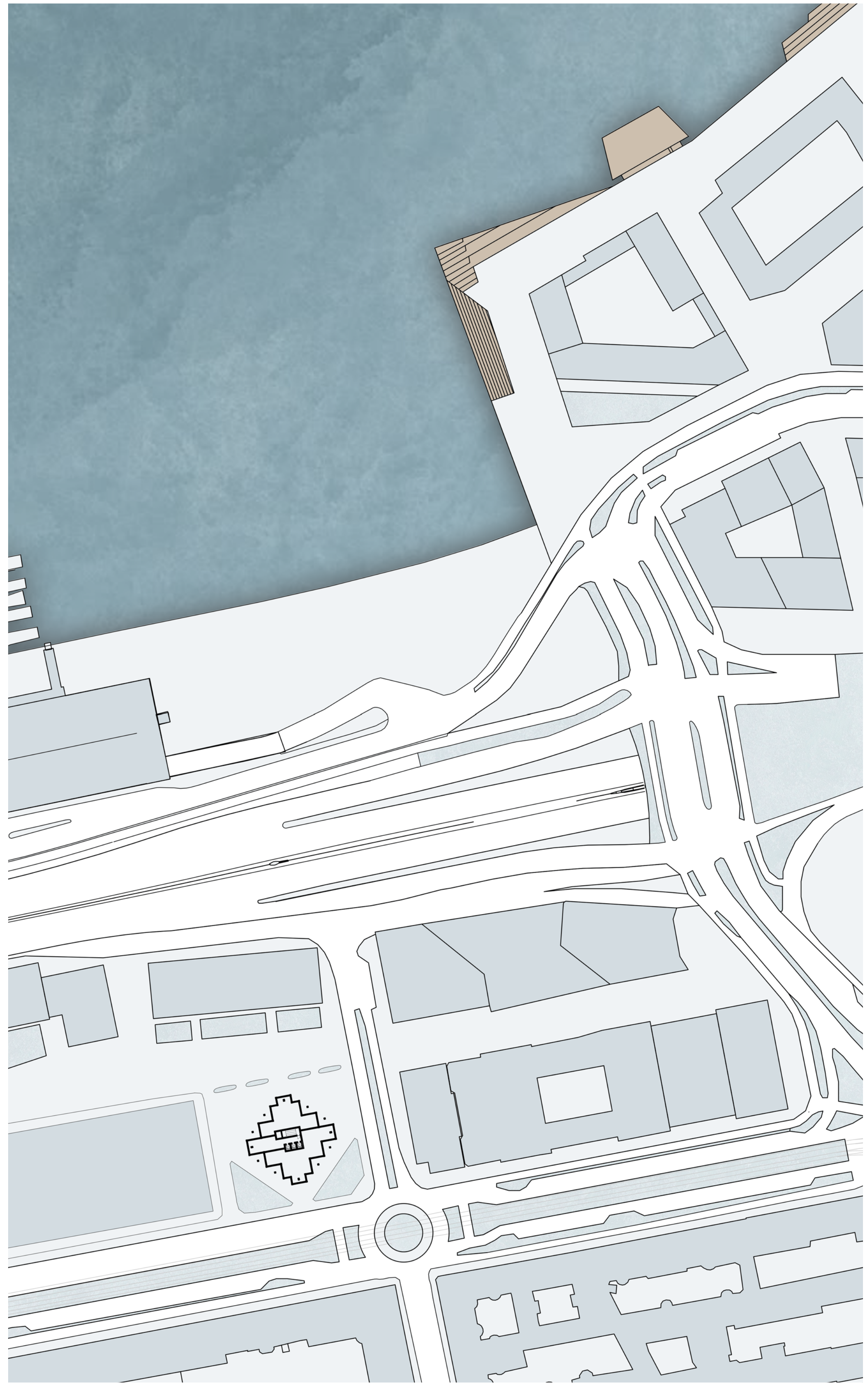


Figure 04: *Image by author (2025). Siteplan in scale 1:4000.*

Figure 05: Image by author (2025). Render of design proposal in its local context on Första Långgatan, Gothenburg.

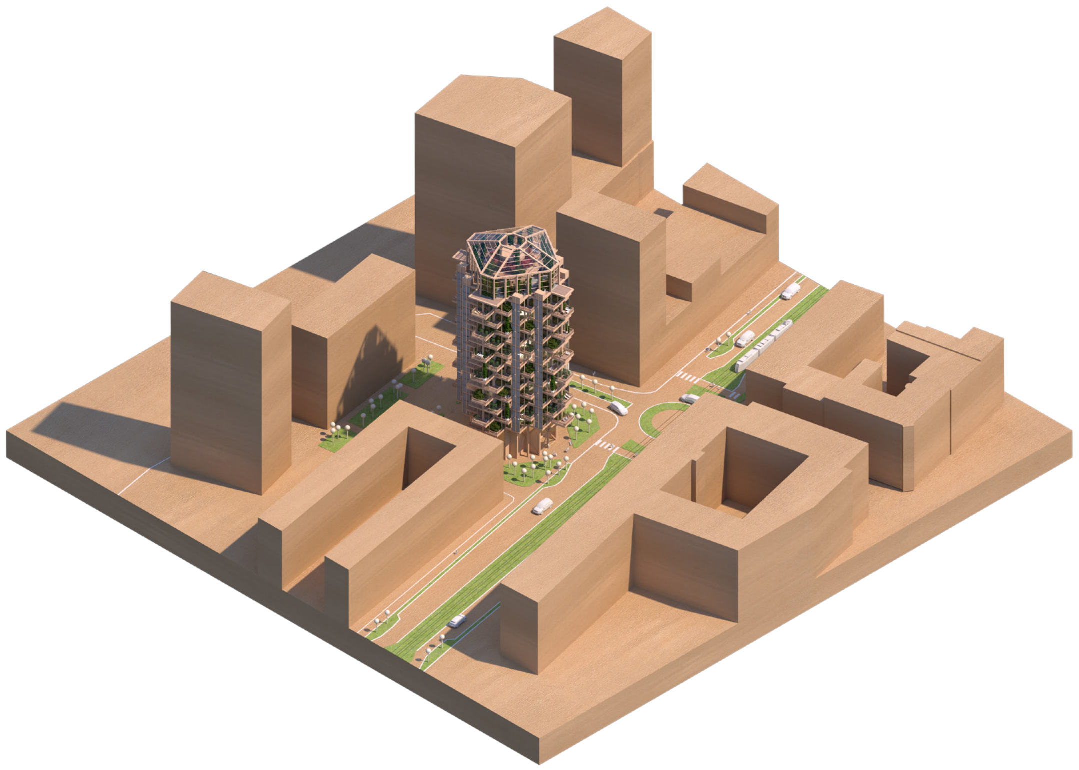


Figure 06: Image by author (2025). Maquette render of design proposal.

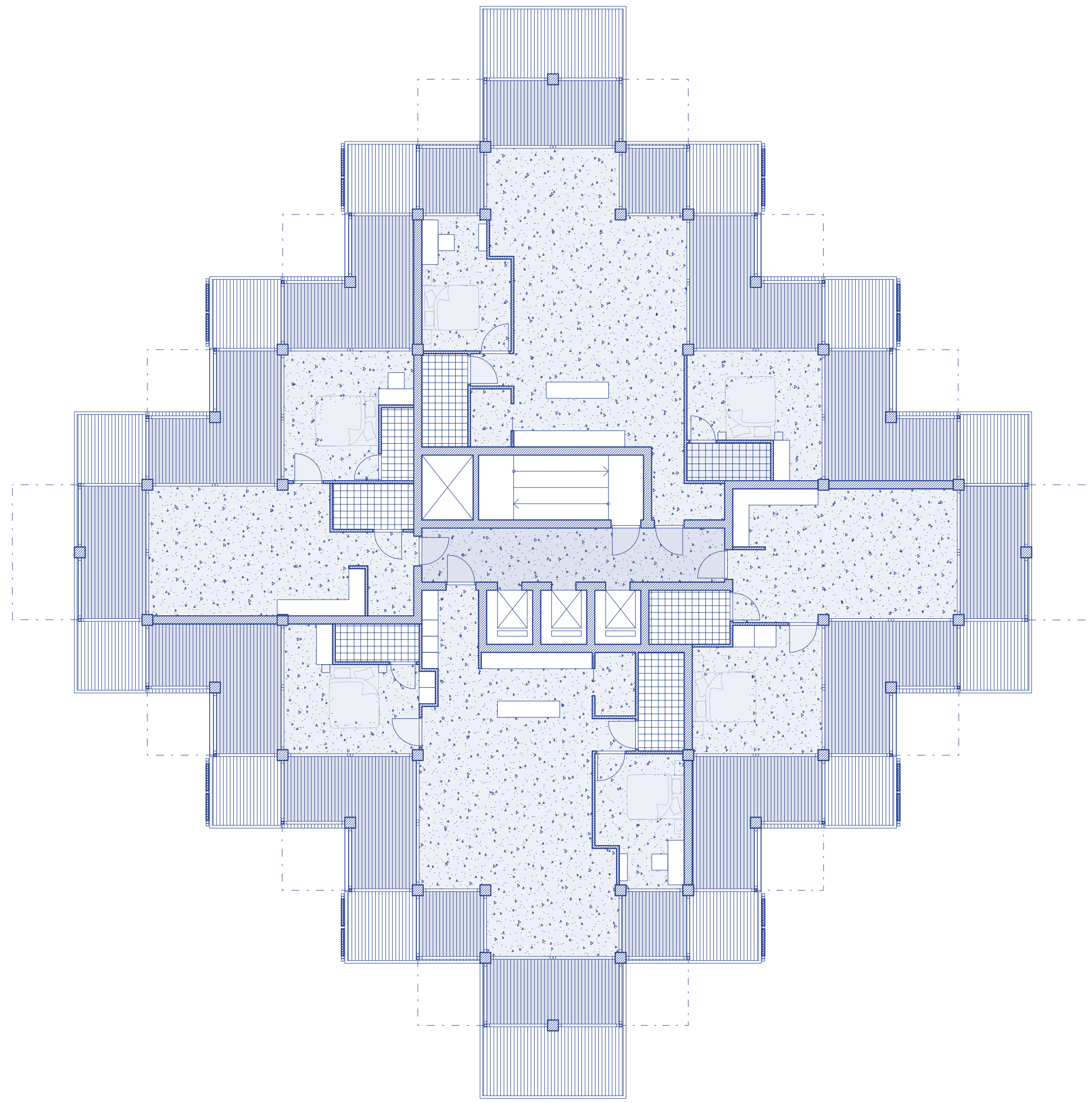


Figure 07: Image by author (2025). Plan drawing of apartment floor.

Figure 08: *Image by author (2025). Interior render showing a living room.*

Figure 09: *Image by author (2025). Render of balconies during winter taken from Järntorget.*

Figure 10: Image by author (2025). Visualisation of balconies with view over Gothenburg

Figure 11: *Image by author (2025). Visualisation of rooftop greenhouse.*

Figure 12: *Image by author (2025). Interior visualisation of a bedroom.*

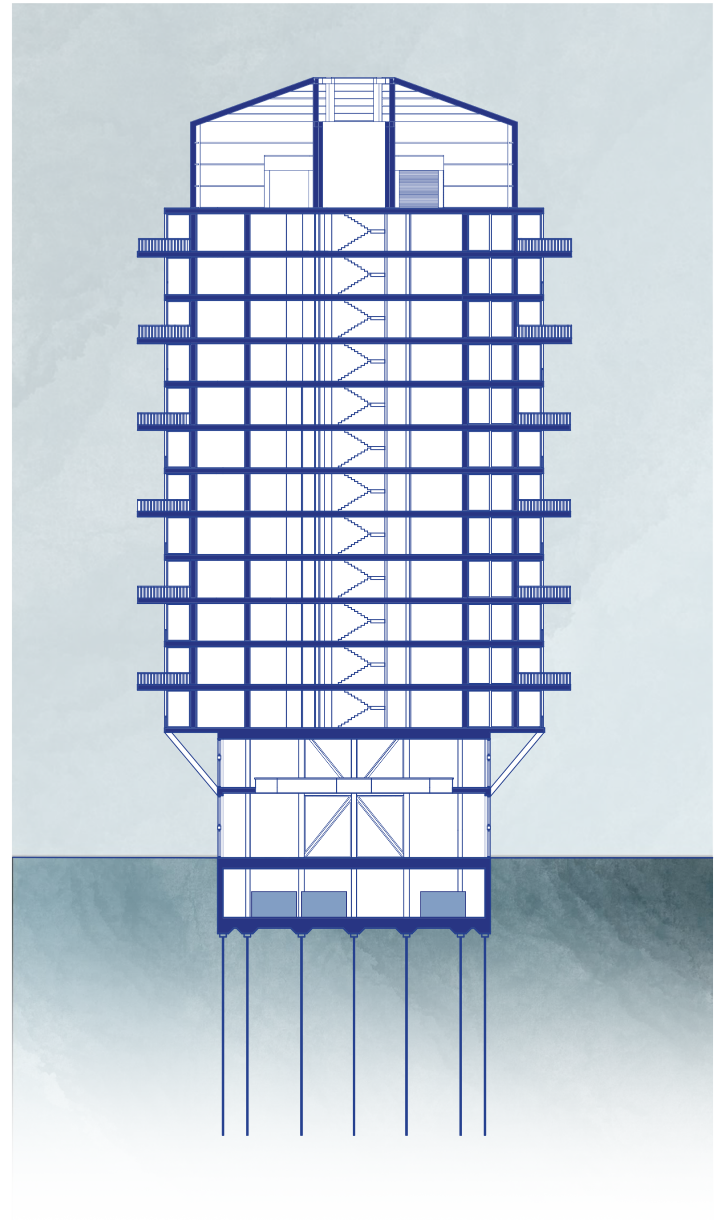


Figure 13: *Image by author (2025). Section drawing through the building.*

Figure 14: Image by author (2022). Industrial buildings in Gothenburgs harbor.

BACKGROUND

The built environment contributes significantly to CO_2 emissions, accounting for at least 37% of global emissions (United Nations Environment Programme, 2023). Currently, atmospheric CO_2 levels have reached 420 ppm according to NASA (2023), exceeding the threshold of 350 ppm identified by Hansen et al. (2008) as an upper threshold to prevent irreversible environmental impacts. This suggests that even if all sectors achieve climate neutrality today, direct actions to decrease atmospheric CO_2 concentration remain essential to prevent irreversible damage. The IPCC (2021) highlights the importance of carbon dioxide removal (CDR), the process of removing CO_2 from the atmosphere, and that it might be required to actively remove CO_2 to counterbalance the emissions from "difficult-to-decarbonise" sectors. One method to remove CO_2 from the atmosphere, known as Direct Air Capture (DAC), has been on the rise. A method that is capable of removing CO_2 from ambient air.

For as long as humans have existed on this planet we have searched for shelter to stay protected, to recover and evolve. However as global urbanization accelerates (Hannah Ritchie et al., 2024), it is critical to rethink buildings not only as shelters but as active tools for combating climate change. If we are to reach the climate goals there needs to be rapid advancements within all sectors. Building on the emerging concept of regenerative cities presented by Girardet, Herbert (2010), where the city serves more and new functions to help us combat these emerging climate issues.

The removal of CO_2 from the atmosphere is a fundamental process that has been occurring for billions of years, through natural processes such as photosynthesis. Abrol, et al. (1993) explains it as the process where plants capture CO_2 and turn it into oxygen, a crucial role in maintaining the Earth's atmospheric balance. This biological carbon cycle has allowed life to thrive. In recent decades, however, human activity has disrupted this balance. Industrialization, deforestation, and fossil fuel combustion have led to excessive CO_2 emissions. Therefore outpacing nature's ability to absorb them. As a result, researchers are exploring ways to mimic or enhance natural carbon capture processes. Buildings, traditionally seen as passive energy consumers, could potentially be reimagined as active participants in carbon sequestration, integrating materials and technologies that can remove CO_2 from the air much like trees do.

How to read the thesis

This thesis combines a design and research approach. Meaning the work is divided in to one theoretical and one design section. The theoretical research presented in the theory and result has laid the foundation for the design proposal that represents one half of the result of this thesis. The design proposal is presented in the first chapter of this thesis and in the results.

RESEARCH QUESTIONS

Main question

How can buildings function as urban trees by integrating carbon capture technologies to mitigate the building sectors emissions?

Subquestions

Can a building remove more CO_2 from the atmosphere than it emits?

Is it possible to create a closed system where a building captures and also utilizes all the captured CO_2 within the building itself?

Structure

Page numbers are coordinated according to the subheadings listed in the index, meaning that one subheading covers one topic. References are conducted through the APA reference system. Included at the end of the thesis a full reference list and an appendix with full calculations.

AIM

This thesis aims to explore the architectural integration of Direct Air Capture (DAC) technologies into the built environment, reimagining buildings not merely as shelters or passive energy consumers, but as active players in carbon-removal. By envisioning buildings as synthetic analogues to trees, the research seeks to develop design strategies that enable the capture, storage, and utilisation of atmospheric CO_2 within a closed-loop architectural system.

The project investigates how carbon capture can be embedded into building envelopes through moisture-swing absorption systems, assessing their performance, spatial implications, and potential to replace or enhance conventional architectural elements such as sun shading or facade treatments. The goal is to evaluate how existing systems can be architecturally implemented at the building scale.

Through a design-based case study situated in Gothenburg, the thesis also examines how the captured CO_2 can be repurposed within the building itself, particularly in relation to building-integrated greenhouses, thus exploring architecture's potential to support localized food production and circular resource flows. The aim is to establish a conceptual and practical framework for how buildings can move beyond carbon neutrality toward climate-positive performance, contributing meaningfully to urban resilience and the broader climate agenda.

DELIMITATIONS

This thesis focuses on integrating existing carbon capture technologies into architectural design and not developing new systems. It focuses on building-scale applications rather than large-scale industrial carbon capture infrastructure. Rather than presenting a fully developed technical system, the study takes a case-study based approach to examine the architectural potential of carbon capture, testing its feasibility and spatial implications.

The research is rooted in a Swedish context, with the chosen site playing a key role in shaping the design proposal. Local climate conditions, material availability, and regulatory frameworks provide a foundation for the study, while the broader implications of the findings may extend beyond this setting. The thesis does not include a detailed cost analysis or extensive LCA, as the primary focus is on exploring the conceptual and design possibilities of integrating carbon capture into the built environment.

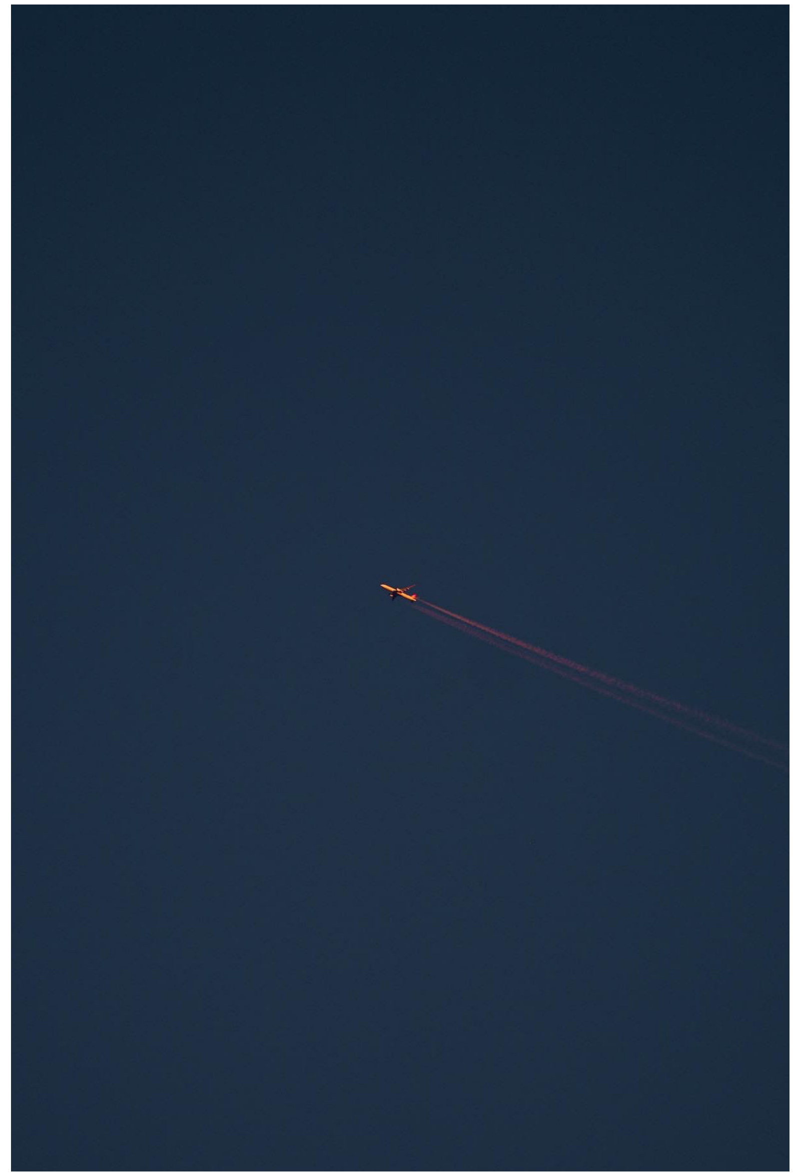


Figure 15: *Image by author (2022). Airplane leaving the Landvetter airport.*

GLOSSARY

DAC	*Direct Air Capture: A technology that extracts CO_2 directly from the atmosphere.*
MSA	*Moisture-Swing Absorption: A passive carbon capture method using materials that absorb CO_2 in dry air and release it when exposed to moisture.*
CDR	*Carbon Dioxide Removal: The broader category of technologies and methods aimed at removing CO_2 from the atmosphere.*
BICC	*Building-Integrated Carbon Capture: The integration of carbon capture technology into architectural elements, such as facades.*
BIA	*Building-Integrated Agriculture: The practice of growing food within or on buildings, often through hydroponic systems or greenhouses.*
LCA	*Life Cycle Assessment: A method for evaluating the environmental impact of a product, process, or system across its entire lifespan.*
BTA	*Bruttoarea (Gross Floor Area): A Swedish term used to describe the total area of all floors in a building.*
Carbon Capture	*The process of trapping and removing carbon dioxide from the atmosphere.*
CO_2 Utilization	*The process of finding practical, beneficial uses for captured carbon dioxide, such as in agriculture or material production.*
Closed-Loop System	*A system in which resources are continuously reused or repurposed, minimizing waste and external inputs.*
Regenerative Design	*A design approach aimed not only at sustainability but at improving and restoring ecological systems.*
Carbon Sink	*Any system or entity that absorbs more carbon than it emits — traditionally forests, but in your thesis, also buildings.*
Greenhouse Utilisation	*he use of captured CO_2 to enrich plant growth in controlled environments like greenhouses.*
Climate-Positive Architecture	*Architectural design that goes beyond neutrality to actively reduce greenhouse gases in the atmosphere.*

Figure 16: *Image by Adam Axelsson, edited by Author (2022). Fog over forest.*

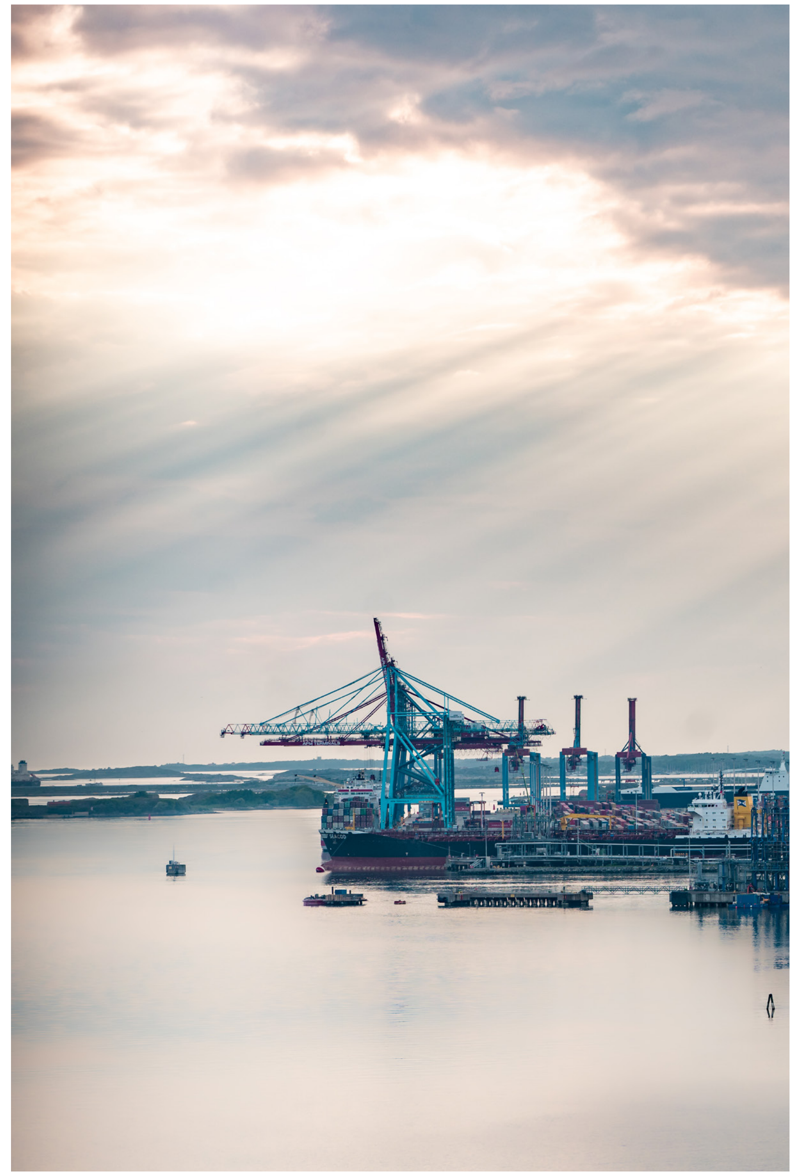


Figure 17: *Image by author (2022). Gothenburgs industrial harbour.*

URGENCY AND PURPOSE

The climate crisis is not a distant threat anymore, it is a rapidly accelerating condition that demands immediate, multifaceted responses. The built environment, responsible for 37% of global energy-related CO_2 emissions (United Nations Environment Programme, 2023), represents both a major contributor to the problem and a largely untapped opportunity for action. As global efforts increasingly focus on decarbonization, it becomes clear that reducing emissions alone will not be enough. According to Hansen et al. (2008), the atmospheric concentration of CO_2 must fall below 350 ppm to avoid irreversible ecological tipping points. A target we have long surpassed, with current levels exceeding 420 ppm (NASA, 2023).

In this context, carbon removal strategies are gaining urgency. The Intergovernmental Panel on Climate Change (IPCC, 2021) emphasizes that in order to meet the Paris Agreement targets, large-scale deployment of carbon dioxide removal (CDR) technologies will likely be necessary. Particularly to offset emissions from sectors that are difficult to decarbonize. Among these technologies, Direct Air Capture (DAC) presents a promising approach, yet it remains primarily implemented at industrial scales in remote areas.

This thesis explores the potential of repositioning carbon capture in an architectural context. By exploring how DAC can be embedded directly into buildings, architecture can evolve from being a passive emitter to an active agent of carbon removal. Inspired by the concept of regenerative cities (Girardet, 2010), where urban systems restore rather than degrade ecological systems, this project positions buildings as synthetic analogues to trees: actively cleaning the air while serving their traditional programmatic functions.

The purpose of this thesis is not only to investigate the technical and spatial feasibility of carbon-absorbing facades, but to critically question and expand the role of architecture in the face of an escalating climate emergency. As the boundaries between design, ecology, and technology continue to blur, architecture can no longer be confined to aesthetics, functionality, or efficiency alone. Once symbols of human shelter, culture, and progress must now embody a deeper ecological responsibility as well.

This thesis argues that architecture could shift from being a backdrop to climate solutions to becoming a central actor. It explores how the integration of Direct Air Capture into the building envelope can serve as both a symbolic and literal shift in how we conceive of buildings. In doing so, it challenges architects to think not only about minimizing harm, but about designing systems that give back, that restore, and that reimagine the built environment as an active partner in shaping a livable future. Architects are creatives and ideas are what develops our society.

Architecture has always reflected the priorities of its time—whether political, economic, or cultural. Today, its priority must be planetary survival. This thesis situates itself at that intersection, proposing that the future of architecture is not merely sustainable, but regenerative, and ultimately, transformative.

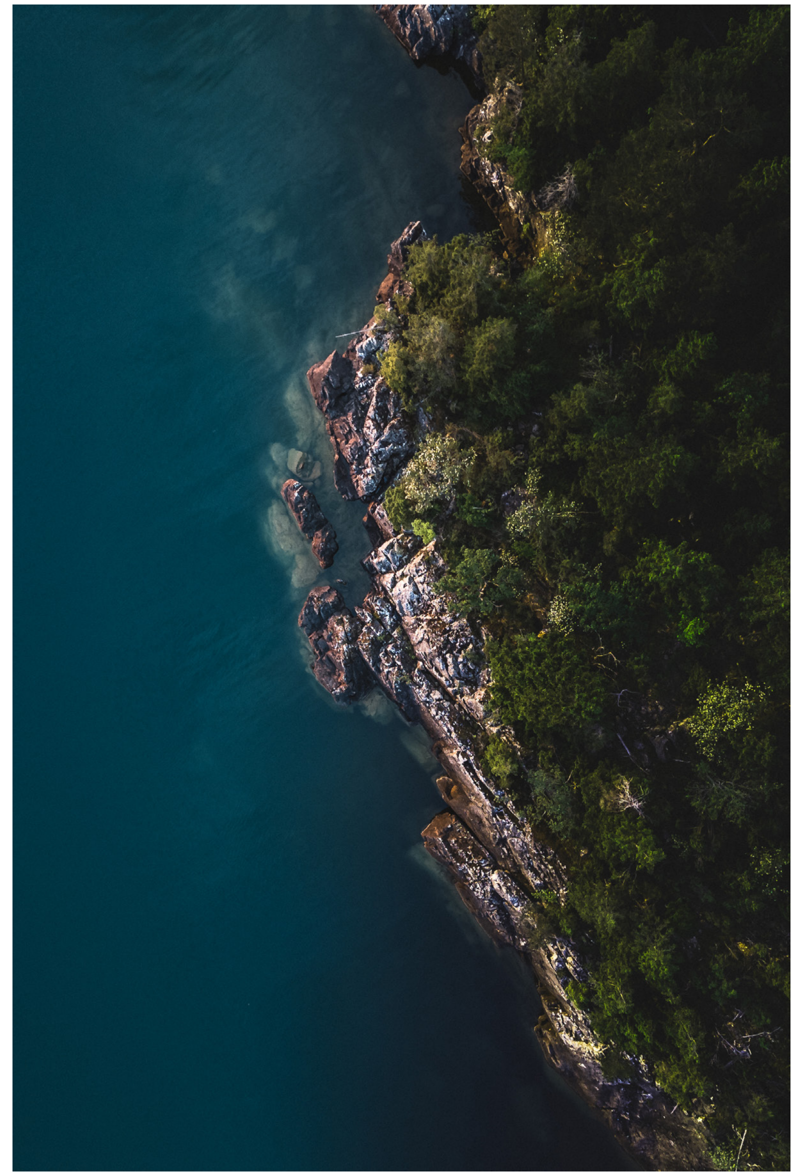


Figure 18: *Image by author (2024). Lake Vättern from a top-down perspective..*

CARBON CAPTURE

The technology to remove CO_2 from air is not new. It has been used in a process known as CO_2 scrubbing for decades. A process used in industrial and large scale plants where there are high concentrations of CO_2. The CO_2 is then removed before letting the air out into the atmosphere. However this is not the same as capturing it from ambient air. In this scenario the levels of CO_2 are much lower. Therefore the goal is not to remove it all from the air, like in the CO_2 scrubbing example. Rather it is to have an efficient enough system to remove it from the ambient air. Both systems use filters with different sorbents with the difference being the efficiency needed to work in different environments (Lackner, Ziock, & Grimes, 1999). The process of capturing CO_2 is similar across different sorbents and methods. At its core, it involves a filter containing a sorbent that chemically reacts upon contact with CO_2.

Capturing air from large scale industrial plants is as mentioned called CO_2 Scrubbing. Meanwhile the process of capturing it from ambient air is called Direct Air Capture (DAC). According to Sodiq et al. (2022) there has been significant progress in the technology behind DAC in the last decades due to the rise of awareness of global warming. The authors also highlight that there are two main types of sorbents divided into either solid or liquid sorbents. Due to the aim of this thesis, to explore the potential of implementing carbon capture on a buildings facade, we will focus on solid sorbents.

It is said that Climeworks, a Zurich-based company, developed the first commercial carbon capture technology. Their system utilizes a fan to draw ambient air into the device, where it passes through a filter containing a sorbent material. Once the filter reaches saturation, it is heated to release the captured CO_2, which is then collected and stored in tanks for further use (Climeworks, 2025).

MOISTURE-SWING ABSORPTION

Moisture-Swing Absorption (MSA) is another promising type of DAC technology (Sodiq et al., 2022). Leading the research on this DAC technology is Dr. Klaus Lackner and in his 2009 paper "Capture of carbon dioxide from ambient air" (Lackner, K. S., 2009) he presents a technology that utilizes panels with filters made of sorbent material. These panels can capture CO_2 in a dry state and release it when exposed to moisture. Unlike Climeworks' system, this technology operates without the need for mechanical airflow. Instead it relies on natural air currents and can function at wind speeds as low as 1 meter per second. This passive approach eliminates the need for energy-intensive blower fans and offers greater flexibility in integrating the system into buildings in a way that is both functional and aesthetic. In Lackners (2009) research he proposes a design for a prototype with a total of 60 filters with the dimensions of 2.5m tall, 1m wide and roughly 30-40 cm thickness. This prototype can fit inside the dimensions of a shipping container at approximately 12 m x 2.5 m x 3 m.

The proposed prototype could capture roughly 1 ton of CO_2 per day. To calculate the feasibility of this prototype they estimate that the energy consumption for a device like this would be around 50 kJ/mol of CO_2 or 1.1MJ/kg of CO_2.

Building upon Dr. Klaus Lackners research on MSA Harvey Brian (2017) presents a building integrated carbon capture (BICC) design that utilises the MSA sorbent technology on a building's facade. Changes from Lackners (2009) proposed design has to be made in width, height, thickness and "cleaning method" for it to be applicable in a facade design. Brian (2017) presents a system with a cleaning chamber that moves along tracks, similar to a window-cleaning system, spraying the fabric filters with water to dissolve the captured bicarbonate from the fibers. This process creates a carbonate-rich liquid and releases CO_2, which can then be compressed and stored.

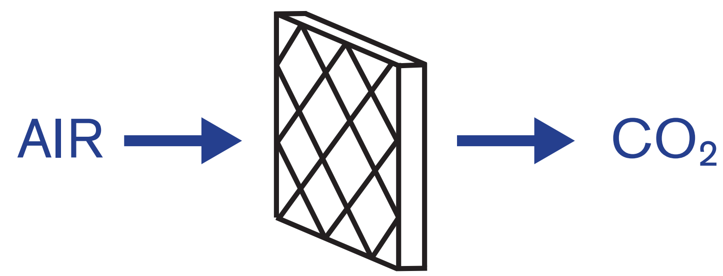
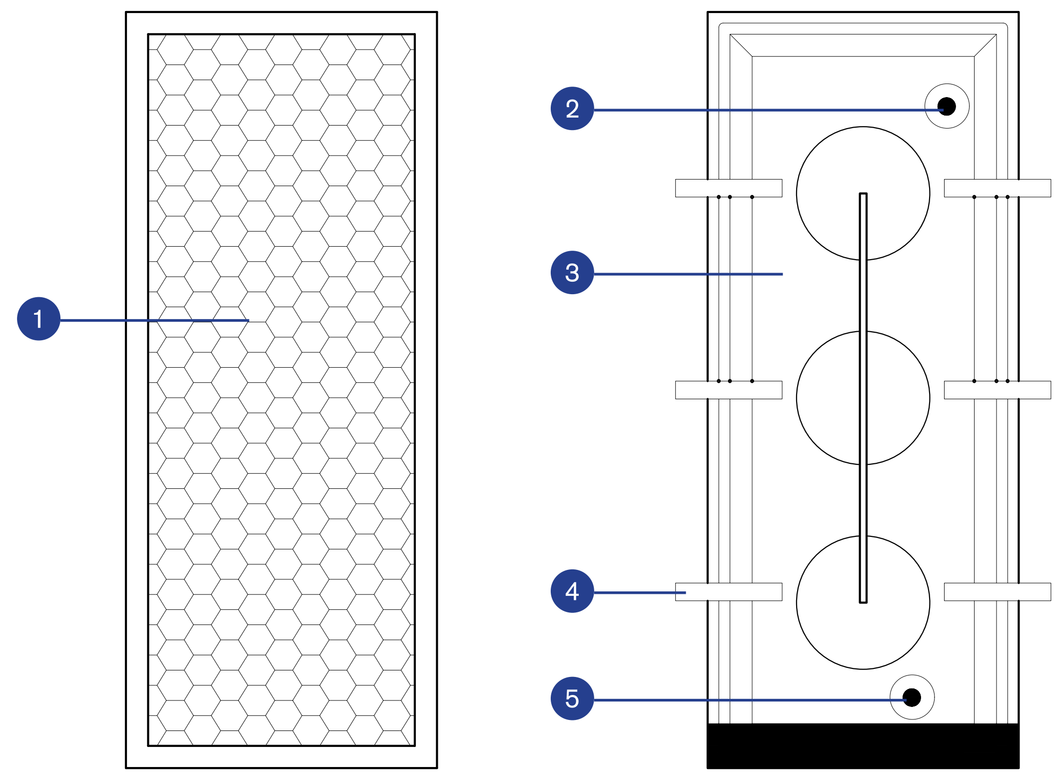


Figure 19: *Image by author (2025). Diagram of Direct air capture.*



1. *Filter face with a honecomb like structure.*
2. *Pipe conection for the captured CO_2.*
3. Back side of the cleaning chamber.
4. Connection to the vertical rails on the facade.
5. Out- and inlet for water pipe.

Figure 20: *Image by author (2025). Building integrated carbon capture design presented by Brian (2017).*

POTENTIAL OF CARBON CAPTURE

See Appendix 1.1 - 1.2 for full calculations

Carbon capture holds great potential and according to Lackner (2009) it is physically possible to create carbon capture devices that have uptake rates of several orders of magnitude to those of trees. By utilizing the research presented by Lackner (2009) we are able to calculate the potential of carbon capture if it were implemented in a building.

If we assume that the filters used in our design have a 10 cm thickness. The thickness is based on the filters presented in Brian's (2017) paper on BICC's where the filters have been modified to function on a building's facade. With this adjustment, the capture potential is estimated at 118.8 grams of CO_2 per square meter of filter per cycle. A cycle refers to the complete process of CO_2 absorption, release through moisture application, and subsequent drying. According to Lackner (2009), this cycle takes approximately 1.5 hours, meaning that, in theory, a single square meter of filter could capture nearly 1.9 kg of CO_2 per day.

To continue the calculation of the potential of CO_2 capture on a building we can make a case study of a fictional building. First of all we assume we have a building that is 30mx30m and with a floor height of 4m. We create a filter based on the BICC design presented by Brian (2017) with the dimensions 3.6x0.8m with a thickness of 10cm. This way these filters can be mounted perpendicular to the buildings facade and there will be some vertical space between the filters where the chamber can be located. On a 30m facade we can then place 16 of these filters spaced 2m apart. This way they can function as both CO_2 capture devices but also provide shading and have space for windows inbetween the installations. And at the same time have filters on both sides and still fit two movable cleaning chambers. From these assumptions we are able to calculate using the data in Lackners (2009) paper that we end up with a CO_2 capture rate of 700kg per floor of building with these filters installed every day, assuming it would have a 100% efficiency.

POTENTIAL OF CARBON CAPTURE

See Appendix 1.3 for full calculations

Based on the information presented above, the potential of carbon capture in the urban environment could be upwards of 700kg of CO_2 per day for every floor of a building. To better understand this number we can put it into comparison with Sweden's total CO_2 emissions at approximately 44 million tonnes of CO_2 each year (Naturvårdsverket, 2024) making it seem like 1 ton is a minisquire amount. But we also need to take into consideration that this is only one floor on one building. According to SCB, Byggföretagen (2024) there were 22.400 new apartment buildings being built in 2024. A number that was significantly lower than previous years during the 21st century. However, if we assume that the rate stays the same for the upcoming years and that 50% of those buildings are equipped with the above proposed carbon capture technology and that they have an average of 10 floors per building. Then we get a potential CO_2 capture of roughly 29 million tonnes per year. Roughly 66% of all of Sweden's yearly CO_2 emissions.

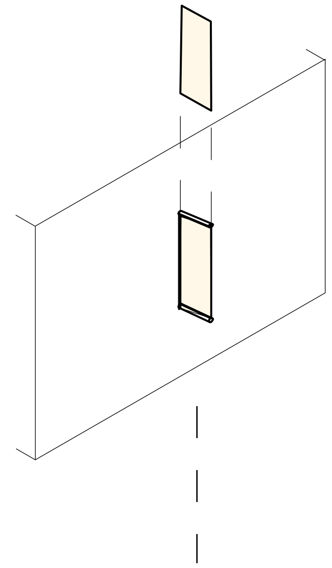


Figure 21: *Image by author (2025). 1m²* filter with a capture potential of 1.9kg/day.

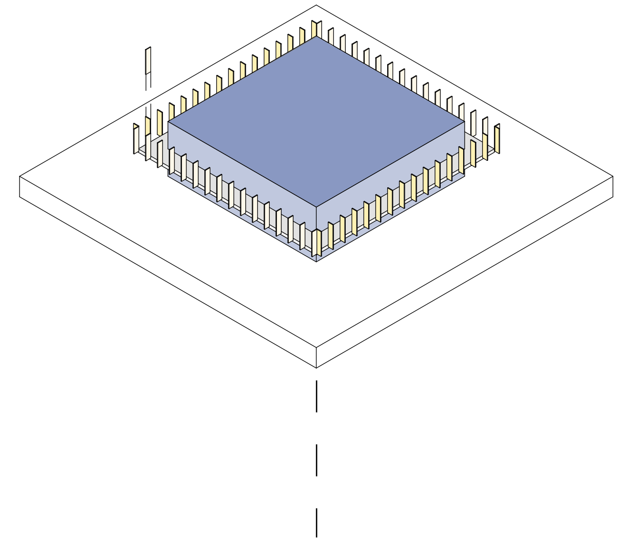


Figure 22: *Image by author (2025). 64 two sided filters on one floor with a total of 184*m² and a capture potential of 700kg/day.

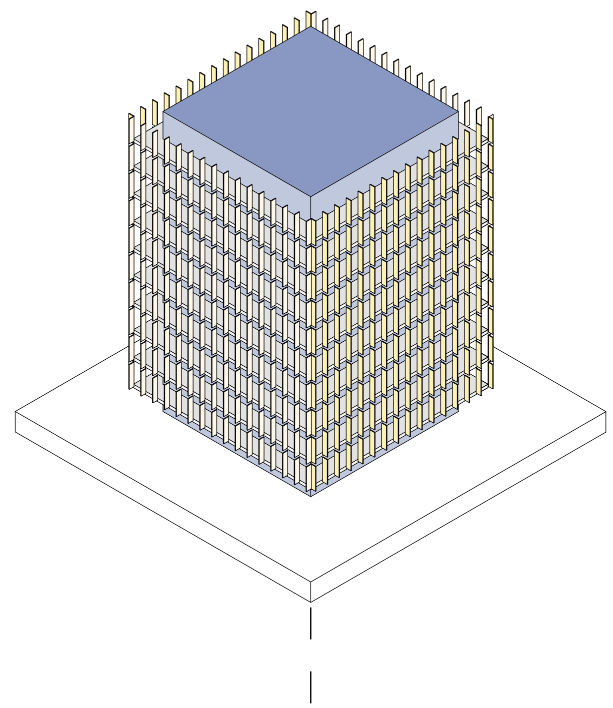


Figure 23: *Image by author (2025). 10 floors with filters resulting in 3,680*m² of filter and a capture potential of 7000kg/day.

CO_2 UTILISATION

In the previous chapter we have explored the potential of carbon capture in the built environment. However one of the major hurdles when it comes to implementing capturing CO_2 on a large scale is the utilization and/or storage of it. CO_2 is often seen as a waste product from energy and industrial industries. But it is a product that has various applications in local markets, including food production, refrigeration, and industrial processes like metal, plastic and even concrete manufacturing. However due to the capture potential discussed in the previous chapter it seems like the capture potential far exceeds the use cases in local markets. Additionally, CO_2 can be injected and stored underground.

To store CO_2 efficiently, it must first be compressed to pipeline grade, a process that demands substantial energy and costs. Next, an extensive pipeline network must be integrated into urban infrastructure to facilitate local capture and storage. Additionally, storage facilities would need to be established as transition points for further transport. Finally, delivering CO_2 to remote storage sites would require expensive pipelines or tankers, with pipeline costs ranging from $50,000 per mile on flat terrain to $700,000 per mile offshore. Such large-scale infrastructure investments are only feasible for cities designed with CO_2 capture in mind (Bryan & Salamah, 2020).

Another option for utilizing the captured CO_2 that according to Bryan & Salamah (2020) seems to hold potential is to convert it into methane gas on site. By doing so the methane could be connected to already existing biogas infrastructure that already exists in most cities. The process to convert CO_2 in to methane includes a two step process, first the Electrolysis reaction that breaks down water into oxygen(O_2) and hydrogen (H). The second one is the Sabatier reaction that combines hydrogen from the Electrolysis process with the captured CO_2 to create methane(CH4).

LOCAL CO_2 UTILISATION

Today there are multiple different use cases for captured CO_2. However the problem still remains. There isn't really a viable and scalable option available. Some of the presented use cases in the previous chapter seem to hold greater potential than others. But as of right now the cost of removing CO_2 is much higher than what the market price of it is.

But to further explore the topic of CO_2 utilization this thesis aims to answer one of the research questions for this thesis "*Is it possible to create a closed-loop system where a building captures and also utilizes all the captured CO_2 within the building itself?*".

When it comes to potential use cases for CO_2 within a building itself there aren't that many options. One market where it could be used is, as presented by Sodiq et al. (2022), the use of it in agriculture. In greenhouses CO_2 could be added to improve plant growth. Studies show that having a concentration of 1000-1300 ppm CO_2 is optimal for plant growth and could increase the yield to between 30-50%, depending on the plant (Christensson, 1986).

Combining this with Building-Integrated Greenhouses (BIGHs) presents a promising approach to closing the carbon loop within a building (D'Ostuni et al., 2024). In D'Ostuni et al. (2024) paper "Integrating Greenhouses into Buildings: A Renewed Paradigm for Circular Architecture and Urban Regeneration" the authors explore the many benefits of implementing greenhouses in a building design. Benefits such as reducing stress, preventing or limiting mental health-related issues, self-production of food (resulting in reduced need for shipping) and improved biodiversity in cities (D'Ostuni et al., 2024).

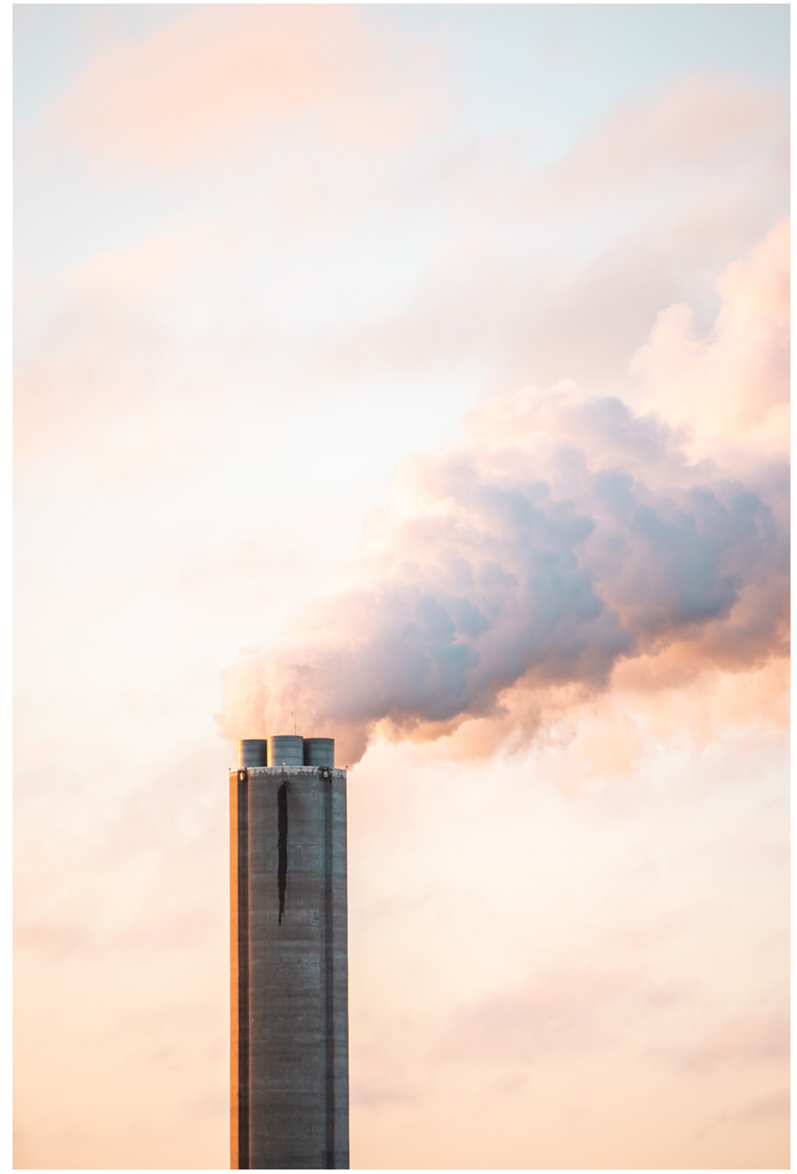


Figure 24: *Image by author (2022). Industrial chimney in Gothenburg.*

GREENHOUSE UTILISATION

See Appendix 1.4 for full calculations

In order to further evaluate the feasibility of integrating greenhouses into building designs, and ultimately closing the carbon loop from capture to utilization, it's first essential to understand how greenhouses operate and what resources they require.

Photosynthesis is the process in which plants use CO_2, water and energy from light to create sugar and oxygen (Abrol, et al., 1993). The amount of CO_2 a plant consumes during photosynthesis depends on many different factors such as what species of plant it is, climate in the greenhouse and sun hours. There are multiple different papers available giving different numbers on the amount of CO_2 needed. To estimate the quantity required for the thesis case study, we present three values drawn from Brattsell Bukowski's (2015) analyses of three separate studies.

Brattsell Bukowski (2015) presents three different values (Low, medium and high consumption). The presented values are based on the amount needed to take the CO_2 levels from 400 ppm (roughly the concentration of CO_2 in ambient air) to 1000 ppm, meaning an increase of 600 ppm. Since photosynthesis needs light to work. The calculations take into consideration that there is an average of 16 hours per day that the process is happening.

Scenario	CO_2 Consumption (g/m²/hour)	CO_2 Consumption (g/m²/day)
Low consumption	4 g/m²/hour	64 g/m²/day
Medium consumption	7.82 g/m²/hour	125.12 g/m²/day
High consumption	10 g/m²/hour	160 g/m²/day

Figure 25: *Table made by author (2025) with data from* Brattsell Bukowski (2015).

With the above presented scenarios we can implement these numbers to better understand the number of green house area we potentially could supply with our case study building. However the upcoming diagrams are using the "High Consumption" values. This is based on the assumption that the plants in the greenhouse that would be implemented in our building would have a higher consumption due to being for food production.

By utilising the same case study as previously, where the double sided filters in our design have a 10 cm thick filter with an area of 2.88m² per side (dimensions 3.6x0.8m), the capture potential of one filter could potentially supply 68m² of greenhouse.

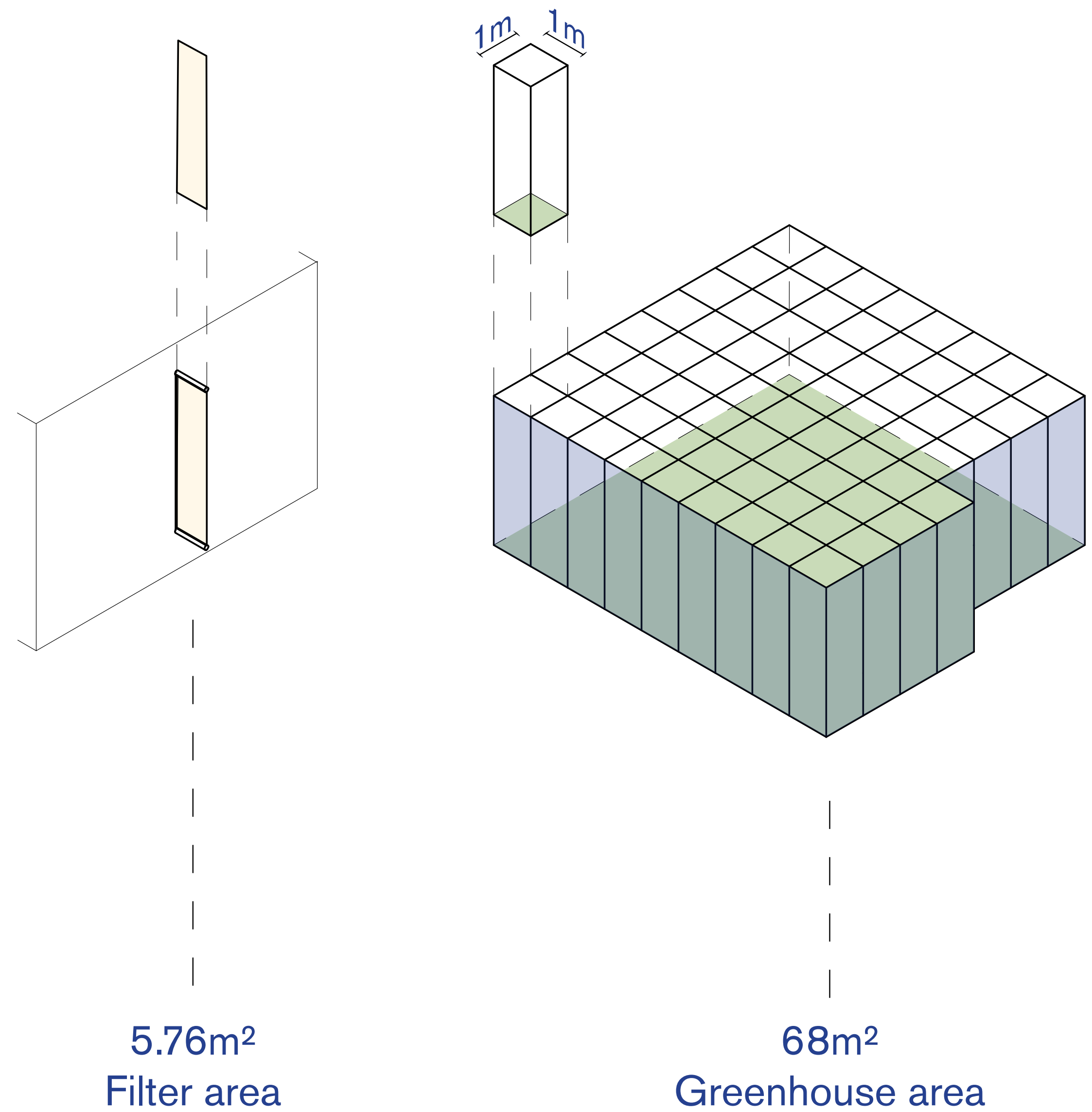


Figure 26: *Diagram produced by author (2025). One single filter with an area of 2.88m2 doing 16 full cycles per day could in theory supply 68m² of greenhouse area to go from 400ppm to 1000ppm.*

Applying this to the case study building with a total of 64 of these filters on every floor. The building that has, as mentioned in previous chapter, a potential capture rate of 700kg of CO_2 per floor. Based on the numbers above would give this building the potential to supply 4,380m^2 of greenhouse area or 4.87 floors of a greenhouse with the same footprint (30x30m) as our case study building.

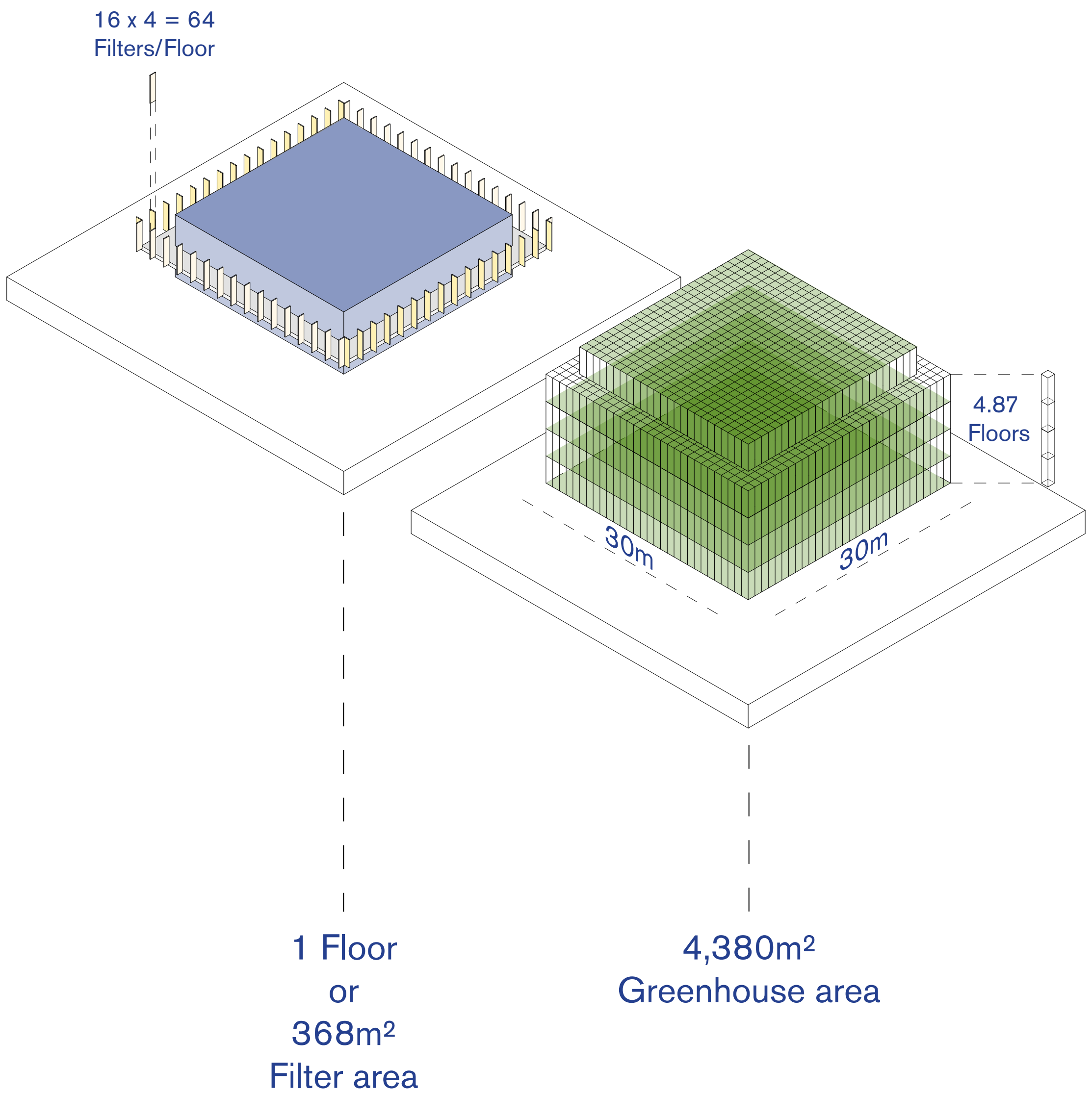


Figure 27: Diagram produced by author (2025). One floor of filters with a combined area of 368m^2 doing 16 full cycles per day could in theory supply 4,380m^2 of greenhouse area to go from 400ppm to 1000ppm.

A 15 story building equipped with this carbon capture technology would have a CO_2 capture potential of roughly 10,500kg/day. That would be enough daily CO_2 for 65,700m^2 or 73 floors of greenhouse. To put this into perspective. Karlatornet, the tallest building in Scandinavia, has 74 floors.

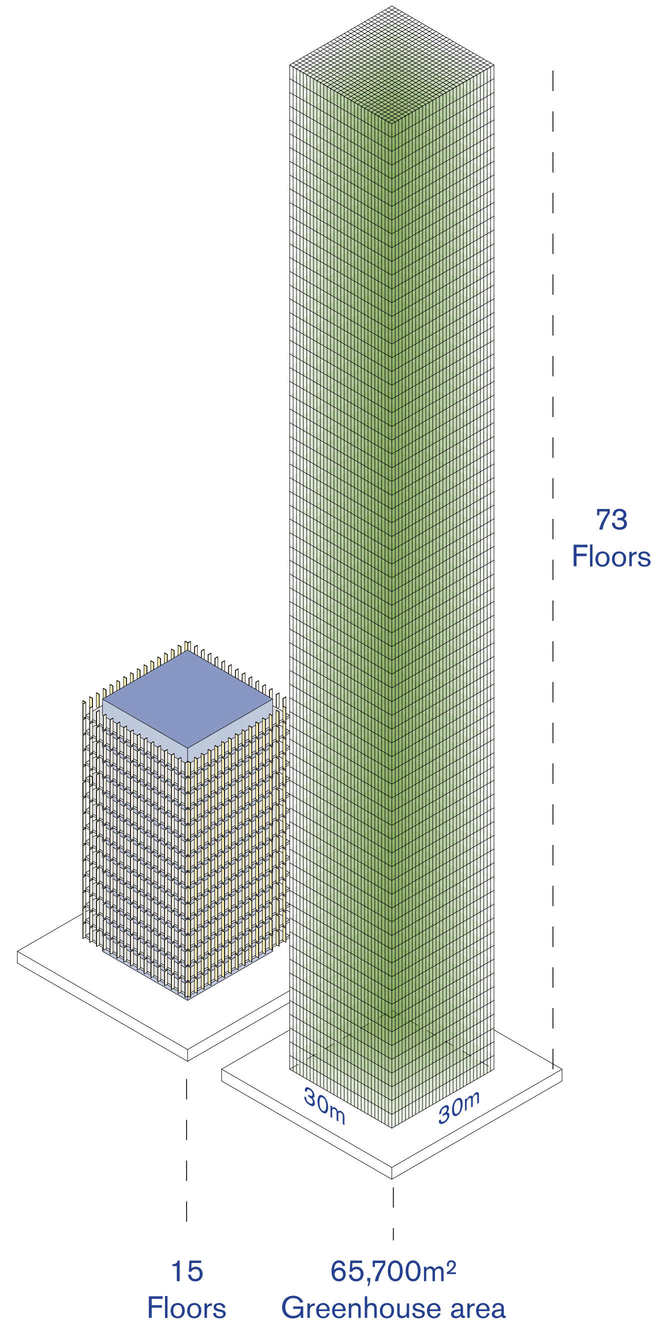


Figure 28: Diagram produced by author (2025). 15 floors with the moisture swing technology could potentially capture enough CO_2 to sustain 65,700m^2 of greenhouse area.

From these numbers we can confirm the statement from Bryan & Salamah (2020) that the potential capture of CO_2 seems to far exceed what local markets could utilize. However this case study only shows what a perfect scenario would look like and doesn't take into consideration local contexts, design of an actual building or the number of cycles actually reasonable in a day. This thesis aims to further explore the potential of a building integrated greenhouses in a local context in Gothenburg where more factors are taken in to consideration.

Food production in local greenhouses

Integrating greenhouses directly into the built environment offers a transformative opportunity to reimagine how we grow and consume food in urban areas. By harnessing sunlight for both plant cultivation and passive heating, these systems can help close the carbon loop. In this section, we will explore the possibilities of food production in greenhouses embedded within buildings.

BIA or "Building integrated agriculture" is described by Gould and Caplow (2012) as "high-performance hydroponic farming systems located on and in buildings, using renewable, local sources of energy and water". The authors argue that BIA offers a promising solution to the challenges of urban food security, resource scarcity, and the environmental footprint of conventional agriculture. By situating high-performance hydroponic systems within and on buildings, BIA enables local food production while simultaneously contributing to energy savings, carbon mitigation, and urban resilience (Gould & Caplow, 2012).

Gould and Caplow (2012) also presents a number of case-studies that have applied this strategy in and/or on buildings to illustrate its applications. One of the case-studies presented in the paper is a project named "Gotham Greens". Gotham Greens is a commercial-scale rooftop farm, demonstrating the potential of urban agriculture at scale. Covering approximately 1,115 m^2 (12,000 ft^2), the facility produces 30 tons of high-quality fruits and vegetables annually, with a wholesale value of around $500,000.

CO_2 STORAGE

If carbon capture and greenhouses were to be implemented in a building there would be a need for a storage solution due to seasonal changes in the capture rate of the carbon. Therefore on-site storage becomes essential. Carbon storage tanks could function as buffers to supply the mismatch between capture availability and utilization demand, ensuring uninterrupted CO_2 delivery during periods of low capture (e.g., inclement weather or off-peak operation).

The design of the storage tanks hinges primarily on two factors: the storage density of carbon dioxide and the duration of supply required between capture cycles. Storage density, expressed in kilograms of CO_2 per cubic meter, determines how much gas can be held within a given tank volume. High pressure compressed CO_2 systems operating at around 44.9 MPa routinely achieve densities near 1 000 kg/m^3, as demonstrated by Stanek et al. (2022). Equally important is the length of time the stored CO_2 must sustain greenhouse enrichment when active capture is interrupted.

Storage configurations typically comprise multiple modular high-pressure vessels installed in secure, ventilated areas (e.g., basements) (Stanek et al., 2022).

Figure 29: *Image by author (2025). Dockhouse rebuilt into a family home.*

Figure 30: *Image by author (2024). Cranes in Gotheburgs harbour.*

RESEARCH THROUGH DESIGN

This thesis uses a research-through-design methodology to explore the integration of carbon capture technologies within the built environment. The approach combines theory, quantitative data analysis, and design experimentation to investigate how buildings can both function and be designed to actively capture and utilize CO_2. While the process of capturing and utilizing CO_2 also plays a role in the design of the building.

LITERATURE REVIEW

The thesis work begins with a literature review presented in the "THEORY" section to establish a foundation for understanding carbon capture technologies and their potential applications in architecture. This includes an analysis of existing Carbon Capture and Direct Air Capture (DAC) systems, their efficiency, design and potential for being applied on a buildings envelope. Additionally, literature on greenhouse CO_2 requirements and their relationship with plant growth and productivity is examined to inform the potential reuse of captured carbon in urban agriculture.

DATA COLLECTION AND ANALYSIS

Following the literature review, quantitative data is gathered and implemented in a fictional building case study to determine the feasibility and potential of integrating carbon capture technologies into architectural systems if it would have a 100% efficency. This involves:

- *Assessing existing DAC technologies for applicability in buildings, including efficiency rates and space requirements.*
- *Calculating the CO_2 capture potential based on optimal conditions.*
- *Evaluating the CO_2 needs of greenhouses and urban farming systems to determine potential symbiotic relationships between captured emissions and greenhouse area.*
- *Exploring the amount of food possible to generate in an building integrated greenhouse.*

DESIGN DEVELOPMENT AND EVALUATION

Using the insights from the literature review and data analysis (case studys), the thesis then transitions into a design phase involving the development of architectural design proposals based on the findings. The proposed design is used as a speculative prototype to test a configuration of carbon capture and quantify the potential CO_2 sequestration impact while alos being able to utilise it within a closed loop system. Key outputs include:

- *Selecting an appropriate site and building typology within the urban context.*
- *Integrating carbon capture technologies into the design through the facade.*
- *Conceptual and technical drawings illustrating the proposed design*
- *Calculations to estimate the effectiveness of the system.*

THREE-STEP METHOD

By combining theoretical research, quantitative data, and design experimentation, this methodology aims to bridge the gap between emerging climate technologies and architectural practice. The results of this study contribute to a broader discourse on regenerative urban design and the role of buildings in climate change and how they can be an active contributor to reducing carbon in the atmosphere. Questioning the role architecture and the built enviroment has in combating the climate crisis.

Figure 31: Image by author (2025). Visualisation of the design proposals balconies.

RESEARCH DESIGN

In the theory section of this thesis, we demonstrated that building-integrated carbon capture has the potential to operate on a massive scale under ideal conditions. However, those “perfect world” assumptions, continuous capture rates, optimal weather, and uninterrupted system performance, rarely hold true in practice. To bridge this gap, the present chapter applies the same underlying principles to a real-world context: a mid-rise building project in the Gothenburg area. By anchoring our design in a specific site, we introduce a range of practical constraints such as seasonal variability, equipment performance, and local climatic factors. Factors that were absent from the idealised case study.

Drawing on the capture rates and storage strategies laid out earlier, we first describe the architectural and mechanical integration of our capture units, greenhouses and CO_2 storage tanks within the proposed building envelope. We then trace how each piece of quantitative data from the theory such as daily capture efficiency, greenhouse enrichment demand, and high pressure storage density has been translated into concrete design parameters. In other words the total greenhouse area, expected annual CO_2 uptake (kg CO_2/year) and required storage volume. This results section thus converts theory into measurable outcomes, revealing how much CO_2 the thesis design can realistically capture, how extensive the greenhouse installation must be, and what storage capacity and spatial commitments are required to sustain continuous enrichment.

BUILDING INTEGRATED CARBON CAPTURE

The design proposal is based on the Moisture-Swing absorption technology presented by Lackner (2009) and the Building Integrated Carbon Capture Design by Brian (2017). However, for this design to fit this thesis design proposal some changes have to be made to the design, while still utilizing the same technology. The design proposal presented in chapter one of this thesis has a gap of 7.5 meters between the balconies on two floors. There is a width of 2.5 meters where the filters can be placed. This is where two filters are placed next to each other and leaving space for rails where the cleaning chamber can travel up and down along. Connected to every cleaning chamber will be two tubes. One for fresh water that is used in the cleaning phase and one for the extracted CO_2. These factors with the rails and cleaning chamber the two filters will have the dimensions of 2m x 1m. This way 6 of these filters can be fitted between the two floors.

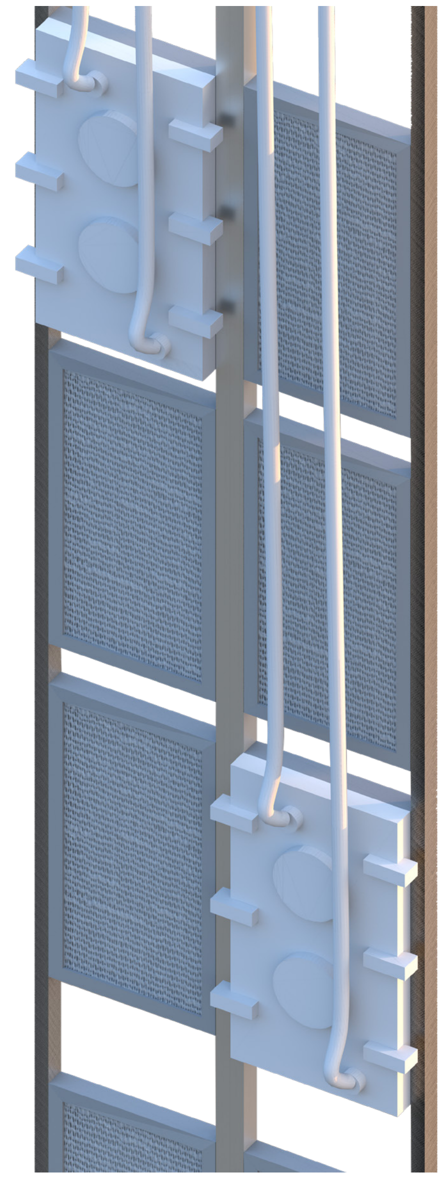


Figure 32: *Image by author (2025). Diagram of the Building integrated carbon capture filters on the design proposal.*

PLACEMENT OF FILTERS

In designing the facade of the building careful consideration had to be made due to the fact that large vertical rail-mounted filters had to be attached to the outer shell of the building. When implementing the filters in the design one way of approaching it is to think of them with a dual function. Where they are not only being another addition on a facade but rather replacing an already existing function from another facade element. With this in mind the placement of the filters plays a crucial role in the design. From conducting a light study on the site, see figure 33-35, the results indicate that the filters will have the biggest impact on solar shading on the west, south and east facade. The south facade sun shading can be solved by implementing balconies on the facade that shade the lower floors since the sun angle is high from this direction. The west and east direction however is being affected from lower solar angles. Meaning here the filters will have the largest impact. Therefore the filters placement have been strategically placed to east and west to function as sun shading in the directions where the sun is low. However, as shown in Figure 35, the balconies and filter modules do not cast significant shade on the outer facade where the greenhouses are located. This intentional design ensures that the greenhouse layer receives the full sun exposure it needs for optimal plant growth.

The design of the overall building also affects the placement of the filters. The footprint of the building is based on one of Heino Engels (2009) structural systems and is inspired by the works of the Austrian based architecture studio, Studio Precht (2025). Then every other floor is rotated 90 degrees to create the variation in the facade design. This opens up for placing the filters between two floors and the rails for the cleaning chambers can continue along the whole facade allowing for a system that can be fed from the roof. This way it remains easily accessible for maintenance.

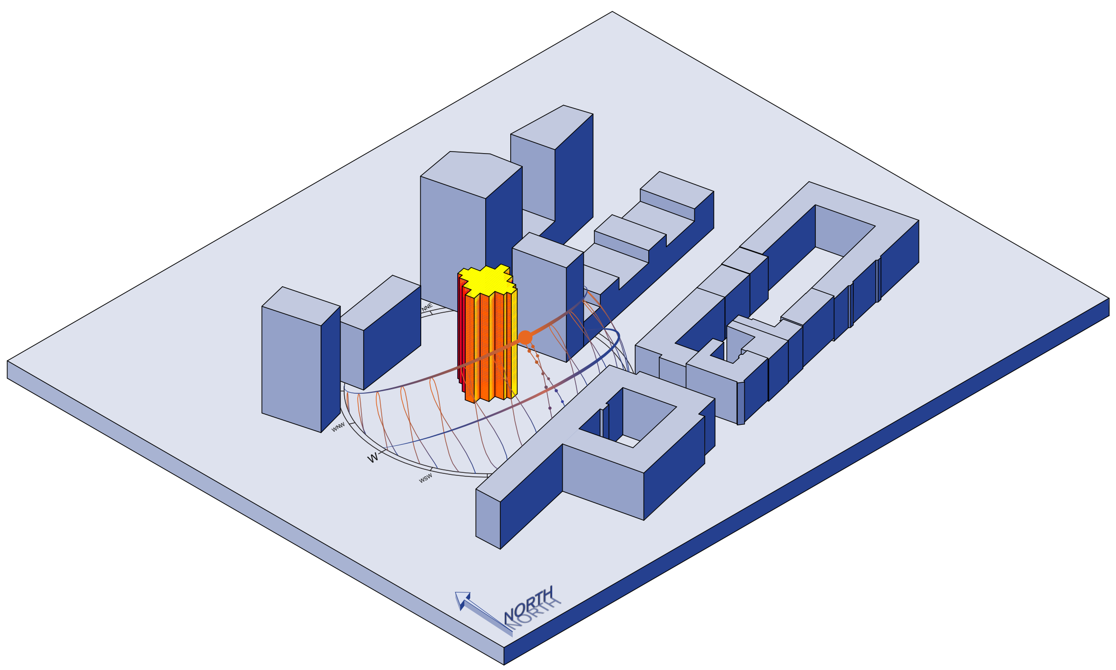


Figure 33: *Image by author (2025). Direct Sun hours on the design proposals inner facade without filters, balcony and greenhouses.*

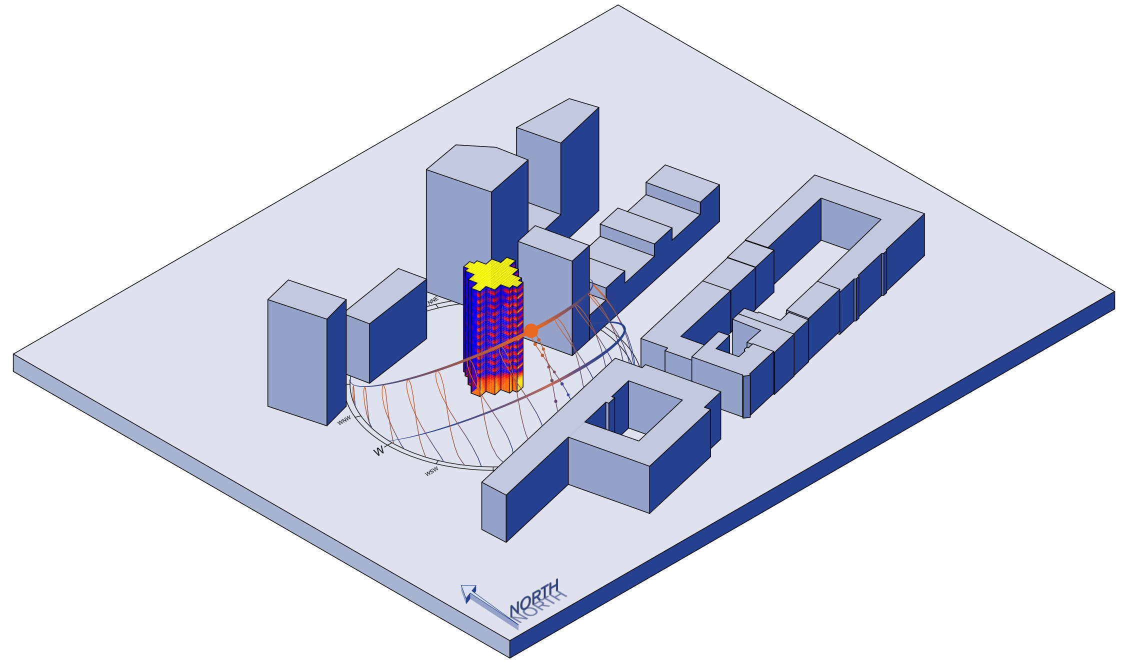


Figure 34: *Image by author (2025). Direct Sun hours on the design proposal with filters and balconies shading the inner facad.*

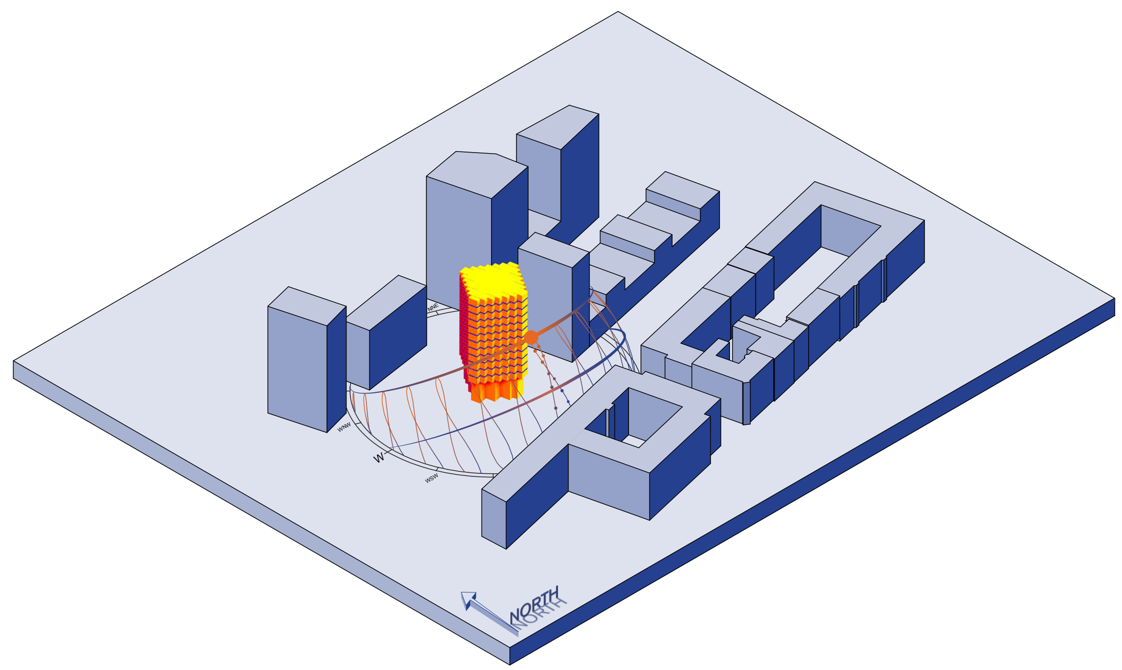


Figure 35: *Image by author (2025). Direct Sun hours on the design proposals outer facade (The greenhouses).*

FILTER CAPACITY

See Appendix 2.1 for full calculations

With the above presented information the design proposal ends up with 48 individual filters with the dimensions of 2m x 1m for two floors resulting in 96m2 of filter area per two floors in the building. The design proposal in this thesis has 12 floors with the filters installed. The amount of floors in the design proposal has been decided with the local context in consideration by matching similar heights to nearby buildings in the same area. This gives the design proposal a total of 576m2 of filter area for the whole building.

From the literature study conducted earlier in the thesis it is known that we can expect roughly 1.9 kg of CO_2 a day per square meter of filter. However the local weather conditions also need to be taken into consideration when calculating the total amount this building would be able to capture. According to Lackner (2009) these filters are heavily dependent on the weather. If it rains they can't dry, and since they capture CO_2 while in a dry state this affects the capture possibility throughout the year. According to Miljöbarometern (2025) there are 165 days per year where there is rain-/snowfall in Sweden. For the sake of this calculation and thesis one can assume the system wouldn't be able to function at all during these 115 days. In reality they would more than likely be able to function for a few cycles per day even though there is rain since there might be a short rainfall for an hour and then the rest of the day be dry. However, for this calculation, the design proposal would then function for 200 days per year and result in 219 172 kg of CO_2 captured per year.

Since there will be extended periods of time, during winter or longer rain periods, where the system might not be able to capture any CO_2, the design proposal requires some sort of storage solution for these periods. Read the "Storage" section.

BUILDING INTEGRATED GREENHOUSE

See Appendix 2.1 for full calculations

This thesis aims to create a system where the captured CO_2 is also utilized within the building itself in an attempt to further explore one of the major hurdles when it comes to carbon capture, what to do with the captured carbon. This thesis aims to achieve this by implementing Building integrated green houses where the captured CO_2 can be used in improving plant growth.

In designing the building the building integrated greenhouses played a large role in the finished design. The design of the building needed to have space around the facade where the greenhouses could have access to direct sun. Therefore the design has an outer layer of greenhouses. However, to make sure that the apartments also get access to an outside area without greenhouses, the 90 degree rotation of the building allows for this to happen in the spots where the floor slabs do not overlap due to the rotation. The Heino Engel footprint design of the building also allows for the greenhouses to be split up in separate greenhouses allowing the owners to use them for different use cases. In the design proposal the two smaller apartments get three greenhouses each with a total square footage of 45.8m^2. While the larger apartments get five greenhouses with a total of 57.8m^2. Giving the building itself 207.2m^2 of greenhouse area per floor with apartments and a total, on all 12 apartment floors, of 2486.5m^2 of greenhouse area. To maximize the agricultural food production that can be produced in the building, the roof of the building is an area that also can be utilized to grow things where larger areas are needed than the smaller greenhouses on the apartment floors. And according to the solar study on figure 33-35 one can also see that the roof is the place on the building that gets the most amount of sun hours per day. Therefore the roof in the design contains a roughly 1200m^2 greenhouse. Combined with the 2486m^2 the total greenhouse area for the building ends up being 3686m^2.

According to Brattsell Bukowski (2015) a high value for the amount of CO_2 used in greenhouses is 10 g/m^2/hour and 160 g/m^2/day, taking into consideration that the photosynthesis only happens for 16 out of the 24 hours in a day. With the design proposals 3686m^2, the yearly CO_2consumption of the proposed building would be 215 262 kg per year. In other words, roughly the same amount captured by the Building integrated Moisture-Swing absorption filters.

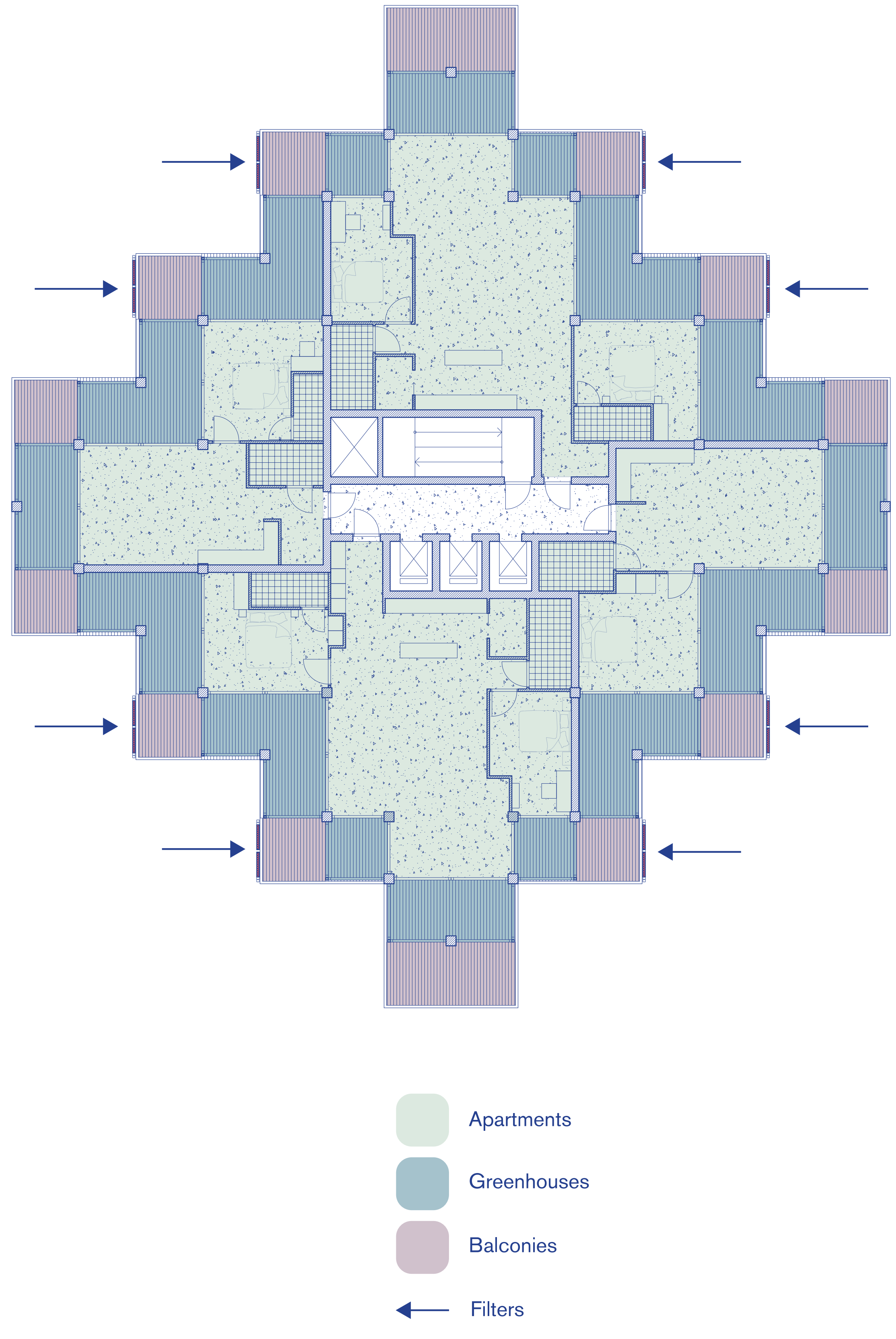


Figure 36: Image by author (2025). Plan diagram.

STORAGE

Since the captured and utilized CO_2 is roughly the same amount, the proposed design can provide all the necessary CO_2. However, since the capture is happening for 200 days of the year and the utilization would need a steady flow every day there needs to be some storage solution. To ensure continuous CO_2 enrichment of the building-integrated greenhouse system, it is necessary to estimate the required volume of carbon dioxide storage for periods when CO_2 cannot be captured or delivered in real-time. The system in this thesis is designed to store a 30-day supply of CO_2 to accommodate for longer periods of rain and cold temperatures.

The demand has been set to 160 grams of CO_2 per square meter per day (Brattsell Bukowski, 2015). With a total greenhouse area of 3,686 m², the system requires:

$$0.16\,kg/m^2/day \times 3686\,m^2 = 589.76\,kg \text{ of } CO_2 \text{ per day}$$

For a 30-day supply, this corresponds to a total storage requirement of:

$$589.76\,kg/day \times 30\,days = 17{,}692.8\,kg \text{ of } CO_2$$

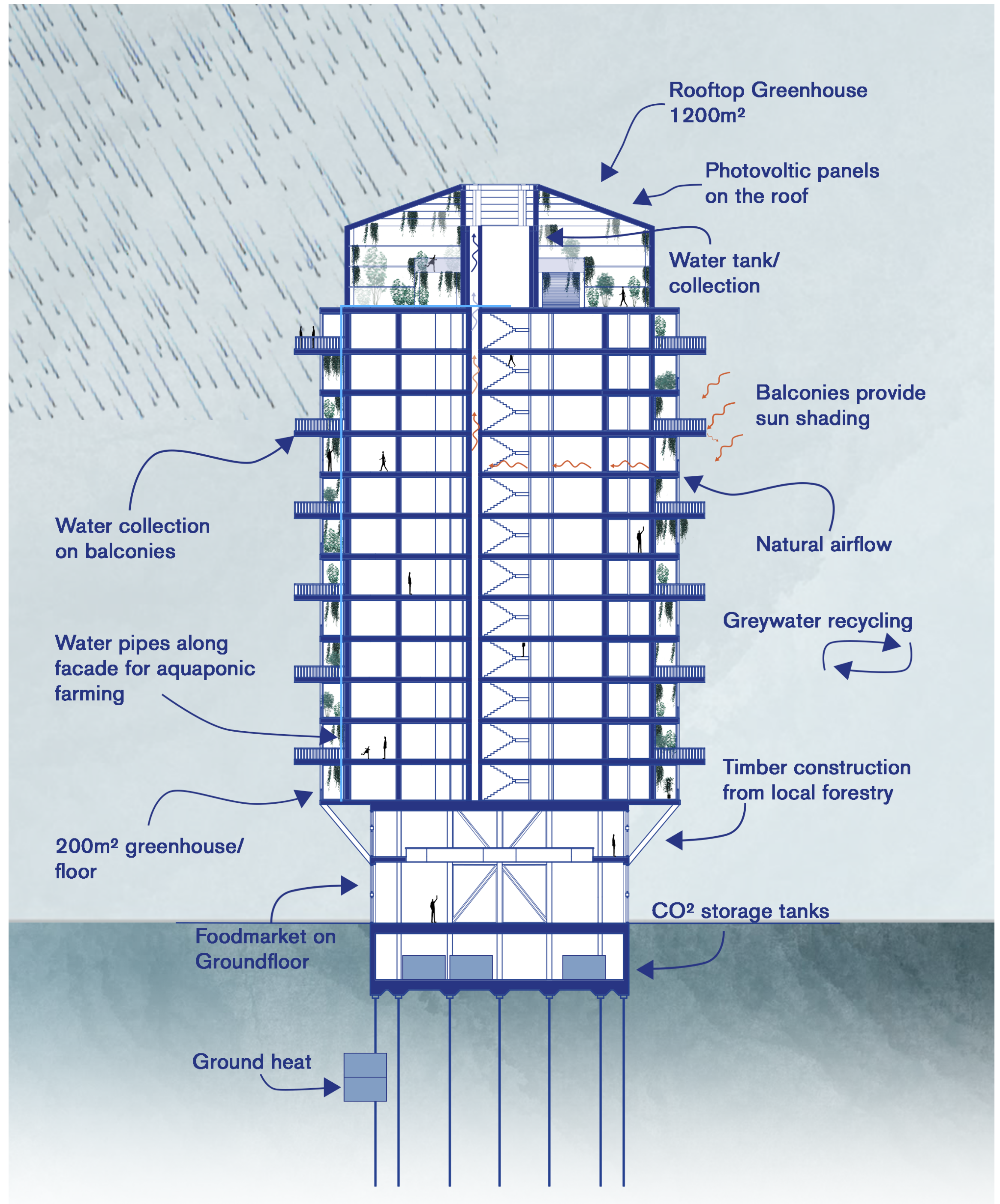
To determine the necessary storage volume, the compressed carbon dioxide energy storage (CCES) system developed by Stanek et al. (2022) was used as a reference. In their system, 8.9 m³ of high-pressure storage (at 44.9 MPa) is capable of storing approximately 8,944 kg of CO_2, yielding a storage density of:

$$8944\,kg / 8.9\,m^3 \approx 1004.9\,kg/m^3$$

Applying this to the storage requirement calculated above, the required tank volume for a 30-day supply is:

$$17{,}692.8\,kg / 1004.9\,kg/m^3 \approx 17.6\,m^3$$

This volume can be distributed across multiple high-pressure tanks, which may be installed in a modular configuration (Stanek et al., 2022). In this thesis design the storage tanks have been placed in the basement of the building (Stanek et al., 2022).



CO_2 captured	-	219,172 kg/year	Number of residents	-	144
CO_2 utilised	-	215,262 kg/year	Total apartment area	-	384m²/floor
CO_2 storage	-	17,6 m³	Total apartment area	-	4608m²
Food produced	-	~129,400 kg/year, enough for 90% of the buildings residents.			

Figure 37: Image by author (2025). Section drawing of design proposal.

FOOD PRODUCTION

Earlier in this thesis BIAs were presented as a promising solution to the challenges of urban food security, resource scarcity, and the environmental footprint of conventional agriculture based on the paper "Building-integrated agriculture: A new approach to food production" by Gould and Caplow (2012). By using the Case-Study presented in the presented paper it is possible to estimate the amount of food that this thesis design proposal could produce. Important to note is that using a Case-Study in this manner does not guarantee it will have the same results. However it provides a valuable estimation of the potential of a system of this kind.

To estimate the productive potential of the proposed system, data from the Gotham Greens rooftop farm in New York City has been used. This system reports an annual yield at 30 tons/year and with a greenhouse area of approximately 1,115 m². This gives a value of 27 kg/m².

The design proposal in this thesis includes a total of 3,686 m² of greenhouse space. Using the reported yield ranges, the estimated total annual food production is:

Estimate (27 kg/m²/year) x 3,686 m²: ~99,500 kg/year

According to Christensson (1986), adding CO_2 to greenhouses can enhance plant growth and that a CO_2 concentration of 1000-1300 ppm can increase yields by 30%, especially in leafy greens and fruiting crops like tomatoes and cucumbers. Applying this yield boost to the estimate results in an annual production of approximately 129,400 kg/year.

Scenario	**Yield (kg/m²/year)**	**Total Yield (kg/year)**
Baseline	*27*	*~99,500*
CO_2 Enriched (+30%)	*35.1*	*~129,400*

These figures, while still being very loose estimations, demonstrate the scalability and environmental advantage of combining BIA with CO_2 capture. In addition to reducing the building's carbon footprint, the greenhouse actively utilizes captured CO_2 to boost biomass production, offering a closed-loop system where architecture and agriculture operate symbiotically.

Figure 38: *Image by author (2025). Rooftop greenhouse for food production.*

The design proposal in this thesis stands as a case study to further explore the role of a building in our urban environment. By implementing new technologies this thesis hopes to question the environmental impact of the built environment. Therefore it is also interesting to explore the impact of these technologies on a larger time frame than only one year. In Sweden and the rest of Europe a building's expected lifespan is at least 50 years and many argue that it should be at least 100 (Altinget, 2023). The building proposed on Första Långgatan has an estimated capture potential of 219,172 kgCO_2/year. Meaning during a 50 year long lifespan the building could capture 10,958,600 kg or almost 11 000 tons. Or over 100 years, 21,917,200 kg or almost 22 000 tons.

A building next to the selected site for this thesis is an office building, Habitat 7, by NCC and designed by Krook & Tjäder Architects. This building is being marketed as one that was designed to reduce climate impact during the construction phase. According to the projects website (Habitat 7, 2024) was the CO_2 emissions for the production phase of the 8,000m² office building 230 kg CO_2e/m² BTA while a reference value for a "normal" office building in Sweden is 395 kg CO_2e/m² BTA. 230kg/m² on 8,000m² would result in 1,840,000kg of CO_2. If these same numbers would be applied to this thesis building design with a BTA of roughly 9,900m² it would have CO_2 emissions of 2,277,000kg during the production phase, if using the same numbers as Habitat 7. With the higher reference value it would be 3,910,500 kg. Comparing this number to the potential CO_2 captured from the thesis design. One can see that the building could capture 2.8X the CO_2 released during the production phase using the reference value.

However, It is also important to mention that the above calculations are very rough estimations that only consider a few number of factors. For example, the reference values used are for offices and doesn't take into consideration the whole lifecycle of the building but rather only the production phase. Applying the reference value to this thesis building BTA without accounting for the environmental impact of the proposed systems also affects the results. The proposed design of this thesis uses many high technology systems including the carbon capture system itself, the building integrated greenhouses, Storage solutions for the captured CO_2 and many more. Therefore the value presented above should not be seen as a final or definitive assessment of the building's environmental impact. A more comprehensive evaluation would require accounting for the entire lifecycle of the building, including the operation, maintenance, and potential end-of-life stages. Moreover, the performance of the proposed systems, such as the carbon capture technology and integrated greenhouses, would need to be assessed in real-world scenarios to determine their actual effectiveness in reducing carbon emissions over time. Additionally, the energy use and resource consumption associated with maintaining and operating these high-tech systems must be carefully considered, as they may offset some of the anticipated environmental benefits. As such, further studies, including detailed simulations and a full environmental life cycle analysis, would be necessary to refine the results and provide a more accurate understanding of the building's overall sustainability.

The proposed Gothenburg mid-rise design integrates 288 moisture-swing CO_2 capture modules, each 2 m × 1 m. The modules are spread across 12 floors, yielding a total active filter area of 576 m². Operating 200 days per year (allowing for 165 rainy/snowy days, Miljöbarometern 2025), and capturing at 1.9 kg CO_2/m²/day (Brattsell & Bukowski, 2015), the facade system captures approximately 219 000 kg CO_2 annually. To bridge seasonal gaps, a 30-day tank buffer is provided by modular high-pressure vessels (44.9 MPa), requiring 17.6 m³ of storage at ~1 004.9 kg/m³ (Stanek et al., 2022).

The building also has building-integrated greenhouses that totals 3 686 m² (2 486 m² across apartment floors + 1 200 m² rooftop). Enriched at 160 g CO_2/m²/day (Brattsell & Bukowski, 2015), it consumes roughly 215 000 kg CO_2/year, closely matching capture rates and confirming a balanced capture-utilization loop. Drawing on Gotham Greens' yield benchmark (27 kg/m²/year; Gould & Caplow, 2012) and a 30 % CO_2-enrichment boost (Christensson, 1986), annual food production is estimated at ~99 500 kg in baseline mode—rising to ~129 400 kg with the CO_2 enrichment.

Over a 50-year lifespan, the system could capture ~11 000 000 kg CO_2; over 100 years, ~22 000 000 kg. By comparison, embodied emissions for a similarly sized office building (9 900 m² BTA) range from 2.28 × 10⁶ kg (Habitat 7, 2024) to 3.91 × 10⁶ kg CO_2 in production. Thus, the design can sequester roughly 2.8 times its own production-phase emissions over its first half-century. Meaning that implementing a system like this could potentially make a building carbon negative.

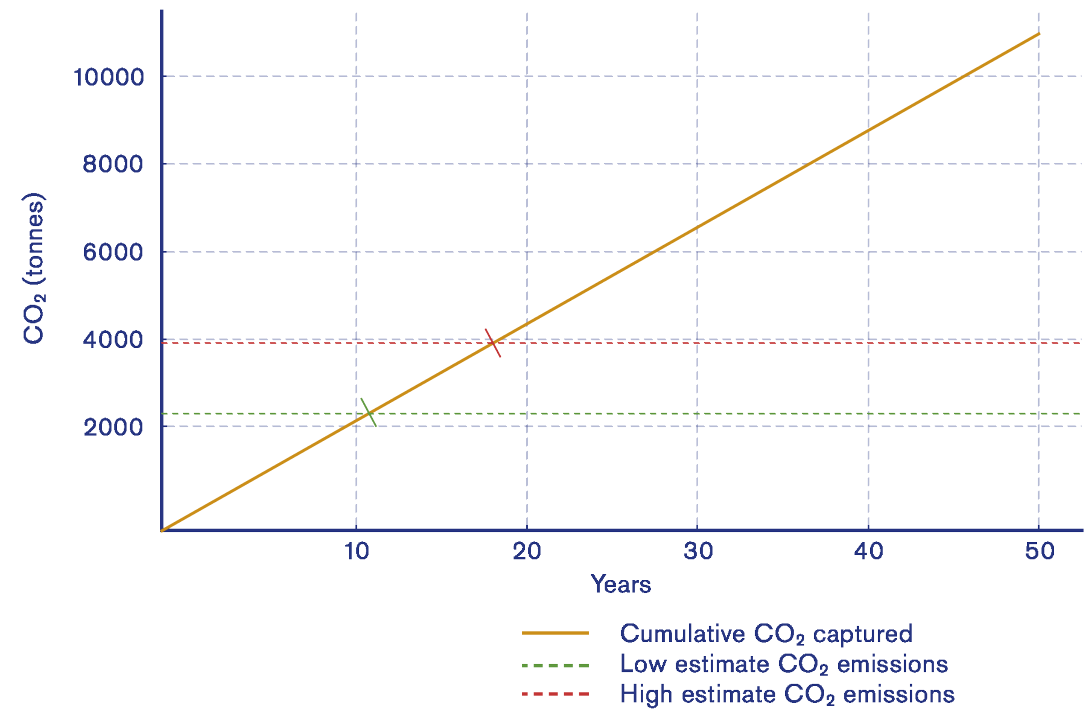


Figure 39: *Image by author (2025). Diagram showcasing the captured CO_2 over 50 years compared to the reference value for CO_2 emissions from a buildings production phase.*

DISCUSSION

Figure 40: Image by author (2024). Karlatornet in Gothenburg

CARBON CAPTURE REALITIES

The complexity of integrating carbon capture technologies into the built environment is both a challenge and an opportunity. The feasibility of such systems, while promising, is still limited by several practical factors. For instance, as discussed earlier in this thesis, the efficiency of carbon capture, more specifically Moisture-Swing absorption carbon capture, depends heavily on external conditions such as weather, with rain and low temperatures impacting the system's performance. This unpredictability adds a layer of uncertainty when evaluating the long-term effectiveness of these technologies in urban settings. The cost and energy needed for these technologies to work are also large concerns when it comes to implementing it on larger scales.

Additionally, the storage and utilisation of captured CO_2 remains a significant hurdle. While the captured carbon could be repurposed within the building, such as for use in greenhouse operations, the scale of CO_2 capture far exceeds the immediate local demand as showcased in this thesis. The building design proposed in this thesis has the potential to support a significantly higher number of carbon capture filters than those included in the current design. In theory, the number of filters could easily be doubled or tripled without major changes. However, increasing the number of filters would result in capturing far more CO_2 than could be utilised locally. This raises important questions about how to manage the excess CO_2 without relying on expensive, large-scale infrastructure for storage and transport. While a closed-loop system, where the building captures and repurposes the CO_2 on-site, offers a potential solution, the scalability of such systems remains uncertain.

While greenhouses offer clear benefits, such as localized food production and improved wellbeing for residents, they also occupy valuable space that could otherwise be allocated for housing, particularly in dense urban environments. This spatial trade-off directly influences the economic feasibility of such buildings, affecting both construction costs and apartment pricing. As a result, although greenhouses provide a meaningful use for captured CO_2, their implementation raises important questions about the scalability of the proposed system. These limitations underscore the need for further research into alternative or complementary methods for utilizing captured CO_2 within architectural and urban contexts.

The most common solution for handling captured CO_2 continues to be deep underground storage. However, even this method remains costly and is still relatively untested, with many unknowns regarding its long-term consequences. For small-scale carbon capture systems, such as those integrated into buildings, underground storage doesn't seem like a viable option. The captured CO_2 would need to be transported to remote locations, which introduces logistical and financial challenges that make this approach impractical for buildings. For building integrated carbon capture systems to make sense I would argue that there would need to be a higher demand on CO_2. If the product could be used in more areas the value of the gas would increase and the utilisation would be easier to handle. Therefore further research on potential use cases and development of products that use CO_2 could play a massive role in the further development of carbon capture as a whole and within the built environment.

Furthermore, while the thesis explores the potential for carbon capture to make buildings climate-positive, it is important to acknowledge that this is not a simple process. A more comprehensive life-cycle analysis (LCA) is needed to understand the full environmental impact of these systems. This includes not only the energy and resources required to manufacture and maintain the technology but also the emissions associated with the building's construction and operation. The idea of a building as a carbon sink is undoubtedly appealing, but achieving this in practice will require further research and development.

In conclusion, while the findings of this thesis indicate a promising future for buildings as carbon sinks, they also highlight the significant challenges and uncertainties that must be addressed. The role of architecture in climate mitigation is undoubtedly evolving, and it is crucial to continue pushing the boundaries of what is possible. As architects, we have the opportunity, and responsibility, to challenge conventional boundaries and reimagine the role of the built environment in addressing the climate crisis.

CLOSING WORDS

This thesis has explored how architecture can actively contribute to reversing climate change by integrating carbon capture technologies into building envelopes. Through a design-driven investigation based on Direct Air Capture (DAC) and Moisture-Swing Absorption (MSA), the work reimagines buildings not only as energy consumers but as carbon sinks where buildings function as trees within an "urban forest." The proposal demonstrates that, under optimal conditions, a mid-rise building could capture more CO_2 during its lifetime than is emitted during its construction, thereby challenging the current definitions of sustainability. It also shows that captured CO_2 can be repurposed in building-integrated greenhouses, creating a closed-loop system that supports local food production, biodiversity, and climate resilience. However, the results must be seen as a conceptual framework rather than a ready-made solution.

From a societal and ethical perspective, the project raises critical questions. Who will benefit from such technologies? Could access to climate-positive architecture be limited to wealthier urban districts, thereby exacerbating environmental injustice? And what are the long-term implications of embedding mechanical systems into the urban fabric? These questions suggest that while technological optimism is important, it must be paired with an equally robust focus on equity, governance, and systemic change.

When researching for this thesis there is one thing that has become very clear to me. Carbon capture is a very polarising subject. In most discussions there are two strong opposite sides that end up in heated discussions. In general this is a good thing. It indicates that there is a deep desire for work around combating climate change. The strongest voices in the debate always seem to be the ones that either are strongly for or strongly against it. The interesting part however is that even the strongest voices against the technology share the same goals as the ones who argue for it. They all want to combat climate change. Those critical of carbon capture often argue that the technology could divert attention from more immediate, necessary measures such as reducing emissions at the source or implementing more natural solutions. On the other hand, proponents see carbon capture as an essential tool to help us meet global carbon reduction targets, particularly in hard-to-decarbonize sectors. Despite these differences in approach, both sides fundamentally want to ensure a sustainable future, which points to a collective awareness of the urgent need for action. In many ways, the debate itself underscores the complexity of the problem we're facing—climate change is multifaceted, and finding solutions requires diverse approaches, collaboration, and even a degree of compromise.

Throughout the process of conducting this thesis, I have worked to clarify my own thoughts on the issue of carbon capture. The strongest point raised by those opposed to carbon capture is that it could divert attention from the more critical task of reducing emissions at the source. There is also concern that the technology could be used by fossil-fuel heavy industries as an excuse to continue business as usual, without making the necessary shifts toward sustainability. I fully agree with this concern, and it is something I find particularly important to address. Humanities most important task right now most likely is to reduce the amount of carbon being released.

However, as discussed earlier in this thesis, we have already surpassed a critical threshold in terms of the amount of carbon released into the atmosphere. Even if every industry were to achieve net-zero carbon emissions today, that would not be enough. The threshold has been crossed, and we now also face the need to actively remove CO_2 from the air. While it is true that carbon capture isn't cost-effective or energy-efficient enough to address all the emissions we continue to release, as this thesis has shown, and the technology may not evolve quickly enough to be the sole solution, I believe that should not diminish its importance.

The goal of this thesis has never been to downplay the significance of decarbonization. There is the very real risk of greenwashing, where industries may use carbon capture as a way to mask their emissions. But despite this concern, the need for carbon capture technology remains. It is one tool in a broader strategy to tackle the climate crisis, and its role cannot be ignored simply because other issues also require urgent attention. Carbon capture is not the solution. But it may be part of it.

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Figure 41: Image by author (2022). Eriksberg, Gothenburg.

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APPENDIX

Figure 42: Image by author (2024). Karlatornet, Gothenburg.

APPENDIX

1.1 CO_2 Capture Efficiency of Filters

This section outlines how much CO_2 a 1 m² filter panel with 10 cm thickness can capture per cycle and per day. The calculation uses assumptions and data based on Klaus Lackner's research (2009), applying the surface-area-based capture method.

Assumptions and Constants:

Parameter	**Value**	**Source**
Filter face area	*1.0 m²*	*Assumed*
Filter thickness	*0.1 m*	*Assumed*
Resin volume occupancy	10%	*Lackner (2009)*
Resin density	1,000 kg/m³	*Lackner (2009)*
Specific surface area of resin	4 m²/kg	*Lackner (2009)*
CO_2 uptake rate	25 µmol/m²/s	*Lackner (2009)*
CO_2 molar mass	44 g/mol	*Lackner (2009)*
Capture time per cycle	45 minutes (2,700 seconds)	*Lackner (2009)*
Cycles per day	16	*Calculated*
Total active capture time per day	43,200 seconds	*Calculated*

Step-by-Step Calculations:

1. Volume of the filter panel: Volume = 1.0 m² × 0.1 m = 0.1 m³
2. Resin volume and resin mass: Resin volume = 0.1 m³ × 0.10 = 0.01 m³, Resin mass = 0.01 m³ × 1,000 kg/m³ = 10 kg
3. Reactive surface area: Surface area = 10 kg × 4 m²/kg = 40 m²
4. CO_2 uptake per cycle: 40 m² × 25 µmol/m²/s = 1,000 µmol/s = 0.001 mol/s
   CO_2 absorbed during one capture phase (2,700 seconds): 0.001 mol/s × 2,700 s = 2.7 mol × 44 g/mol = 118.8 g
5. CO_2 uptake per day: 0.001 mol/s × 43,200 s = 43.2 mol × 44 g/mol = 1,900.8 g = 1.9008 kg

Final Results:

Per cycle - 118.8 g.
Per day - 1.9 kg.

1.2 CO_2 Capture on Case Study

This section calculates the CO_2 capture potential of a fictional 30 m × 30 m building with filters installed on all four facades, using double-sided filters based on assumptions and data from Lackner (2009) and previous appendix calculations.

Assumptions and Constants:

Parameter	**Value**	**Source**
Building footprint	*30 m × 30 m*	*Based on case study design*
Floor height	*4m*	*Based on case study design*
Filter dimensions	3.6 m × 0.8 m	*Based on case study design*
Filter thickness	10 cm (0.1 m)	*Based on case study design*
Filters per facade	16	*Based on case study design*
Number of facades with filters	4	*Based on case study design*
Filters are doublesided	Yes	*Based on case study design*
CO_2 captured per m² per day	1.9008 kg/m²/day	*Lackner (2009)*

Step-by-Step Calculations:

1. Area per filter: 3.6 m × 0.8 m = 2.88 m²
2. Number of filters per floor: 16 filters × 4 facades = 64 filters
   Double-sided: 64 × 2 = 128 filter surfaces
3. Total filter face area per floor: 2.88 m² × 128 = 368.64 m²
4. CO_2 capture per floor per day: 368.64 m² × 1.9008 kg/m²/day = 700.88 kg/day

Final Results:

Filter face area per filter - 2.88 m²
Total number of filter surfaces - 128
Total filter face area per floor - 368.64 m²
CO_2 capture per m² per day - 1.9008 kg
Total CO_2 capture per floor/day - ~700.9 kg of CO_2

1.3 CO_2 Capture per Year - Case Study

Following the previous calculation, each floor with the proposed filter setup captures 700.9 kg of CO_2 per day, assuming continuous operation 365 days per year.

Step-by-Step Calculations:

1. Annual CO_2 capture per floor:
   700.9 kg/day × 365 days = 255,828.5 kg/year = 255.83 tonnes/year

2. Annual CO_2 capture per building (10 floors):
   255.83 tonnes/floor/year × 10 floors = 2,558.3 tonnes of CO_2 per building per year

3. Number of new apartment buildings (SCB and Byggföretagen, 2024):
   22,400 buildings

4. Assumptions for national scaling:
   50% of buildings equipped with the technology - 11,200 buildings

5. Total CO_2 capture potential per year:
   11,200 buildings × 2,558.3 tonnes/building/year = 28.65 million tonnes/year

Final Results:

CO_2 capture per floor per year	-	~255.83 tonnes
CO_2 capture per 10-floor building/year	-	~2,558.3 tonnes
Number of new buildings equipped	-	~11,200 buildings
Total CO_2 capture potential per year	-	~28.65 million tonnes

Notes:
- Calculations are based on ideal conditions.
- Slight discrepancies due to rounding may occur.
- Potentially offsets ~66% of Sweden's annual CO_2 emissions.

1.4 Greenhouse Utilisation Calculations

This section outlines the relationship between CO_2 captured from the case study building and the greenhouse area that could be supplied with CO_2 to enhance plant growth. Calculations are based on assumptions from Brattsell Bukowski (2015) and Lackner (2009).

CO_2 Consumption Assumptions for Greenhouses:

Scenario	**CO_2 Consumption (g/m²/hour)**	**CO_2 Consumption (g/m²/day)**
Low consumption	*4*	*64*
Medium consumption	*7.82*	*125.12*
High consumption	10	*160*

Notes:
- High Consumption (160 g/m²/day) is used for this case study, assuming intensive food production crops.

Step-by-Step Calculations:

1. CO_2 Capture per Filter:
   - Filter area: 2.88 m²
   - CO_2 captured: 2.88 m² × 1.9008 kg/m²/day = 5.475 kg/day

2. Greenhouse Area Supplied per Filter:
   - 1 m² greenhouse requires 0.16 kg/day
   - 5.475 kg/day ÷ 0.16 kg/m²/day = 34.22 m²
   - Double-sided filter: 34.22 × 2 = 68.44 m²

3. CO_2 Capture per Floor:
   - Total capture: 368.64 m² × 1.9008 kg/m²/day = 700.88 kg/day

4. Greenhouse Area Supplied per Floor:
   - 700.88 kg/day ÷ 0.16 kg/m²/day = 4,380.5 m²

5. Floors of Greenhouse Supported:
   - Footprint: 900 m²/floor (30 m × 30 m)
   - 4,380.5 m² ÷ 900 m²/floor ≈ 4.87 floors

6. Scaling to a 15-Story Building:
   - 700.88 kg/day × 15 = 10,513.2 kg/day
   - 10,513.2 kg/day ÷ 0.16 kg/m²/day = 65,707.5 m²
   - 65,707.5 m² ÷ 900 m²/floor ≈ 73 floors

Final Results:

CO_2 captured per double-sided filter	-	~5.475 kg/day
Greenhouse area supplied per filter	-	~68 m²
CO_2 captured per building floor	-	~700.88 kg/day
Greenhouse area supplied per floor	-	~4,380 m²
Greenhouse floors supplied per floor	-	~4.87 floors
CO_2 captured by 15-floor building	-	~10,513 kg/day
Greenhouse area supplied by 15-floor building	-	~65,700 m²
Greenhouse floors supplied by 15-floor building	-	~73 floors

2.1 CO_2 Capture and Utilisation in the Proposed Building Design

This section details the calculations for the potential CO_2 capture and utilization based on the proposed building design developed for a local context in Gothenburg. Calculations are based on Moisture-Swing Absorption technology (Lackner, 2009) and data from greenhouse CO_2 utilization studies (Brattsell Bukowski, 2015).

Assumptions and Constants:

Parameter	**Value**	**Source**
Building footprint	*Local Gothenburg context*	*Proposed design*
Floor height	*4 m*	*Proposed design*
Number of floors with filters	12 floors	*Proposed design*
Filters per two floors	48 filters	*Proposed design*
Filter dimensions	$2\ m \times 1\ m = 2\ m^2$	*Proposed design*
Filter thickness	10 cm (0.1 m)	*Proposed design*
Total filter area per two floors	$96\ m^2$	*48 filters × 2 m²*
Total filter area for the building	$576\ m^2$	*12 floors (filters installed)*
CO_2 captured per m²/day	$1.9008\ kg/m^2/day$	*Lackner (2009)*

Step-by-Step Calculations:

1. Daily CO_2 Capture for the Building:
   576 m² × 1.9008 kg/m²/day = 1,095.86 kg/day

2. Adjusted for Local Weather Conditions:
   200 operational days per year assumed.
   1,095.86 kg/day × 200 days = 219,172 kg/year (219.17 tonnes/year)

Greenhouse Utilisation Assumptions:

Parameter	**Value**	**Source**
Greenhouse area per apartment floor	*207.2 m²*	*Proposed design*
Number of apartment floors	*12*	*Proposed design*
Roof greenhouse area	$\sim 1{,}200\ m^2$	*Proposed design*
Total greenhouse area	$3{,}686\ m^2$	*Proposed design*
CO_2 consumption in greenhouses	$160\ g/m^2/day$ ($0.16\ kg/m^2/day$)	*Brattsell Bukowski (2015)*
Photosynthesis hours per day	16 hours	*Brattsell Bukowski (2015)*

Step-by-Step Calculations:

1. Daily CO_2 Demand for Greenhouse:
   3,686 m² × 0.16 kg/m²/day = 589.76 kg/day

2. Annual CO_2 Demand for Greenhouse:
   589.76 kg/day × 365 days = 215,262.4 kg/year (~215.26 tonnes/year)

Final Results:

Daily CO_2 capture - ~1,095.9 kg
Annual CO_2 captured (200 days) - ~219,172 kg
Daily greenhouse CO_2 demand - ~589.76 kg
Annual greenhouse CO_2 demand - ~215,262 kg

Storage Requirement Calculations:

A 30-day storage buffer is proposed to cover rainy periods.

1. Daily CO_2 needed for storage: 589.76 kg/day
2. 30-Day Storage Requirement: 589.76 kg/day × 30 = 17,692.8 kg
3. Storage Volume:
   Reference: Stanek et al. (2022) - 1,004.9 kg/m³ storage density.
   Volume needed: 17,692.8 kg ÷ 1,004.9 kg/m³ ≈ 17.6 m³

Storage Summary:

30-day CO_2 requirement	-	~17,692.8 kg
Storage density (Stanek et al.)	-	~1,004.9 kg/m³
Required storage volume	-	~17.6 m³

Notes:

- This calculation assumes ideal daily capture during dry weather and continuous greenhouse operation.

- A 30-day storage buffer is a conservative estimate to ensure steady CO_2 supply.

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