THE UPSCALING OF SUSTAINABLE TECHNOLOGIES

DIRECT AIR CAPTURE

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Abstract

This thesis aims to detect and examine factors that promote the upscaling of direct air capture (DAC) from the vantage point of Strategic Niche Management (SNM). SNM is a theoretical social science approach that helps to identify the challenges and opportunities of the diffusion of sustainable technologies like DAC. The thesis pays special attention to the role of government, particularly the European Union (EU), in the upscaling process. Therefore, it addresses the research questions: What factors, predicted by SNM, influence the upscaling of DAC technologies? Additionally, what role does government play in these factors? These questions are answered using a literature review and a case study based on data collected through a multi-media approach. Findings suggest that niche operation is the predominant factor in promoting the upscaling of DAC. The nurturing and preservation of this niche is, however, dependent on the three subfactors: articulation of expectations, learning, and social networking. Findings also demonstrate precedence among these internal niche processes, highlighting the crucial role of expectations at the current stage in the innovation process followed by social networking and learning. Moreover, it is indicated that the EU has the capacity to influence the upscaling of DAC via the regulatory environment.

Abbreviations

CDR	Carbon Dioxide Removal
CE	Carbon Engineering
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DG	Directorate-General
ETS	Emission Trading System
EU	European Union
GT	Global Thermostat
IPCC	Intergovernmental Panel on Climate Change
NETs	Negative Emission Technology
R&D	Research and Development
SNM	Strategic Niche Management

List of Figures and Tables[1]

[1] Figures and tables without sources have been specifically created for this thesis. Sources can be found attached to the particular figure or table in the thesis.

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1. Introduction

"I am here to say our house is on fire" (WEF, 2019). This opening line by Greta Thunberg at her speech at the World Economic Forum in 2019 sums up our current state in the climate crisis. To extinguish this fire, there is an urgency for climate change mitigation. An expert, scientific and policymaking panel commissioned by the United Nations recommends that we "[L]imit global warming to well below 2, preferably 1.5 degrees Celsius, compared to pre-industrial levels." (United Nations, n.d.). To meet this goal, formulated within the Paris Agreement as well as mentioned by reports such as the Intergovernmental Panel on Climate Change (IPCC), the European Union (EU) along with a multiplicity of nation-states have committed to reaching 'net-zero' by 2050 (European Commission, n.d.-a). According to the IPCC Glossary, "[n]et zero emissions are achieved when *anthropogenic emissions* of *greenhouse gases* to the *atmosphere* are balanced by *anthropogenic removals* over a specified period." (IPCC-a, 2018). Carbon dioxide (CO_2) is one of these greenhouse gases and counts as the most important in the context of climate change as it affects global warming through human activities the most (EPA, 2020). Thus, net zero in praxis, is directly tied to the amount of CO_2 emissions emitted into the atmosphere. This is kept track of in the form of a "carbon budget" (Minx et al., 2018, p. 2), which is dependent on the formulated goal, for example, the 1.5°C goal (Minx et al., 2018). There are three paths to help balance this carbon budget: avoiding emissions, e.g., through building a wind energy plant instead of a coal plant; reducing emissions, by replacing coal plants through renewable energy; and removing emissions (Pilpola et al., 2019).

This thesis deals with the last path, which is facilitated through the development and usage of "negative emission technologies" (NETs) (Beuttler et al., 2019, p. 1). One group of these NETs are direct air capture (DAC) technologies which "refers to a range of technological solutions that are able to extract CO_2 from ambient air at any location on the planet" (Beuttler et al., 2019, p. 2). This technology promises the possibility of offsetting CO_2 emission, meaning providing an opportunity to remove CO_2 from the past and, in theory, being able to go back to pre-industrial levels (Yousefi-Sahzabi et al., 2014). However, while it is a highly promising technology for climate change mitigation, DAC's potential is mainly limited by upscaling and costs associated with the technology (Fuss et al., 2018). Currently, DAC has primarily received attention from several entrepreneurial firms (Nemet et al., 2018).
In contrast, DAC has not received much attention from EU and national policymakers (Rosell, 2019). As a result, the development of DAC in EU member states has been slow compared to other countries, like the USA, Canada, and Switzerland (Lebling et al., 2021). The employment of DAC has been mostly limited to demonstration sites and has not been successfully upscaled (Fuss et al., 2018; Nemet et al., 2018). This results in the following research question:

What factors, predicted by Strategic Niche Management (SNM), influence the upscaling of direct air capture technologies? Additionally, what role does government play in these factors?

Answering this question is socially relevant because, as aforementioned, DAC plays an essential role in meeting climate targets set in the Paris Agreement, which the EU has signed and ratified (European Commission, n.d.-d). This thesis focuses on the relationship between SNM and upscaling and sheds light on how these different theoretical assumptions can complement each other in the context of DAC. In praxis, this report evaluates the outcomes of an SNM analysis, providing a special focus on upscaling. Moreover, special attention is given to the role of government.

This descriptive research question will be answered by breaking it down into three interrelated sub-questions.

Sub-question 1(SQ1): What is the role of direct air capture in meeting long-term climate change mitigation goals?

Sub-question 2(SQ2): What factors, expected by Strategic Niche Management, influence the upscaling of innovations like the direct air capture technologies produced by Climeworks?

Sub-question 3(SQ3): What is the EU's role in promoting the upscaling of innovations/ addressing the needs formulated by the Strategic Niche Management analysis?

2. Theory

DAC is an important innovation that can help countries and regions pursue net zero carbon emissions. However, to be effective, an innovation must scale up at an accelerating rate. Upscaling is part of the innovation process. In this context, it can be defined as " 'aggregating' the niche technologies towards broader and more widespread application in society or, phrased differently, to accelerate the process from the initial 'niche' to a large scale transformation that replaces dominant (unsustainable) practices" (Coenen et al., 2011). This thesis's goal is to examine **if and how factors predicted by Strategic Niche Management can explain the upscaling of DAC**. Therefore, this section describes the upscaling process and discusses the factors which the SNM expects will facilitate or hinder it (SQ2), paying particular attention to the role government, like the EU, can play in this process (SQ3).

2.1. Upscaling

Upscaling ('scale up') is a critical stage in the innovation process, which can be split into processes and developments on the demand and supply side (*Figure 1*) (Nemet et al., 2018).

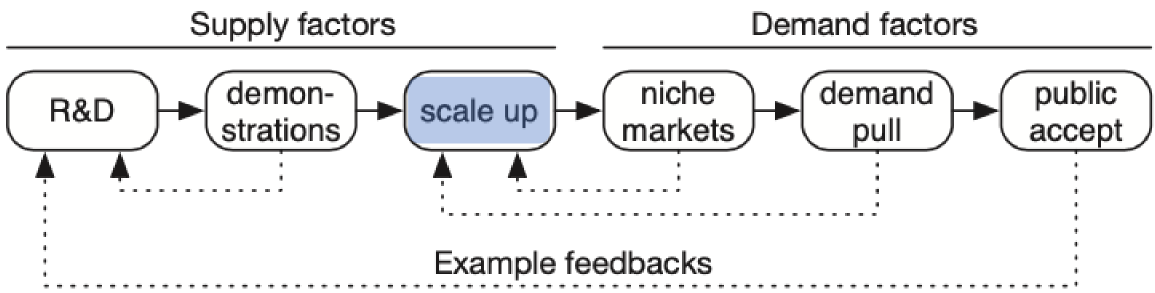

Figure 1: "Stages of innovation." (Nemet et al., 2018, p. 5) [color added for emphasis]

Upscaling happens through the growing, accumulation, and broadening of local projects. These processes increase the potential for the niche to enter the market and transition into the regime (Naber et al., 2017; Ruggiero et al., 2018). In the context of NETs, upscaling is seen as a more practical concept, namely "the increase in unit size […] to take advantage of scale economies, i.e. that costs rise at less than the rise in output" (Nemet et al., 2018, p. 3). Besides the **increase in unit size,** the **increase in mass manufacturing of units** is relevant (Nemet et al., 2018). The difference between these concepts can be clarified when looking at the upscaling process of a DAC firm that upscaled by *stacking several DAC machines together* but has not upscaled in the sense of *mass-producing their DAC machines*, as they are still hand-made (GN, 2021). Hence, upscaling is dependent on both of these concepts, which will be used throughout the report to examine factors that affect upscaling in the context of DAC.

The literature identifies various barriers to upscaling as the "process of increasing the unit size of technologies to commercially-viable scales is non-trivial and can take considerable time" (Nemet et al., 2018, p. 7). They include technological readiness (e.g., effectiveness, quality), its costs, risks, and side effects (e.g., environmental), its integration in the present regime, and in general, the support by actors (e.g., public, government). Several theoretical approaches on how these barriers can be overcome have been put forward in the literature (Nemet et al., 2018). Among them is Strategic Niche Management.

2.2. Strategic Niche Management

Strategic Niche Management (SNM) revolves around the observation that sustainable technologies often do not make it past the development stage and fail to enter the market. It can be defined as the "creation, development and controlled break-down of test-beds (experiments, demonstration projects) for promising new technologies and concepts with the aim of learning about the desirability (for example in terms of sustainability) and enhancing the rate of diffusion of the new technology." (Weber et al., 1999, p. 9). SNM's initial purpose is to provide a tool to identify chances and challenges for introducing sustainable technology into society and stimulate development (van Est & Brom, 2012). With that, it opens the "black box of technology" (Verbong et al., 2008, p. 557). SNM offers tools to help explain how innovations that are not easily diffused, like DAC, can develop. The approach provides a framework for understanding the developments and progress of innovation and formulates factors or recommendations about what processes need to be escalated to enter the market. While being a social science approach, SNM has only been exploited to a limited extent in social and policy science.

2.2.1. Niche as Focus

Niches are an essential concept within SNM and are a central factor in promoting upscaling. A niche in the context of SNM can be defined as "locus of radical innovations" or "'protected spaces' such as R&D [Research and Development] laboratories, subsidised demonstration projects, or small market niches where users have special demands and are willing to support emerging innovations" (Geels, 2012, p. 472). Within a niche, niche actors work on innovations which differ from the existing regime, the "locus of established practices and associated rules" (Geels, 2012, p. 472), with the hope of introducing their novelties into the regime or even replace part of it (Smith et al., 2014). However, factors like lock-ins make for only incremental development and make it difficult for a new technology to develop and enter the market.

The described niches are so-called "technological niches" (Weber et al., 1999, p. 10) in which experimental projects are deployed. This "smart experimentation" (Weber et al., 1999, p. 11) includes R&D, pilots, and demonstration projects. For instance, in DAC, demonstrations revolve around its integration with storage or re-use options in which the technology is tested under real-world conditions (Beuttler et al., 2019; Nemet et al., 2018). There are many advantages of these projects, for example, that they "bring together actors from the variation environment (researchers, firms, technology developers) and selection environment (users, policy makers, special interest groups), facilitate network building, stimulate learning processes and produce outcomes that may lead to adjustments in expectations" (Verbong et al., 2008, p. 557). Technological niches can further develop into "market niches" (Weber et al., 1999, p. 11), in which the technology is introduced into specific markets. These specific markets still offer limited protection but are no longer sheltered to regular market selection (Weber et al., 1999).

Hence, the following purpose of niche formation can be formulated: "Niche protective spaces shield the innovation against premature rejection by incumbent regime selection pressures, until the innovation is proven to be sufficiently robust to compete and prosper in unprotected market settings" (Smith et al., 2014, p. 166). To do that, a technology is developed under laboratory conditions and increasingly exposed to real-world conditions (Weber et al., 1999). In sum, in a niche, a technology can develop, be tested for its viability, gain financial support and set in motion various processes like learning processes (Weber et al., 1999). Thus, operation in niches is the central factor predicted by SNM in promoting the upscaling process.

2.2.2. Internal Niche Processes

According to SNM, three central processes actively nurture the emergence and existence of niches around technology, which determine and facilitate the upscaling and diffusion of technology (Naber et al., 2017; Raven et al., 2016). These niche-building processes are the articulation of expectations, learning processes, and social networking.

Firstly, the **articulation of positive expectations** "that are robust (shared by many actors), specific and credible (substantiated by multiple projects)" (Smith et al., 2014, p. 117). These expectations have multiple functions, such as guiding and organizing internal innovation activity and attracting external actors for resources and attention (Geels, 2012). Secondly, **learning processes** are essential to identify barriers, opportunities, and needs. Moreover, they "not only accumulate facts, data and first-order lessons, but also generate second-order learning about underlying assumptions and values about an innovation and its application" (Smith et al., 2014, p. 117). Thirdly, **social network formation** ensures that "support is broad (plural perspectives) and deep (substantial resource commitments)" (Smith et al., 2014, p. 117). Next to expanding social and resource support, these social networks also function to add legitimacy to the technology itself (Geels, 2012).

It is important to note that these "SNM processes are not isolated, but they interact with and influence each other" (Naber et al., 2017, p. 343). In sum, according to SNM, the existence and occurrence of these three processes are factors for the building, nurturing, and preservation of niches and, thus, three subfactors in promoting the upscaling of sustainable technologies (*Figure 2*). It remains unclear whether one, a couple, or all of these factors are in play in the development of innovation like DAC.

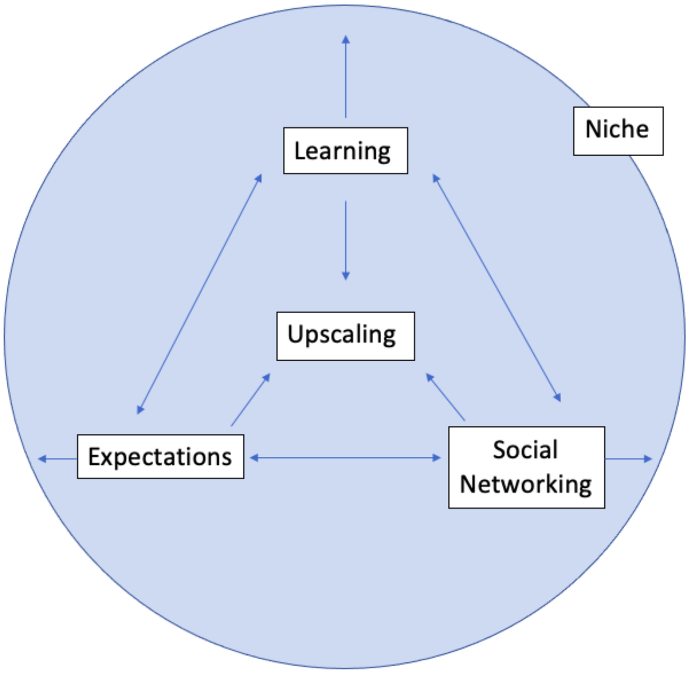

Figure 2: Factors for upscaling predicted by SNM. Arrows show the promoting effects.[2]

[2] Own illustration in reference to Geels, 2012; Konrad et al., 2012; Naber et al., 2017; Nemet et al., 2018; Ruggiero et al., 2018; Verbong et al., 2008

2.3. The Government's Role in Upscaling

SNM is fundamentally conceptualized as a bottom-up process and focuses primarily on "niche-internal dynamics" (Boon & Bakker, 2016, p. 183). Thus, this model does not focus on external niche dynamics and external niche actors. Boon & Bakker (2016) suggest that Strategic Niche Management processes involve a multiplicity of actors and persist of the "interplay between niche insiders and outsiders" (p.183).

To answer SQ3, the role of government like the EU, as a niche outsider, must be included in the model. Government has an influential role in overcoming DAC's biggest challenge, "achieving a climate-relevant scale" (Beuttler et al., 2019, p. 6). While the analyzed SNM processes have a niche building function, and hence, contribute to the upscaling of DAC, DAC firms can only influence the regulatory environment to a certain extent. The niche market and the demand for a technology, which contribute to the process of upscaling (see *Figure 1*), are heavily dependent and "conditioned by policies" (Nemet et al., 2018, p. 7) which only government can implement. Thus, according to theory, the government has a central role in upscaling innovations like DAC through its influence over the regulatory environment (*Figure 3*).

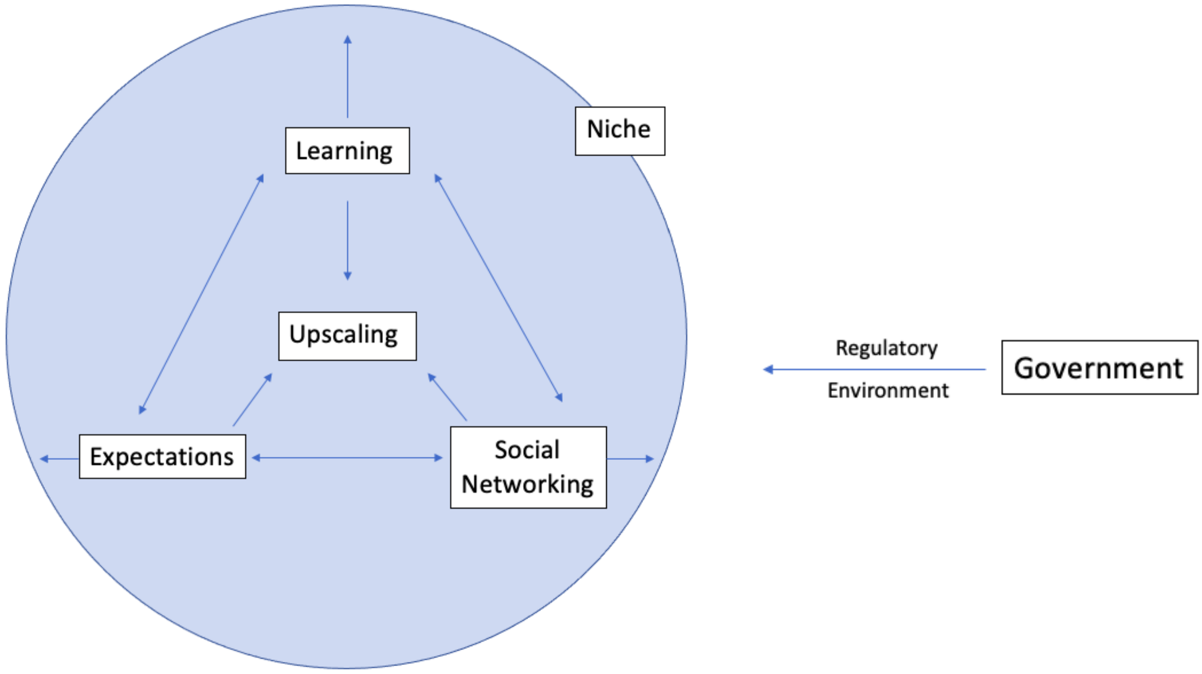

Figure 3: The government's role in upscaling. Arrows show the promoting effects.[3]

3. Research Design and Methods

In the following chapter, the methods and research design used in this thesis are laid out. These include a literature review, a multi-media analysis, and a case study.

[3] Own illustration in reference to Geels, 2012; Konrad et al., 2012; Naber et al., 2017; Nemet et al., 2018; Ruggiero et al., 2018; Verbong et al., 2008

3.1. Literature Review

To answer the SQ1, this thesis involves a literature review. This sub-question aims at examining the role of DAC in meeting long-term mitigation goals. To bring the reader up to date on the current knowledge on the topic and to highlight the importance of this research, a short, traditional literature research is performed (Cronin et al., 2008). This gives the reader a summary of the essential facts and status quo needed to understand the following analysis.

After reviewing the literature found under keywords related to SQ1, namely 'direct air capture'; 'negative emission technologies'; 'long term mitigation goals' and 'net zero', key aspects were summarized and synthesized. Primary sources included peer-reviewed journal articles, government reports, and websites. These were complemented by non-research literature, i.e., a podcast that featured a discussion with an expert on the state of the art. These sources are included in the type and count of sources in Appendix A.

3.2. Multi-Media Analysis

To assess SQ2, the promoting factors for the upscaling of DAC predicted by SNM, and SQ3, the EU's role in these factors, a multi-media analysis is conducted. Multiple media are used as data sources to compensate for the limited scientific literature about the upscaling of DAC. These media include documents, podcasts, and expert interviews (*Figure 4*). Moreover, this triangulation of data sources increases the validity and reliability of the results (Hales, n.d.). The type and count of sources can be found in Appendix A.

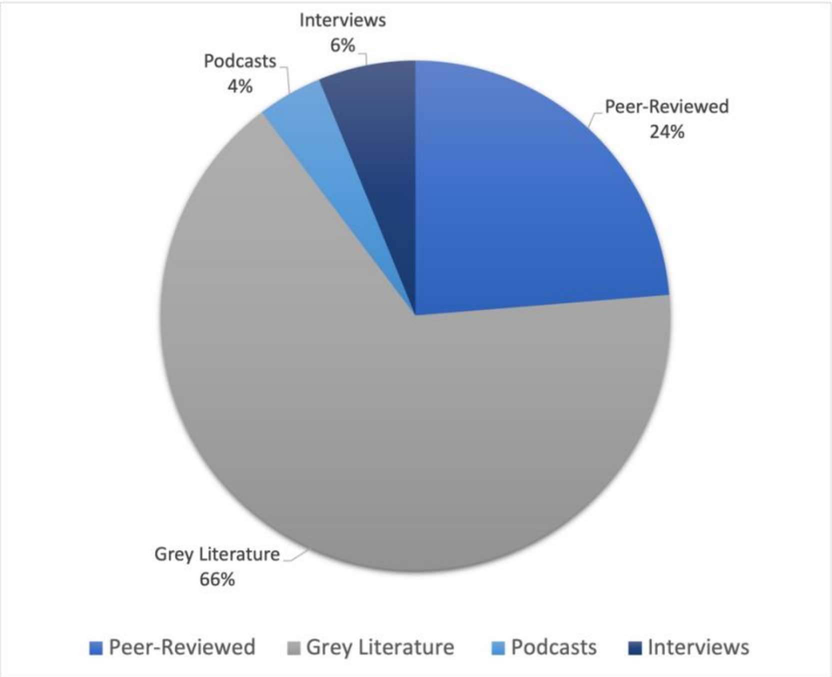

Figure 4: Percentage of different media types (N=97)[4]

[4] Own illustration in reference to Appendix A

3.2.1. Documents

Firstly, documents are used as the primary form of data acquisition. The documents include scientific articles retrieved from scientific journals; newspaper and magazine articles; working papers; books; book chapters; EU documents, press releases and website information; and website information, reports and press releases from various other organizations. Additional data was gathered from LinkedIn, databases such as NexisUni, and other relevant websites. The scientific articles are acquired using search engines such as Web of Science, Scopus, and Find UT through a keyword search. These keywords include key concepts like 'NETs' and 'carbon capture'' but also more specific terms relating to this topic such as 'direct air capture', 'Climeworks', 'upscaling', and 'Strategic Niche Management'. Documents are included in this research based on several formal attributes. For example, whether they are published in a peer-reviewed journal. Data derived from newspapers is checked for validity by comparing it to other data acquired and assessing the type of newspaper in which it was published. Similar formal requirements apply to the other kinds of documents. The percentage of peer-reviewed literature versus grey literature and other data sources can be found in *Figure 4*. The small percentage of peer-reviewed sources compared to other sources also indicates the limited extent to which the topic of this thesis and DAC in general, has been studied by the scientific community.

3.2.2. Podcasts

Secondly, podcasts are also utilized. While journals and policy documents are commonly used in social science research, the use of podcasts is still rare. However, researchers increasingly use podcasts as resources in their data-generating activities (Kinkaid et al., 2019). Especially for a critically understudied topic in the social sciences like DAC, podcasts become a new media resource for social sciences like newspapers and documentaries.

3.2.3. Expert Interviews

Thirdly, six expert interviews were conducted as complementing data to the aforementioned media. The interview partners were selected on the following basis: researchers in the field of NETs or DAC, partners of Climeworks, or public employees on EU or national level dealing with policy around NETs or DAC. The interviews are referenced as (Letter assigned to interviewee, 2021).

The interviews were conducted based on an open-ended questionnaire. Questions were slightly altered and added depending on the position of the interview partner and their responses in the interview. An overview of these interviews can be found in Appendix E.

The recorded interviews were first anonymized regarding the interview partners' names, specific positions, and institutions. Secondly, they were transcribed and questions whose responses were not relevant to the topic or repetitive were deleted from the transcript. These transcripts were then coded in one or two rounds using atlas.ti, as explained below. The transcribed interviews and the codebook can be found in the Appendix (Appendix B and C). In the first round, overall concepts were applied to code the transcripts, which were selected using a deductive approach. These were 'Climeworks', 'Learning', 'Networks', 'Expectations', 'Upscaling' and 'Policy Measures' (*Figure 5*). Out of the three niche processes, expectations were mentioned the most. This suggests that the articulation of expectations could be the most important promoting factor, while learning and networks are less important at the current stage of the innovation process. This might be because DAC and DAC firms are still in their infancy when the handling and communication around promises, risks, and uncertainties is critical for niche building and preservation. Learning and networks might become more prominent in a later stage of the upscaling process when the nurturing of the niche is the most crucial. During each stage, government involvement in the form of policy measures could be critical, which is reflected by the distribution of concepts mentioned (*Figure 5*).

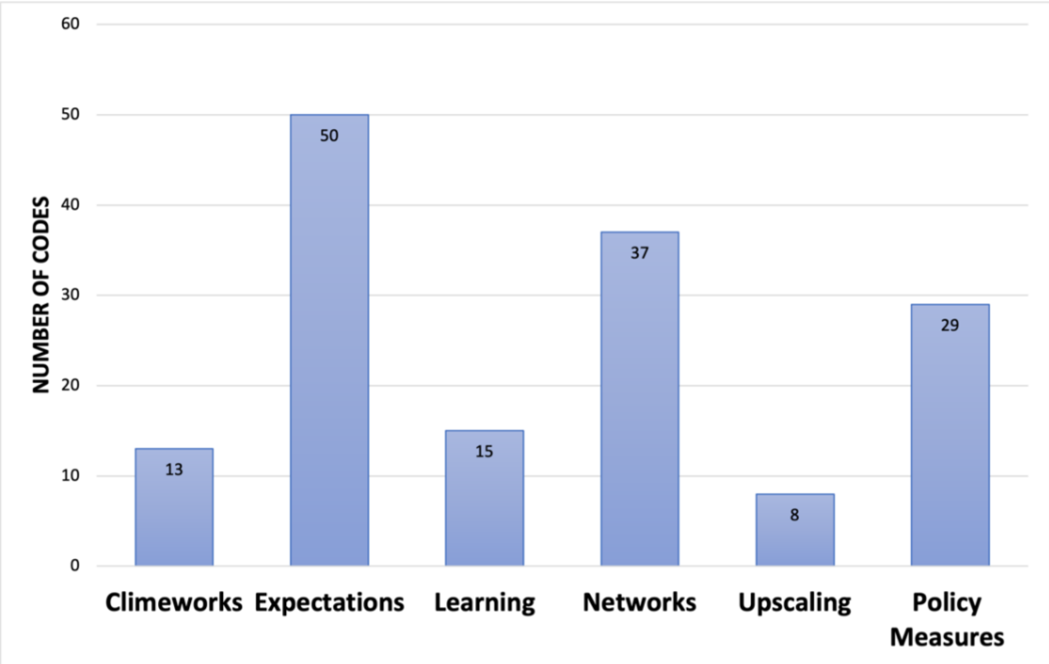

Figure 5: First Round Coding – Distribution of codes per concept[5]

The concepts 'Climeworks' and 'Upscaling' are not coded a second time, as there would be extensive repetition with the other concepts. The remaining code documents were coded again, using sub-concepts formulated through an inductive approach to the overall concepts. First, learning is split up into learning actions (how to learn), such as demonstrations, projects, academic research and attitude, and learning gains (learning for what). 'Networks' is divided into partnerships, including present and potential partners, and network actions, including the how-to and the reasons for the necessity of networking. 'Expectations' is split into three categories: promises, concerns/barriers, and strategy (such as attitude, communication, target audience). 'Policy Measures' is divided into regulations, funds, and guidance. The distributions of the codes of the second coding round can be found in *Figure 6*. This figure suggests a prominence of expectations as well as networks and over learning. This may indicate that in order for a firm and a technology to develop and move to a later stage in the upscaling process, support (e.g.,

[5] Own illustration in reference to Appendix C

financial) through partners is crucial. The high number of codes also implies this. Furthermore, the importance of promises in expectations is suggested. The communication of unique promises and positive expectations might be essential in attracting support. Lastly, this figure implies that regulation might be the essential policy tool for government. This could be because their binding nature mobilizes and involves various actors and directly influences the legal framework around DAC (*Figure 6*).

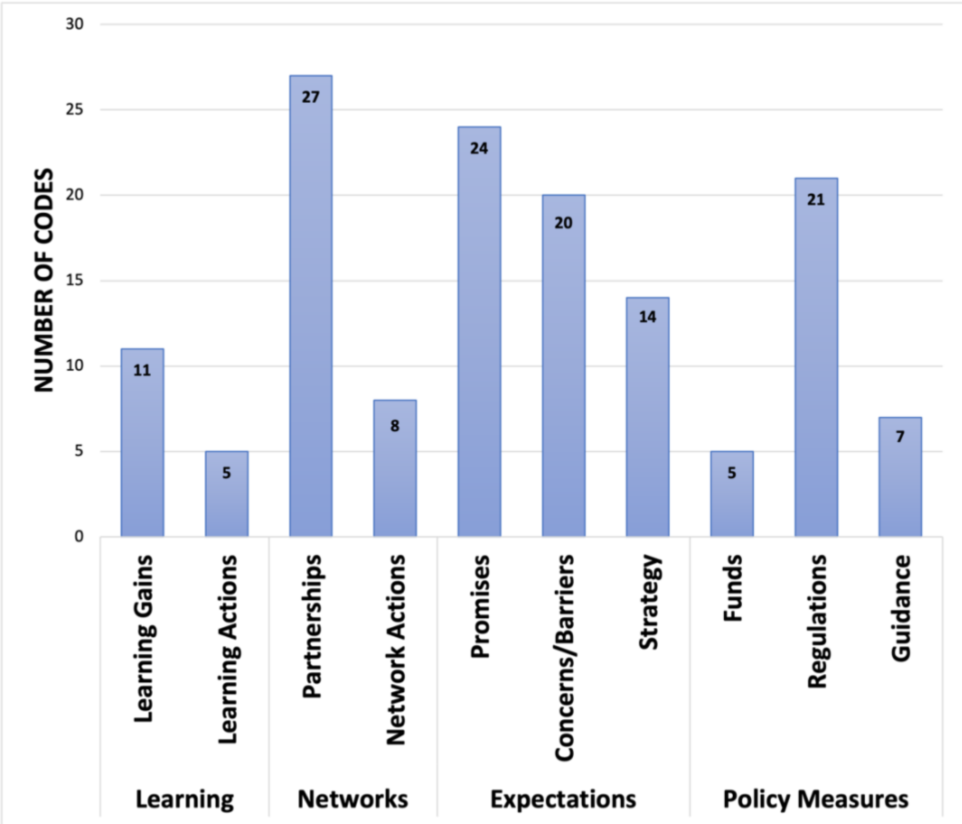

Figure 6: Second Round Coding – Distribution codes per concept[6]

A second independent coder checked these codes to ensure intercoder reliability. The overlap between the first and second coder was 64 percent. This is a relatively low number and could be due to imperfections in the codebook. The number also increases the awareness about the interpretation of the first coder and how it shaped the results. Besides, it raises the reflexiveness about the results.

3.3. Case-Study Design

The data analysis is based on a case study analysis of a Switzerland-based DAC company, Climeworks. Climeworks is one of the three leading companies active in DAC besides Carbon Engineering (CE) in Canada and Global Thermostat (GT), in the USA (Lebling et al., 2021). Climeworks, founded in 2009, was the first company to build a commercial plant in Switzerland and a negative emission plant in Reykjavik (Beuttler et al., 2019). Their principal objective is to commercialize its DAC technology to

[6] See footnote 5

restore a "healthy balance of CO_2" (Climeworks, n.d.-f) which is directly connected to the net zero goals of the EU. Moreover, it aims at going a step further toward "climate positive [which can be defined as] actions that go beyond net zero: [CO_2] emissions that have been emitted are removed from the air as well as additional carbon dioxide." (Climeworks, n.d.-f). To achieve this, Climeworks is primarily invested in the process of upscaling DAC and becoming climate-relevant (Climeworks, n.d.-g).

In total, 15 machines built by Climeworks are in operation across Europe, some were sold to consumers while others are still operated and belong to Climeworks. Hence, Climeworks is financed through three options: selling their carbon removal machines, selling the captured carbon, and offering carbon removal services to customers (Climeworks, n.d.-a). Climeworks' carbon capture systems absorb ambient air, filter the air using a solid solvent, and then desorb it to filter and purify the CO_2 using a temperature-vacuum-swing process (Beuttler et al., 2019) (*Figure 7*).

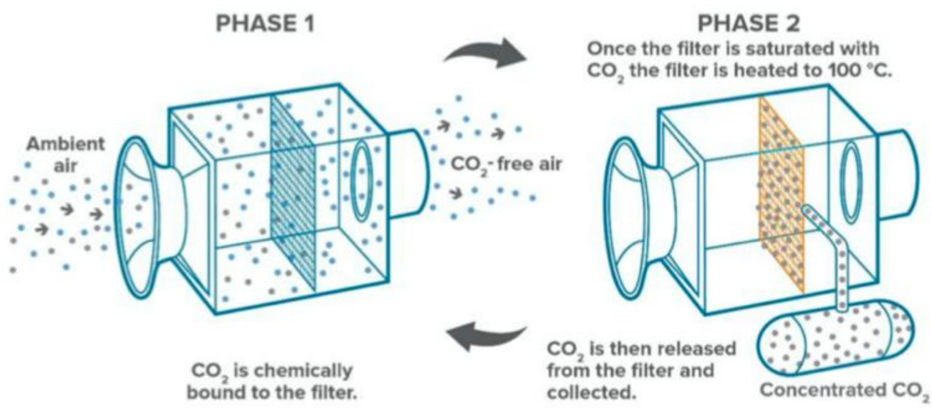

Figure 7: "Schematic illustration of Climeworks direct air capture process." (Beuttler et al., 2019, p. 3)

Climeworks is a standout case that brings a unique opportunity to generate knowledge on DAC upscaling for various reasons. For example, it is the first company to run a commercialized DAC plant, hence showing the ability to upscale (Beuttler et al., 2019). Moreover, it is the leading firm in Europe, with not much else in Europe comparable to its scale and stage of development (Lebling et al., 2021). This fact makes it a highly interesting case to evaluate for social and scientific reasons, as mentioned before. The case study serves a hypothesis-generating goal about ways Strategic Niche Management contributes to the upscaling of innovations, in this case, DAC (Gerring, 2008). This is done using a multi-media analysis, including documents, podcasts, and interviews as described above.

4. Background on DAC

SQ1 aims at investigating the role of DAC in meeting long-term climate change mitigation goals. This is achieved by reviewing current literature in the context of long-term mitigation goals, NETs, and DAC. The findings of this review highlight the role of NETs in meeting long-term mitigation goals like net zero. The role of DAC, however, is uncertain as it is dependent upon upscaling.

4.1. Ways to Net Zero

To meet the 1.5°C global warming target for 2100, formulated by the Paris Agreement, achieving net zero by mid-century is critical (European Commission, n.d.-a). To reach net zero, balancing the carbon budget either through an immediate halting of CO_2 emission, which is difficult as most of infrastructure and industry is tied to it, or through removing an equal amount of CO_2 to the amount that is emitted into the atmosphere is essential (Budinis et al., 2018).

4.2. Negative Emission Technologies

Negative emissions can be defined "as *intentional human efforts to remove CO_2 emissions from the atmosphere*" (Minx et al., 2018, p. 3). The removal of carbon emissions is facilitated through "Carbon Dioxide Removal (CDR) or negative emissions technologies" (NETs) (Beuttler et al., 2019, p. 1). CDR and the usage of NETs appears in various mitigation pathways constructed by, e.g., the IPCC and, hence, is indispensable for meeting net zero goals (see *Figure 8*) (Beuttler et al., 2019). However, CDR is primarily seen as a complementary sector rather than an alternative to cutting emissions (IEA, 2020). As a result, the role of CDR in mitigating climate change may be underestimated, which may also help explain the limited attention that this alternative has received from policymakers on EU level. While a net zero goal cannot be achieved by a single NET, but only in combination with additional efforts to reduce emissions and other NETs (Minx et al., 2018), it is still essential to understand the pathways through which NETs can be adopted and supported through specific entrepreneurial efforts and policymaking.

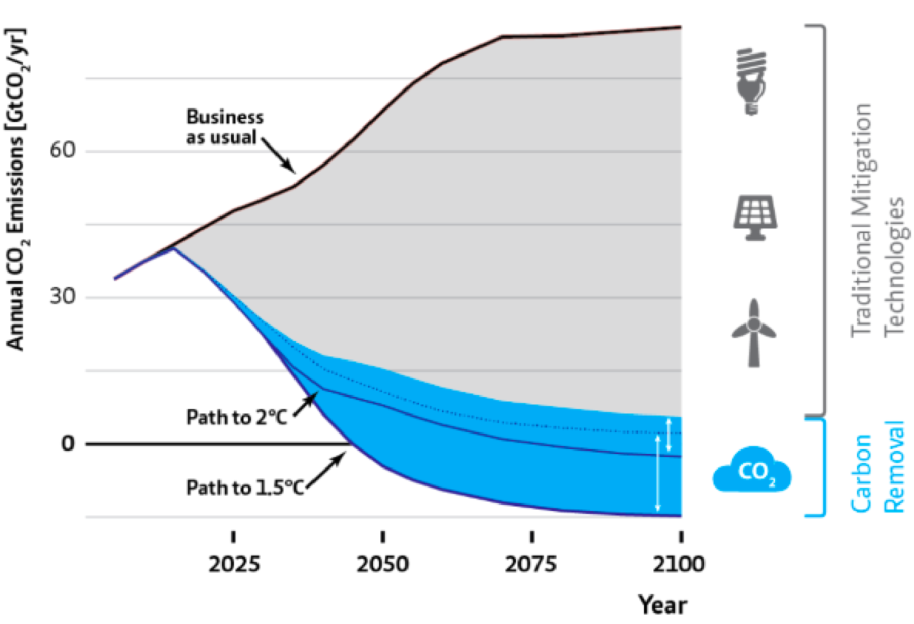

Figure 8: "How to keep global warming below 1.5°C or 2°C" (MCC, 2016)

The process of CDR includes several different NETs ranging from technology-based solutions as well as solutions that are tied to the management of ecosystems or nature-based solutions (The Interchange, 2020). The different forms of NETs are summarized in *Figure 9*.

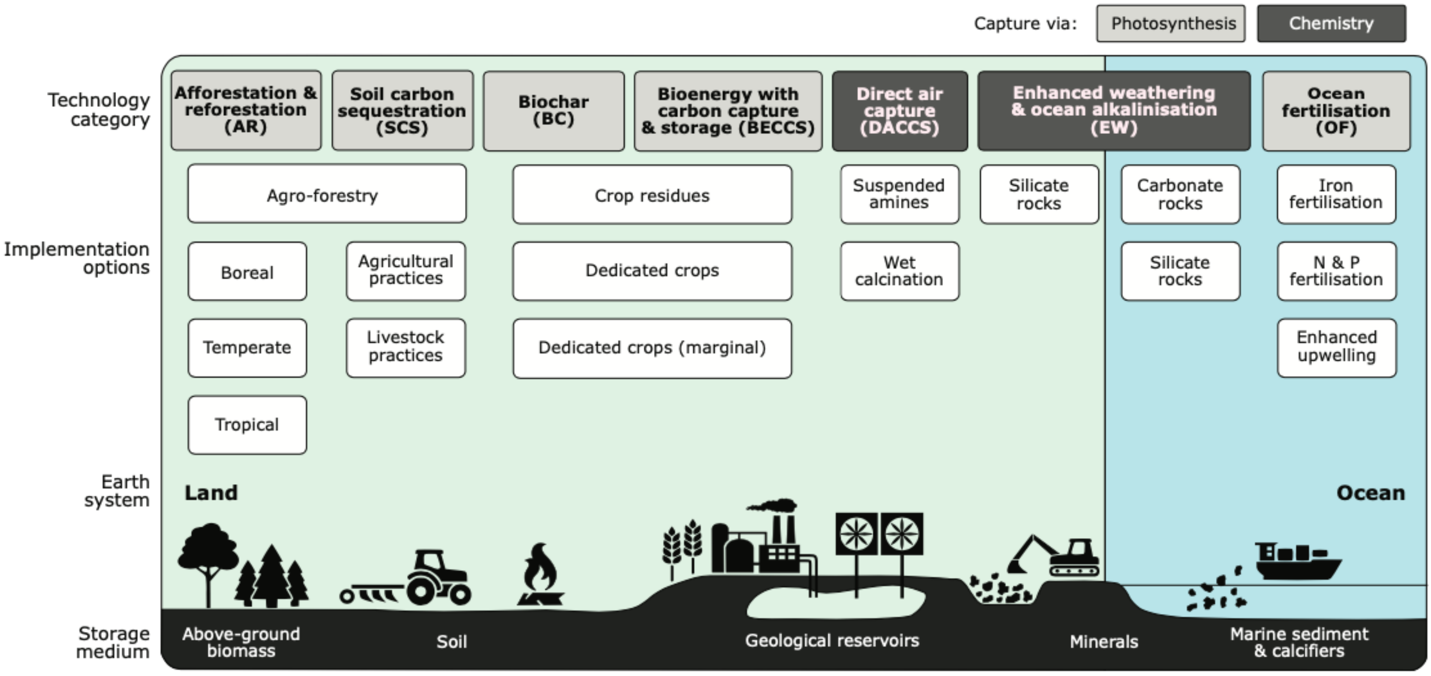

Figure 9: "A taxonomy of negative emissions technologies (NETs)." (Minx et al., 2018, p. 6)

4.3. Direct Air Capture (DAC)

DAC technologies are closely related to point source air capture technologies deployed at places with high CO_2 concentrations, e.g., in a coal plant's smokestack (The Interchange, 2020). In contrast to point-source capture, however, DAC technologies are built to filter CO_2 from ambient air. This is possible as CO_2 is, in low concentration, more or less distributed around the globe (Beuttler et al., 2019). The filtered CO_2 is then stored away in geological formations or further utilized to produce fuels, building materials like cement, chemicals, and other products (IEA, 2020). This technology is regarded as highly promising as its potential to become climate-relevant is mainly limited by upscaling and costs (Fuss et al., 2018).

This literature review indicates the critical role of NETs in meeting long-term mitigation goals, explicitly the net zero goal. The role of DAC, however, remains questionable and is restricted by and dependent on upscaling.

5. Strategic Niche Management Analysis

Given the crucial role of upscaling in DAC to achieve its full potential in climate mitigation, SQ2 aims at assessing the factors predicted by SNM, influencing the upscaling of innovations like DAC. In the following analysis, this is exemplified by applying the factors derived from theory on the case study, Climeworks. The findings of this analysis, which are based on a multi-media analysis, support the predictions made by the model (*Figure 2*). The results underline the crucial rule of the niche as a primary promoting factor for the upscaling of DAC. Furthermore, it indicates the importance of the three internal niche processes as subfactors for niche building and preservation. However, findings indicate an order of precedence among the internal niche processes, with the articulation expectations being the most crucial promoting factor at this stage in the upscaling process. Expectations are followed by social networking as the second most important promoting factor over learning.

5.1. Upscaling of DAC

The biggest challenge in the context of upscaling in DAC, besides increasing unit size, is the mass manufacturing of the units (Nemet et al., 2018, p. 7). The scales at which DAC is produced and employed are not yet climate-relevant. Hence, the potential of DAC is directly dependent on upscaling (Nemet et al., 2018). According to literature, potentials for the level of CO_2 removal are estimated at around 10-15 gigatons a year in 2100 (Fuss et al., 2018). Realizing this potential of DAC is crucial, however, directly tied to several barriers that impact the upscaling of DAC, including Climeworks' technology.

Firstly, **cost** evaluations per ton of CO_2 captured range from $500 to $800, depending on the plant's location, energy source, and size (Gertner, 2019; Lebling et al., 2021). To put this into perspective, the cost of reforestation is around $50 per tonne (Lebling et al., 2021). The second barrier is the **current regulatory environment** which is directly connected to costs. As one of the interviewees describes:

> "*Yes, it is a bit of a dilemma because it's a new and promising technology which would have to be scaled up quickly so that the costs fall, but at the same time we're looking at the priorities, and in climate policy there are higher priorities to address the climate problem.*" (W, 2021)

Hence, according to Interviewee W, the priorities in the regulatory environment must change and catch up with the technological development of DAC (S, 2021; W, 2021). Due to this and the costs, there is still a limited market for the captured CO_2 (B, 2021; Malm & Carton, 2021). The third concern is the high **energy demand** (H, 2021). This is dependent on the temperature needed to separate the captured CO_2 from the filter (Lebling et al., 2021). Fourthly, due to the limited extent that DAC has been studied, there are **various uncertainties**. These include environmental, ethical, and societal uncertainties. Environmental concerns include waste management and leakage concerns in the context of the storage of captured CO_2 (Minx et al., 2018; Nemet et al., 2018). Societal acceptance and landscape considerations present some societal uncertainties, e.g., storage possibilities in highly populated areas (B, 2021; M, 2021; W, 2021). Ethical considerations revolve around the topic of DAC's influence on industry and policy as it could provide "policy-makers with a convenient excuse for mitigating less now" (Minx et al., 2018, p. 21) and support the continuation of the usage of fossil resources (Yousefi-Sahzabi et al., 2014). Moreover, with big emitters like the oil company Shell funding DAC projects, ethical questions arise (H, 2021). These uncertainties influence the public opinion of DAC and the general support (e.g., financial, cultural) for the technology (Nemet et al., 2018). In sum, this variety of barriers makes the upscaling DAC a complex but essential process in technology diffusion.

As laid out in the theory section, SNM predicts one predominant factor and three subfactors that promote upscaling of DAC by overcoming mentioned barriers. The operation in a protective niche, the main factor, is facilitated and strengthened by the three niche building processes: articulation of expectations, learning, and social networking. These processes represent the three subfactors.

5.2. Climeworks' Niche

Building a niche around a sustainable technology to shield it from market pressure is the primary factor for upscaling, predicted by SNM. DAC is mainly "deployed in small niche markets" (Minx et al., 2018, p. 12), in which also Climeworks operates. These niche markets "are very small compared to scales relevant for climate stabilization, in which gigatonnes are what matter" (Nemet et al., 2018, p. 13). Because of its limited scale, it is still not entirely a market niche but still transitioning from a technological niche (Geels, 2012). However, the robust niches still carry out their function, as they shield the Climeworks' DAC and contribute to its further development and diffusion. For instance, by giving it the time and resources to bring the costs of CO_2 per ton down to be competitive with other mitigation methods and CO_2 providers. The existence of these robust niche markets is also a reason for the high attention of entrepreneur firms like Climeworks (Nemet et al., 2018). **This indicates the importance of a niche, as predicted by SNM.** The facilitation and preservation of this niche are, however, dependent on the three subfactors: the internal niche processes.

5.3. Internal Niche Processes

According to the constructed model (*Figure 2*), the protection through the niche is established, secured, and strengthened through the occurrence and facilitation of the three internal niche processes. Hence, they are central subfactors in overcoming barriers and promoting Climeworks' DAC technology. These processes are bottom-up. Thus, in the following, these processes are assessed at a company level.

5.3.1. Articulation of Expectations

Expectations can be promises as well as concerns and have a performative role in innovation systems, development, and guide learning (Ruggiero et al., 2018). The articulation of positive expectations by Climeworks and reaction to concerns voiced by stakeholders is essential in attracting attention, resources, and supporters. Hence, expectation management also has a positive effect on the social networking process. Reacting to expectation dynamics as well as employing expectation-building activities is, therefore, an essential part of SNM (Konrad et al., 2012; Naber et al., 2017). More importantly, expectation management "legitimates niche protection" (Ruggiero et al., 2018, p. 582) and, thus, is predicted by SNM to be a central factor in strengthening and preserving Climeworks' niche and, through that, promoting upscaling.

5.3.1.1. Climeworks' Promises

Climeworks aims at "capturing 1% of the global greenhouse gas emissions by 2025" (Rosell, 2019, p. 7), promising their service users not only carbon neutrality but carbon positivity (Climeworks, n.d.-f). This 1% goal would require the production of over 7.3 million of Climeworks' DAC collectors, which can only be achieved through upscaling (Chalmin, 2019). To reach this target, Climeworks makes a set of specific promises on its website. First, Climeworks promises **scalability** of its technology due to its "modular plant design, working at low-temperature heat and with minimal land-usage footprint" (Climeworks, n.d.-b). The core of the modular design are Climeworks' CO_2 collectors as CO_2 absorption and desorption processes occur in this one device. Additionally, Climeworks' machines use the low-temperature heat at around 100°C to release the captured CO_2, which not only opens the possibility of using a multiplicity of energy sources like waste heat but also makes their energy need superior to other leaders in DAC like Carbon Engineering (Climeworks, n.d.-a; Nemet et al., 2018). Its energy demand is met by renewable energy sources (Climeworks, n.d.-a). The technology also has the advantage of location-independence. Climeworks machines can be erected anywhere where renewable energy is available, even in remote areas, storage sides or reuse industries at minimal to no transport costs (B, 2021; Beuttler et al., 2019). Its small physical footprint is connected to the following promise. The second stated promise is **efficiency** by having the "[s]mallest land and water usage of all approaches (Climeworks, n.d.-f). Climeworks' machines do not need arable land and, in general, require a much smaller footprint than other NET solutions, especially bio-based solutions (Beuttler et al., 2019). Malm & Carton (2021) summarize Climeworks' DAC technology as "photosynthesis on steroids: Climeworks claims to do the job of 36,000 trees with the footprint of one" (p.7). Furthermore, no additional water must be added in the process (Fasihi et al., 2019). Thirdly, Climeworks promises **accessibility** of climate action through carbon removal services, "to empower as many people as possible. Because we are all in this together" (Climeworks, n.d.-f). It sells services to businesses and individuals to offset their costs (Rosell, 2019, p. 8). Promises four and five are connected to these services as Climeworks promises **transparent** and **measurable** climate action (Climeworks, n.d.-f, n.d.-b). Kilograms of CO_2 removed can be accurately measured and included in a yearly certificate for Climeworks' removal service users (RRC, 2020). Sixthly, promises revolve around the **storage of the captured CO_2: natural, safe, and permanent** (Climeworks, n.d.-c, n.d.-f). It achieves this by using the method of storage currently facilitated in cooperation with the Icelandic firm Carbfix, which differs from conventional sequestration. The captured CO_2 is pumped into the basalt rock in liquid form and mineralizes in less than two years, hence preventing leakage (Malm & Carton, 2021, p. 2). If not stored, the captured CO_2 is reused as raw material for several products like e-fuel and in greenhouses (Beuttler et al., 2019; Chauvy & de Weireld, 2020; Nemet et al., 2018). The reuse of CO_2 can also contribute towards a circular loop and CO_2

economy (Beuttler et al., 2019; H, 2021). The last directly stated promise is related to the urgency of climate action: **time efficiency**. Climeworks states, "Since time is critical, use a solution that removes one ton of CO_2 very rapidly from air" (Climeworks, n.d.-b).

An additional promise deduced from Climeworks' website is the **low lifetime emission** of Climeworks' plants. "Grey emissions are below 10%, which means that out of 100 tons of carbon dioxide that our machines capture from the air […] only up to 10 tons are re-emitted." (Climeworks, n.d.-d). This is because Climeworks' machines currently have a lifetime of around ten years, with a payback period of approximately one year (GN, 2021). Moreover, the filters, which selectively filter CO_2, can be reused thousands of times, contributing to a small CO_2 footprint (GN, 2021; RCC, 2020).

Each of these commitments demonstrates the uniqueness and ambition of Climeworks and its DAC technology that sets it apart from other NETs and DAC firms. Hence, it may also strengthen Climeworks' position within its niche beside the niche itself. These findings suggest that the articulation of positive expectations by Climeworks does draw attention to its DAC and, through that, increases the chance of gathering more resources and support and legitimizing current support by, e.g., stakeholders, as is expected under SNM. This lays the foundation for learning as well as social networking, niche development, and, with that, the upscaling from its current, limited scale.

5.3.1.2. Climeworks' Reaction to Concerns

As mentioned before, expectation management includes the reaction to expectation dynamics, including reacting to concerns. There are five significant concerns and barriers concerning DAC which must be related to Climeworks.

First, the concern is related to the matter of upscaling: the **potential of Climeworks' technology**. As DAC in general, Climeworks' scale of the machines and the diffusion of the technology is too small to be meet its 1% goal and be climate-relevant (Climeworks, n.d.-g). Currently, the world's largest plant is built by Climeworks and partners in Iceland, which is supposed to capture 4000 tones of CO_2 per year. However, this still not the scales needed for climate-relevance as an interviewee underlines:

> *"They are one of the leaders [...] in actually making direct air capture to work [...]. Still, the unit they have installed on Iceland is large but still not on the scale of what needs to be done, it's still very small [...] [especially as] we need to retrieve gigatons of CO2 per year."* (H, 2021)

This highlights the role of mass production in upscaling apart from the upscaling the size of plants, which Climeworks has not started. Additionally, recent studies have questioned the potential of negative emissions, as results indicated reductions to be more effective in climate change mitigation (Der Spiegel, 2021). However, Climeworks has stressed that its technology and company are not <u>the</u> solution, but all efforts are necessary for tackling climate change, however small they are (GN, 2021). Second, the **financial feasibility**. The costs associated with DAC also make Climeworks' carbon removal services very expensive at "€980 per ton of CO_2" (Malm & Carton, 2021, p. 23). However, Climeworks is planning to bring down the costs to $100 per ton/ CO_2 within the decade through, e.g., technological development, upscaling, and production changes to reach an 'economy of scale' (Beuttler et al., 2019; Gertner, 2019; RCC, 2020).

Thirdly, the high **energy demand** (H, 2021). However, as stated in the promises, competitors have higher energy needs, as they need a higher temperature to release the CO_2 from the filter (Lebling et al., 2021). Fourthly, in reaction to the number of **uncertainties**, Climeworks has assessed several of them in their life cycle assessments, e.g., waste (Minx et al., 2018). However, some uncertainties about the large-scale deployment of DAC remain. Christoph Beuttler, Climeworks' Head of Policy, has reacted to ethical concerns in the RRC (2020) podcast. He states that not talking about DAC because of ethical concerns, such as the possible influence of DAC on industry, is a moral hazard as well. To overcome this ethical dilemma and the dependency on some fossil resources, Climeworks aims to establish a closed carbon cycle with hard to decarbonize sectors (GN, 2021).

Besides demonstrating the same functions as articulating positive expectations, the reaction to concerns helps may relativize the barriers, motivate and guide processes like learning, e.g., in the context of efficacy. Hence, it facilitates niche nurturing and the upscaling of Climeworks' technology.

5.3.1.3. Vision and Strategy

The way that a company communicates its vision and expectations is essential in attracting attention (Naber et al., 2017). Climeworks states that its vision is to inspire one billion people and become climate-relevant, which, given the concerns and barriers, is very difficult to achieve in the near future (GN, 2021; RCC, 2020). This vision is communicated through various channels, including podcasts, news articles, social media and Climeworks' website, hence, reaching and informing a wide variety of people about its ambitions (Climeworks, n.d.-e). This generating of enthusiasm among various societal groups is essential in the current stage in the upscaling process (H, 2021). In contrast to this very positive vision stands Climeworks' expectation management strategy, which is focused on scientific facts and on not to overpromise: "we are literally talking about our future […] therefore we tend to be on the conservative side with our communication" (RCC, 2020). Even though vision and strategy contradict each other to some extent, they fulfill an essential function: they contribute "to the outlook on, and narrative around, the current climate crisis" (Beuttler et al., 2019, p. 5). This narrative is also crucial in the context of further cost prevention, as with the rising of temperature, the mitigation costs increase. As interviewee H (2021) states: "*But it is hard […] to make people already feel those costs now. So, it takes a lot of vision […].* To make its vision more comprehensible, Climeworks has published a "scale-up roadmap" (Climeworks, 2020d) which combines its vision with its conservative calculations (RCC, 2020).

In balancing an inspiring vision against the communication of rather conservative information about Climeworks' technology encourages attention and mobilizes support while building trust in the company. In sum, the management and articulation of positive expectations and visions legitimizes niche protection as well as guides and mobilizes social networking and learning. Thus, findings suggest that it lays the foundation for the other niche process at the current stage in the upscaling process. To conclude, this analysis supports the **promoting effect of the articulation of expectation and expectation management, predicted by SNM, on other internal niche processes, niche building, and, hence, the upscaling** of unit size as well as the potential for upscaling through mass production.

5.3.2. Learning Processes

The goal of learning is to find "solutions for overcoming barriers that prevent an innovation from functioning properly" (Ruggiero et al., 2018, p. 582). Crucial for successful learning processes is their broadness, meaning not only that they focus on technological facts and elements but also the connection between technological and social aspects. Furthermore, learning should be reflexive, hence, adjust to outcomes produced and changing conditions, e.g., in the environment (Naber et al., 2017). Two of the essential tools of the learning process are outlined below.

5.3.2.1. Demonstrations

While R&D, the stage previous to demonstrations, focuses on the development of prototypes and experiments under lab conditions, demonstrations make it feasible to test the technology under real-life conditions (Nemet et al., 2018). Demonstrations offer the possibility of "*learning by doing*" (B, 2021) and to figure "*out [a] million different hurdles that you have to overcome, and you optimize as you go*" (S, 2021). Besides, demonstrations establish a knowledge flow among the actors involved and the aggregation of expertise, ensuring the broadness of learning (S, 2021). They start in the simplest manner and grow over time. Hence, they already show the ability to upscale by learning from earlier projects, which also indicates the reflexiveness of their learning (Naber et al., 2017; Nemet et al., 2018). Climeworks is involved in several demonstrations and research projects around Europe, testing the performance of their technology and its combinability with storage and reuse options (European Commission, n.d.-e; Kotecki, 2019). Regarding demonstrations, interviewee B (2021) states: "*so far […] they [Climeworks] are doing a good job"*. Starting with its first demonstration prototype in 2011, Climeworks has built the world's first commercial plant in Switzerland and is currently working on the first negative emission plant in Iceland (Beuttler et al., 2019). Hence, it has demonstrated its ability to learn from experiences and earlier projects to upscale its demonstrations. Climeworks' modular design has an essential role in this learning and upscaling process. As Christoph Beuttler states: "it allows us to […] build smaller plants at different sizes relatively quickly through which we can learn quickly and then […] improve quickly" (RCC, 2020).

The learning through demonstration, hence, promotes further upscaling by reducing barriers, e.g., by cost reductions (Beuttler et al., 2019). They also legitimize Climeworks' articulated expectations, communicated to customers, industry and governments, by working towards and meeting these expectations in real-life conditions. Hence, learning through demonstrations strengthens the niche and, therefore, its potential to promote upscaling. Although being a tool for learning, demonstrations are dependent on networking efforts to bring actors together and attract new stakeholders (H, 2021; Nemet et al., 2018).

5.3.2.2. Studies and Assessments

The involvement and employment of studies and assessments are critical in furthering technological development and its potential. (INERATEC, 2019; Ruggiero et al., 2018). There are several studies in which Climeworks plays a role. First of all, Climeworks is an essential building block in the carbon cycle of the production of "renewable jet fuel from air" (INERATEC, 2019), planned to be studied as initiated by the Rotterdam The Hague Airport. The study is meant to set out the basic setup and conditions for a demonstration plant and assess its costs (INERATEC, 2019). Hence, the study is directly connected to the notion of learning by doing. Secondly, Climeworks' technology has been evaluated through a lifecycle assessment in 2021, carried out by RWTH Aachen University. This study has given insight into the "technology's net environmental benefit" (Climeworks, 2021b). The aspects evaluated in the study can be seen in *Figure 10*.

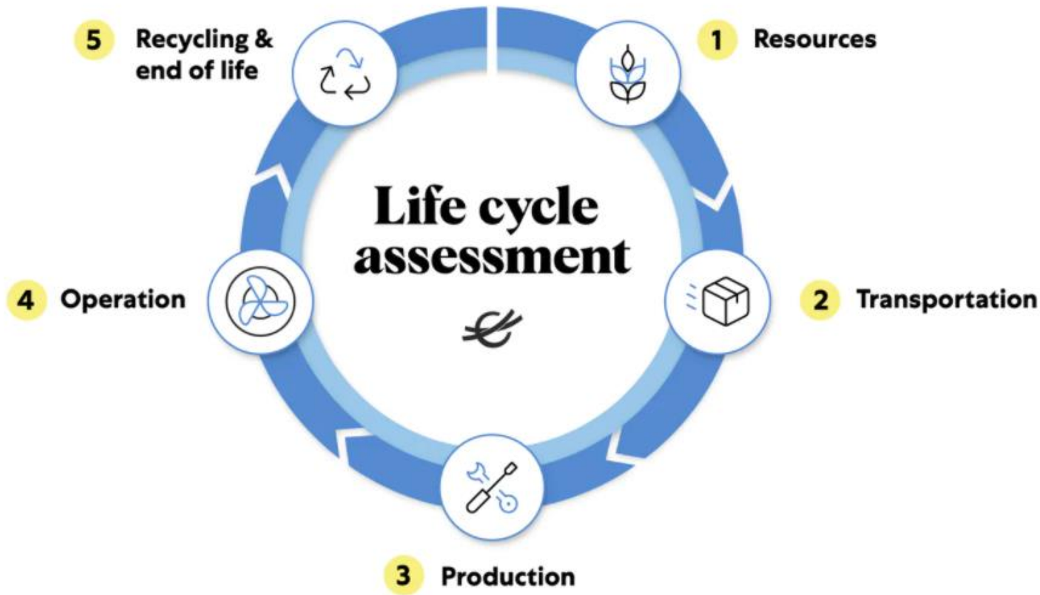

Figure 10: Life cycle assessment evaluating Climeworks' technology (Climeworks, 2021b)

This study's outcome underlines the expectations formulated by Climeworks. They indicate that "Climeworks' plants can reach a net carbon dioxide removal efficiency of more than 90%" (Climeworks, 2021b). Moreover, it highlights Climeworks' potential to increase efficiency by 6%:

> "Moreover, the study indicates that scaling up direct air capture to remove up to billions of tons of carbon dioxide can be viable and not limited by material or energy requirements, which in turn means the technology can significantly contribute to achieving the climate targets of the Paris Agreement." (Climeworks, 2021b)

The outcomes of the assessments and studies promote upscaling by legitimizing niche support, thus facilitating niche preservation and development as expected by SNM. They also have a legitimizing effect on the articulated expectations, making them more "specific and credible" (Smith et al., 2014, p. 117) (H, 2021). In sum, **this supports the promoting effect of learning processes, as expected under SNM**.

5.3.3. Social Networking

Social networking has a central function in the niche. It "contributes to create alignment inside a niche and coordinate[s] the actors that can support local projects." (Ruggiero et al., 2018, p. 582). It especially supports niche development when two factors are given. First, the network should be "broad, meaning that multiple actor types (firms, users, policy makers, academics, entrepreneurs, scientists, etc.) are included" (Naber et al., 2017, p. 343). The inclusiveness of the network is essential as diverse and potentially conflicting views within it can facilitate the development of the technology (Naber et al., 2017). Second, when the networks established are "deep, which means that actors should be able to mobilise commitments and resources within the networks" (Naber et al., 2017, p. 343). Climeworks' networked niche is illustrated in *Figure 11*.

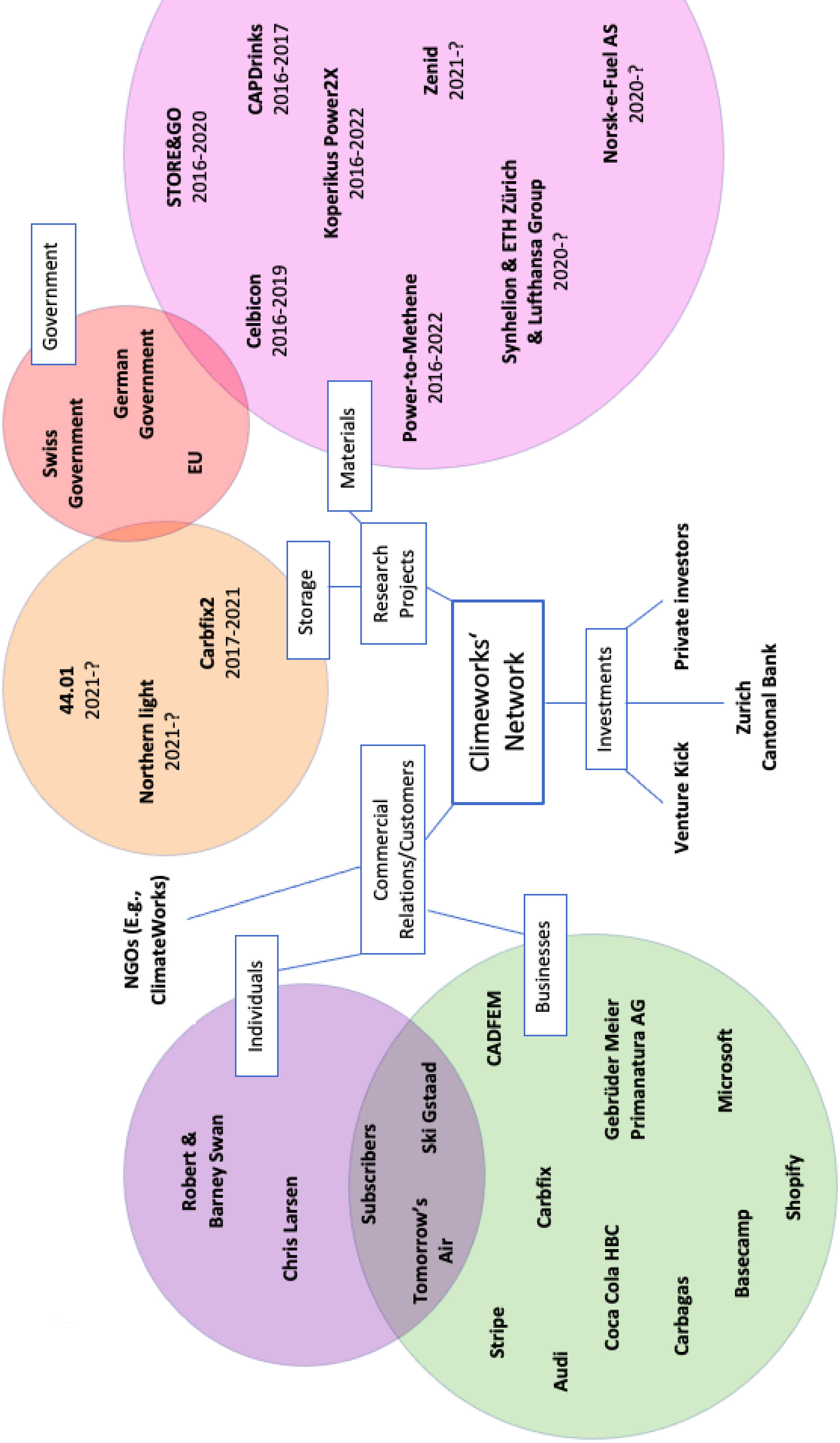

Figure 11: Climeworks' Networked Niche[7]

[7] Note: This Figure is not exhaustive. Own illustration in reference to (Appendix D)

5.3.3.1. Research and Demonstration Projects

As elaborated in the tools for learning, Climeworks is part of a multiplicity of demonstration projects. Several of them can be seen in *Figure 11*. The social networking through research and demonstration projects promotes Climeworks' technology and its upscaling in various ways. Firstly, it facilitates learning and the legitimization of expectations. This has been laid out in the sections above. Secondly, it secures funding for the development and upscaling of the technology and explores market opportunities. By partaking in a wide variety of projects, including storage and materials for which the captured CO_2 could be used, Climeworks connects to potential business partners or customers. The EU-funded research project 'CAPDrinks', for instance, marked the beginning of the commercial relationship between Coca-Cola HBC and Climeworks (Chalmin, 2019; Kotecki, 2019). Through this, Climeworks also demonstrates its viability in several market niches for CO_2 use (Malm & Carton, 2021). Fourthly, it attracts new research opportunities. Through the participation in many demonstrations, Climeworks was able to further its technological development and the upscaling of its technology (Nemet et al., 2018). This secures its presence in Europe and industry-related research projects. This can be seen in the number of cooperation and demonstrations in early stages, e.g., Zenid and Norsk-e-fuel (Climeworks, 2020b; INERATEC, 2019). Lastly, engaging in these demonstrations generates the broadness of Climeworks' network. Connections include industry players like Lufthansa, universities like the ETH Zurich, and governments like the EU (European Commission, n.d.-e; Green Car Congress, 2020).

5.3.3.2. Commercial Relations and Investments

Climeworks partakes in a multiplicity of commercial and investment relations with various actors, including individuals, businesses, and NGOs (*Figure 11*). This type of social networking has two central functions in the niche nurturing process, hence, in promoting the upscaling process. The first one is to secure funding. As mentioned before, funding has an essential role as it is vital to facilitate the upscaling process (Nemet et al., 2018). However, this also means that the lack of investment usually results in the "valley of death" (Nemet et al., 2018, p. 6) for the commercialization of the technology. Types of funds gathered by Climeworks include equity, grants and capital through the selling of their carbon removal services (Climeworks, n.d.-a; Crunchbase, n.d.-b). The second function is of a symbolic nature. Through the commitment of big companies like Microsoft and Stripe, other companies and individuals are inspired to act and follow the trends (Climeworks, 2021f; W, 2021). An example is the purchase of 300 tones of CO_2 removal bought by Chris Larson following the commitment of these companies. These voluntary actions give Climeworks momentum and help facilitate the upscaling as it will "help kickstart the market for this much-needed climate technology" (Climeworks, 2021f).

5.3.3.3. Other Networking Efforts

Apart from specific networking efforts through demonstration projects, investment, and commercial relations, there are other undertakings by Climeworks to attract new actors. Firstly, they are showcasing their technology in the 'Our future planet' exhibition in London. Through this effort, Climeworks aspires "to create awareness for carbon dioxide removal solutions and inspire people to take climate action" (Climeworks, 2021d). Secondly, Climeworks had organized challenges such as 'Earth Day Challenge' to attract new stakeholders and customers. The success of the efforts can be seen in the number of subscribers that increased to 6.000 following the challenge (Climeworks, 2021a). Lastly, Climeworks hosted a DAC summit in 2020 and partakes in panel discussions around DAC technology. This has the function of informing the public, possible stakeholders, and customers as well as the exchange of knowledge (Climeworks, 2020a, 2020e). These **networking efforts also display the connectedness of the three strategic niche processes** as they also facilitate learning, e.g., through the exchange of expertise, and the management of expectations, e.g., through the articulation to the public and the discussion of expectations from different societal groups.

5.3.3.4. Visibility and Resources

Visibility can be seen as a driver for social networking as well as an indicator for successful networking efforts. Resources like funding are closely related to visibility as there is a direct connection between the attention a company gets and investors (Bushee & Miller, 2012). Hence, visibility and funding, as an essential resource for upscaling, are also closely connected to the articulation of expectations and indicate the 'deepness' of Climeworks' network (Naber et al., 2017; S, 2021). In the following, Climeworks will be compared to the two other key DAC firms: Global Thermostat (GT) and Carbon Engineering (CE), to understand its position. The findings are shown in *Table*.

Climeworks built the first commercial and the largest DAC firm in the world (RCC, 2020). With over 125 employees, it is close to CE (around 100 employees), and larger than GT (approximately 30 employees) (Carbon Engineering Ltd., n.d.; Climeworks, n.d.-e; Global Thermostat, n.d.). Climeworks also employs the largest team of DAC experts (Beuttler et al., 2019). The difference in visibility becomes apparent when looking at their LinkedIn followers: Climeworks is at around 17.600 followers, close to CE (ca. 20.000), but far more visible than GT (ca. 4.100) (Carbon Engineering Ltd., n.d.; Climeworks, n.d.-e; Global Thermostat, n.d.). However, LinkedIn only indicates the visibility of Climeworks in an audience that is on average in the upper level of income and education (Tran, 2020). Besides the active engagement on LinkedIn, Climeworks is also present in several podcasts and featured in newspaper articles which broadens its reach. The database Nexus Uni gives information about companies' visibility as it shows the number of news articles found under a specific keyword. Under 'Climeworks' around 1900 news articles were found since its founding in 2009 (Nexis Uni, n.d.-b). In comparison, around 2350 could be found under 'Carbon Engineering' and 1200 under 'Global Thermostat' (Nexis Uni, n.d.-c, n.d.-a). Furthermore, when looking at the distribution of news articles under 'Climeworks', the trend is going up (Nexis Uni, n.d.-b) (*Figure 12*). To conclude, these numbers indicate that Climeworks' visibility is increasing and can be compared with the Canadian firm Carbon Engineering.

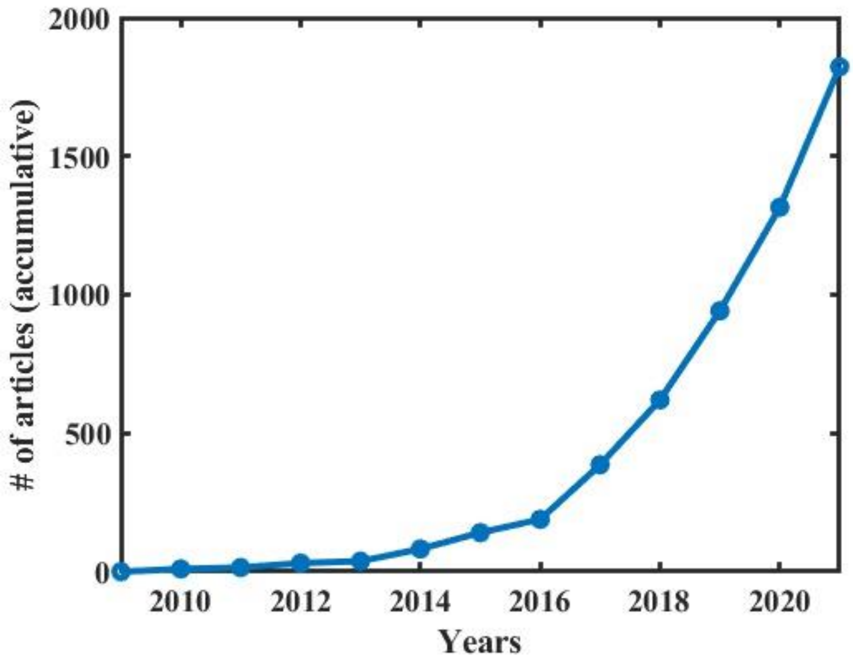

Figure 12: News articles found under the keyword 'Climeworks'[8]

	Climeworks	Carbon Engineering	Global Thermostat
# of employees	128	104	28
# of LinkedIn followers	17.607	20.035	4.191
# of Nexus Uni articles	1907	2335	1179
Amount of Funding	ca. $125M	ca. $110M	ca. $51M

Table: Difference in visibility among the key DAC players[9]

Furthermore, resources like funding are an indication of its visibility. The growth of this resource can be observed, for instance, when looking at a specific type of funding: direct investment in form of grants and equity. This specific type of funding for Climeworks was gathered through four rounds (Chalmin, 2019). These are visualized in *Figure 13*. For comparative reasons, Swiss Francs were converted into US dollars, using the exchange rates of the particular year (Exchange Rates UK, n.d.).

[8] Own illustration in reference to Nexis Uni, n.d.-b
[9] As of the 5th of June, 2021. In reference to Carbon Engineering Ltd., n.d.; Climate Advisers, n.d.; Climeworks, n.d.-e; Crunchbase, n.d.-a, n.d.-b; Global Thermostat, n.d.

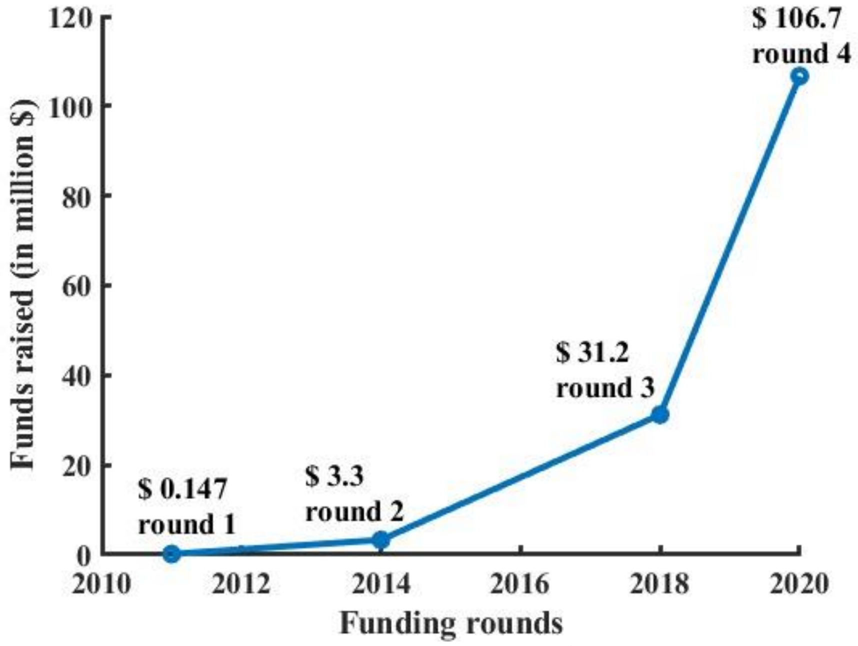

Figure 13: Funds raised by Climeworks in funding rounds[10]

This exemplifies and indicates the increase in funding, which may be ascribed to the visibility of Climeworks and its networking efforts. In sum, the networking with various actors through partnerships and Climeworks' networking efforts increase its visibility and mobilize and facilitate the gathering and maintenance of financial, symbolic backing as well as support in the form of expertise. **Hence, this analysis underlines the promoting effect of social networking, as predicted by SNM.** Additionally, networking, e.g., through partaking in demonstrations, facilitates learning. Thus, it provides the infrastructure for learning.

The findings of the SNM analysis support the model (*Figure 2*), thus, underline the interconnectivity of the three internal niche processes and their promoting effect on niche development, building, and preservation. This, in turn, promotes further upscaling of unit size and the potential for mass manufacturing. Important to note is, however, that these processes do not only strengthen the niche itself but might also promote Climeworks' position within the niche and in other market niches, e.g., for CO_2 use. The results particularly highlight the role of expectations as the foundation and guide for learning and social networking at the current stage in the upscaling process. Moreover, the findings indicate social networking to be the second most important process to promote and facilitate learning. The role of partnerships is prominent in this process. These findings are also suggested by the codes (*Figure 5* and *6*).

However, as laid out in the model (*Figure 3*), the internal niche processes facilitated by Climeworks can

[10] Own illustration in reference to Crunchbase, n.d.-b

only influence the regulatory environment, an essential barrier of DAC impacting the niche extrinsically, to a limited extent. This directly translates into a need for change in the current regulatory environment through government involvement.

6. The EU's Role in the Upscaling of DAC

Even though the role of NETs in meeting climate goals is clear and DAC is of promising nature, the urgency to scale these up to climate relevance is not reflected in current policy (Minx et al., 2018). This discrepancy is connected to SQ3 which investigates the EU's role in promoting the upscaling of innovations/ addressing the needs formulated by the Strategic Niche Management analysis?

Based on the multi-media analysis, findings suggest support for predictions made in the model (*Figure 3*). They underline the EU's capacity in promoting upscaling through influencing the regulatory environment. Additionally, the findings highlight the role of regulations as a primary tool in addressing needs resulting from the SNM analysis.

6.1. The EU's Role in DAC

With Climeworks' machines being present all over Europe and the fact that none of the leading DAC companies originate from an EU country, the EU's role in facilitating and promoting DAC comes to attention. While Switzerland is not an EU member state, it is connected to the EU, Switzerland's most important trading partner, and its goals in various ways. The net zero goals of Switzerland and Climeworks are, for example, very similar to the EU (IISD, 2021). Moreover, Switzerland is tied to the EU through many agreements, primarily related to trade. One specific example is the "emission trading system" (ETS) (Council of the EU, 2019) which will be further discussed in the following sections.

There is an assortment of Directorates-General (DGs) involved in policy around NETs, which are relevant for DAC regulations. The Climate Action DG is the main actor in the matter of climate change and is responsible for several programs connected to NETs, such as the ETS (European Commission, n.d.-c). Additionally, the DG of the Joint Research Center facilitates and observes developments in carbon capture and subsequent processes (European Commission, 2020). This DG is directly tied to the 'Horizon 2020 research project'. Through this funding scheme, the EU, alongside the German and Swiss Government, also has an indirect effect on Climeworks' network through the funding of several demonstrations in which Climeworks partakes (*Figure 11)* (European Commission, n.d.-e; IET, n.d.; Sunfire, n.d.). One example of Horizon 2020 funding is the Carbfix2 project. As a participant in their research project, Climeworks received an EU contribution of € 450.000 (European Commission, n.d.-e). This involvement of governments indicates a regulatory environment that is willing to support R&D and demonstrations for DAC. Hence, it shows how government can contribute to upscaling. Other DGs that may be involved in regulations around DAC are DG Energy, which currently focuses mainly on carbon capture from point sources, and the DG Environment (European Commission, n.d.-b, 2014).

In conclusion, this indicates that the EU has the capacity to be an essential actor in influencing the regulatory environment around DAC, suggesting support for the prediction made by the model. This could be achieved through indirect involvement, like funding, or direct involvement, like policy. However, at this current stage, with limited actions being taken, the EU's role cannot be fully predicted.

6.2. Policy and the Upscaling of DAC

As predicted in the model, governments like the EU have the capacity to play a critical role in upscaling through influencing the regulatory environment (*Figure 3*). In the upscaling of DAC, the current regulatory environment is a fundamental barrier that must be overcome through government involvement (S, 2021). The need for change within the regulatory environment to promote upscaling, formulated by the SNM analysis, can be split into categories: the need for consistency and for revision of the current EU's regulatory framework (B, 2021; M, 2021).

6.2.1. Need for Consistency

Consistency in policy promotes upscaling in various ways. For example, by setting a "long term picture" (U, 2021), the regulatory framework can provide stability and, hence, promote the investment in DAC. For industry to transform and for stakeholders to know when and if to invest in a technology like DAC, it needs to be ensured that in the future "*government still is behind this technology. You have to have a kind of forecast for the next 10 years*" (H, 2021). This consistency and stability can be provided through several steps. First, introducing a binding net zero goal for 2050, which the EU has already done (Breitsprecher, 2021). Secondly, after the target is set, various assessments like an 'Integrated Assessment' (Fuss et al., 2018, p. 37) can be performed to calculate pathways for CO_2 reduction (RCC, 2020). These assessments are also necessary to "*review [...] the role that direct capture could play in reaching the respective net zero targets*" (W, 2021). With this information in mind, policies can be designed to "allow the scale up on the removal side" (RCC, 2020). Moreover, to provide even more consistency and stability and also mitigate the ethical concerns of NETs, the calculated pathways for net zero can be split into removal and reduction. By setting clear and binding goals for removal, even more specific policies can be designed. These policies allow for educated investment decisions by EU member states and industry that can facilitate the scale-up of DAC (H, 2021; RCC, 2020). The instating of a long-term vision can also have a motivating effect on other governments and stakeholders, thus, also promoting internal niche processes (H, 2021; Naber et al., 2017).

6.2.2. Need for Revision

The need for revision becomes apparent through the need for consistency. Apart from the limited number of existing policies concerning the use of atmospheric CO_2 like the "European Renewable

Energy Directive 2 (RED2)" (Beuttler et al., 2019, p. 6), the legal framework is "*a little behind*" (S, 2021). This is due to the fact that DAC has not gotten much attention from EU policymakers (U, 2021). Policies and mechanisms that could promote the upscaling of DAC are inconsistent and outdated, which causes several barriers to the upscaling process. An example is the ETS, the EU's most important, market-based tool for fighting climate change (Rosell, 2019). It is based on emission allowances that can be bought and sold between emitters and decrease over time (European Commission, n.d.-c). While it provides a financial incentive for emitters to reduce their emissions, investments in DAC are not accounted for, hence, making investments into the upscaling of DAC less appealing under this scheme (European Commission, n.d.-c; W, 2021). Including DAC in this trading scheme or implementing a similar mechanism for NETs would decrease the barriers to upscaling (Rosell, 2019). Another barrier that could be resolved by EU policy is the carbon price. The current carbon price is around $40 per ton, which is very low compared to the current price of DAC and even Climeworks' goal of getting to $100 per ton (Beuttler et al., 2019; M, 2021). Artificially raising this carbon price, e.g., through tax regulations, to meet the carbon price of NETs like DAC would push the market for CO_2 captured from ambient air and thus promote the upscaling of DAC (Rosell, 2019; Yousefi-Sahzabi et al., 2014). Other mechanisms and policies such as a tax credit, which already operates in the US, mandates, and specific funding and subsidies for DAC could also push its development and scale (Meckling & Biber, 2021; Rosell, 2019). However, developing and implementing these changes to the EU's regulatory framework needs strong social and political will from the member states as S (2021) states: *"People sometimes think that [..] we have many years from [...] [presenting] solutions. That's not correct. We have many solutions. [..] They have to be scaled up"* (S, 2021).

In sum, by providing a consistent, stable, and revised framework for DAC regulatory environment, **the EU has the capacity to have a promoting effect on the niche itself as well as on the internal niche processes, hence, the upscaling of DAC.** This effect, however, needs to be re-evaluated at a later stage, when the EU has made more extensive use of its capacity. These findings suggest support for the model (*Figure 3*) and its prediction that the EU can influence the upscaling of DAC via the regulatory environment around DAC. Moreover, the role of regulations is highlighted. The codes also suggest these findings (*Figure 5* and *6*).

Nevertheless, EU efforts are increasing, which can be seen in the recently announced partnership of the EU Commission and Bill Gates to mobilize "investments in clean technologies for low-carbon industries" (European Commission, 2021), including DAC. However, until these efforts have increased and changes are applied to the current EU's regulatory framework, voluntary actions such as from Stripe and national efforts are the starting point for the expansion of the DAC market and the facilitation and promotion of upscaling (Climeworks, 2021f; RCC, 2020; W, 2021).

7. Conclusion

This thesis aims at answering the main research question: **What factors, predicted by SNM, influence the upscaling of direct air capture technologies? Additionally, what role does government play in these factors?** This is accomplished by breaking this social science research question down into three sub-questions.

In answering the first sub-question (SQ1), the literature review highlights the crucial role of NETs like DAC in meeting long-term mitigation goals set by the EU and other governments, explicitly net zero. Moreover, it indicates that the potential of DAC is mainly dependent on upscaling, thus emphasizing the relevance of the main research question and the following analysis. The remaining sub-questions are analyzed by employing a multi-media analysis and a case study.

The second sub-question (SQ2) asks what factors, expected by SNM, influence the upscaling of innovations like the DAC technologies produced by Climeworks. The findings of this thesis support the model, predicted by SNM, as all of the three internal niche processes seem to have a promoting effect on each other. Additionally, they also have a promoting effect on the niche building, nurturing, and preservation, and, through that, on the upscaling of DAC by facilitating the overcoming of barriers. Moreover, the analysis indicates an order of precedence between the processes, highlighting the articulation of expectations as the most essential promoting factor followed by social networking and learning. However, the internal niche processes, as well as the operation in a niche, only have limited influence on a predominant barrier, the current regulatory environment.

The third sub-question (SQ3), ergo, questions the EU's role in promoting the upscaling of innovations/addressing the needs formulated by the SNM analysis. This directly connects to the findings of SQ2, as it addresses the EU's role in promoting the upscaling of DAC by employing changes to the regulatory environment. These needed changes translate into the need for consistency and the need for revision of the EU's current regulatory framework. Findings suggest that the EU has the capacity to promote upscaling indirectly, through funding, and directly through regulations. Hence, the findings indicate support for the predicted influence of government via the regulatory environment on the niche and internal niche processes and upscaling. This, however, should be re-evaluated at a later stage.

There are multiple limitations to this thesis. A limitation of theory, for example, is that by only looking at the niche level, broader developments (e.g., regime or landscape) that could influence the upscaling of DAC are overlooked. In addition, due to the limited scope of this thesis, actor relationships and the EU's instruments and powers in policymaking have not been assessed thoroughly. A limitation of the model is that its explanatory power is limited because of its simplicity. The SNM is a model of a social phenomenon: innovation. Therefore, it abstracts and simplifies from reality. Hence, the extent to which it reflects the complexity of the real world is reduced. Additionally, as this is a social science model, the highly technical elements that influence the upscaling of the technology are not exhaustively included. Thus, the validity is limited. Notwithstanding, the model offers indications of opportunities for identifying areas for future research, e.g., networking and learning. A limitation of the methods is that, due to the scope of this thesis, only a limited number of data could be gathered and reviewed. Moreover, the applicability of the codebook is limited as it was constructed by only a single coder, which could also explain the relatively low percentage of overlap with the second coder. Besides, by having only one interviewer and interpreter of the data, personal biases can influence the analysis and results.

Future research can help to address these limitations. Limitations of theory and models can be addressed by including other theoretical approaches and tools, e.g., a multi-level perspective, an actor analysis, policymaking, and agenda-setting in the EU or intergovernmentalism. Moreover, these approaches and tools, as well as the findings from this thesis, could be used to expand and revise the model or create complementary models. Other data sources could be included to address limitations of the methods, e.g., survey data, or a quantitative study could be conducted. Furthermore, the codebook could be revised by a multiplicity of coders to increase its applicability.

Keeping these limitations in mind, the findings of this thesis have a high societal and scientific relevance. Many technologies that could potentially play an essential role in mitigating climate change are underexploited in the EU. This is, as with DAC, not because of a lack of technological readiness but because of a lack of political will and policymaking. This thesis shows the marketability and viability of DAC technologies and their potential in being one of the relevant technologies within a climate mitigation toolkit. DAC technology, which could already be put to use, could help facilitate the transition to sustainability in a just way, giving society and industry time to adjust. However, this thesis has shown that the choice of mitigation tool in the form of technology is highly political and politized. This indicates the need for science-based policy to avoid blind spots and for social science to adjust and broaden its focus towards the relationship of policy and sustainable technologies.

Besides the societal and scientific relevance, this thesis has some other clear strengths. Using an innovative multi-media analysis, it exhibits triangulation which increases the robustness of data. Moreover, even though the explanatory power of SNM is limited, using this theoretical approach in this context might show its potential for future studies. This is because, as of right now, SNM is not exploited enough in the context of social and policy science. Additionally, including new data sources, like podcasts, increases the broadness of data and the possibility of new and relevant data insights.

This thesis tries to contribute to filling some of the knowledge gaps in social science literature about the understudied topic of the upscaling of DAC technologies. Besides, it highlights the potential of DAC in meeting crucial long-term climate goals such as net zero. Current unwillingness to explore this possibility can be a missed opportunity. In this sense, upscaling this technology to a climate-relevant scale, however, as underlined by this thesis, needs a strong political and societal will. For that, this research also implies starting points for policy interventions and further research. This leads to an essential and final question. How long must our house burn before we invest in a hose and start to extinguish the fire sincerely?

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9. Appendix

Appendix A: Type and Count of Sources

Source Type		Count
Documents	Journal Articles (Peer-Reviewed)	23
	News/Magazine Articles	8
	Press Releases from Organizations	18
	Websites from Organizations	16
	Working Papers	1
	Reports (Governments, Intergovernmental, Institutes)	6
	Book Chapters	1
	Books	2
	Other Websites	5
	Databases	3
	LinkedIn	4
Podcasts	--	4
Interviews	--	6

Appendix B: Interview Transcripts

See the separate zip file, handed in with this thesis. Transcript of W was excluded for anonymity reasons.

Appendix C: Codebook

Category (C)	**Sub-Category (SC)**	**Description**	**Examples**	**Count (SC/C)**
Climeworks	None	Information directly connected to Climeworks.	E.g., Climeworks is one of the main partners	13/13
Learning	Learning Gains	What for, why learning is essential.	E.g., the education of people, improving processes	11/15
	Learning Actions	How to learn.	E.g., learning by doing, demonstrations	5/15
Networks	Partnerships	Possible, future and existing partnerships of Climeworks.	E.g., Store & GO, greenhouse sector	27/37
	Network Action	How to network.	E.g., bringing different actors together	8/37

Expectations	Promises	Advantages and potentials of direct air capture/Climeworks' technology.	E.g., supply CO_2 in remote areas, sustainability	24/50
	Concerns/Barriers	Disadvantages and obstacles for direct air capture.	E.g., cost, energy demand	20/50
	Strategy	How to communicate expectations.	E.g., not to overpromise, optimism	14/50
Upscaling	None	The direct mentioning of upscaling or related words.	E.g., scale, of scales.	8/8
Policy Measures	Funds	Financial support.	Financial support. E.g., grants, subsidy	5/29
	Regulations	Regulations that directly or indirectly influence direct air capture.	E.g., emission trading system, carbon tax.	21/29
	Guidance	Support apart from funds and regulation.	E.g., vision, providing a platform for knowledge exchange.	7/29

Appendix D: Sources of "Climeworks' Networked Niche"

(Beuttler et al., 2019; Bio-based News, 2018; Chalmin, 2019; Climeworks, n.d.-a, 2017, 2020b, 2020c, 2020f, 2020g, 2021c, 2021e, 2021f; Crunchbase, n.d.-b; European Commission, n.d.-e; Green Car Congress, 2020; IET, n.d.; INERATEC, 2019; Kotecki, 2019; S, 2021; Sunfire, n.d.; Volkswagen, 2020)

Appendix E: Overview of Interviews

Interviewee	**Date**	**Time**	**Length**
B	4.5.2021	10:30 am	38:53 min
H	4.5.2021	11:30 am	26:53 min
S	5.5.2021	12:00 pm	28:10 min
U	5.5.2021	5:00 pm	31:03 min
M	7.5.2021	10:00 am	31:47 min
W	10.5.2021	2:00 pm	40:26 min