Institutional Analysis of Direct Air Capture in the context of Aviation Sustainability

Master Thesis Report

by

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Summary

The aviation industry is one of the most challenging sectors to decarbonise. There is an urgent need to reduce emissions in order to meet its committed goal of achieving net-zero flying by 2050. Along with the existing and proposed decarbonization options such as electric aircraft, hydrogen fuel, and operational improvements, a hard-to-abate sector like aviation would require large amounts of carbon dioxide removal in order to achieve net zero. One such technology-based carbon removal option is Direct Air Capture (DAC) which has the potential to emerge as a potential game-changer to mitigate aviation's environmental impact. This thesis report presents an analysis of the suitability of adopting DAC for aviation sustainability, viewed through an institutional analysis lens using the Institutional Analysis and Development (IAD) framework. DAC is framed as a technology niche from the Multi-Level Perspective to get a descriptive understanding of the problem context and the interconnected parts in the larger picture of aviation sustainability innovations. Specific to DAC, multiple dimensions of DAC integration in the aviation sector, including technology, actors, and policy analysis are carried out. Employing the IAD framework, the underlying institutional arrangements, rules, and incentives influencing the adoption of DAC for carbon removal in the aviation industry are examined.

Data was collected from grey literature, industry reports and interviews with aviation industry professionals. To assess the suitability of DAC for aviation sustainability, various evaluative criteria such as carbon emission reduction potential, technological feasibility, cost-effectiveness, and market acceptance were considered. There are tradeoffs in using DAC for aviation such as complexity in carbon markets, uncertainties in carbon credit pricing, and challenges in accurately measuring DAC's carbon removal effectiveness. It is seen that DAC holds promise as an innovative carbon removal technology with potential applications in aviation including but not limited to the use in sustainable aviation fuel production. The current state of technology is nascent but the proposed policies under the EU have the potential to drive the commercialization of this technology. The aviation industry stakeholders, along with carbon market operators, DAC providers, and government policymakers, are key actors involved. The incentives and motivations of actors in determining the success and scalability of DAC for aviation are illustrated.

Based on the analysis, the following recommendations are provided. To minimize residual emissions from aviation, several strategic approaches can be undertaken. Firstly, fostering collaborative research and development among airlines, DAC technology providers, and research institutions can be vital to tackle technological challenges and creating tailored DAC solutions for aviation. Secondly, governments should extend their support through policy incentives and research grants, encouraging DAC development and integration within the aviation industry. Thirdly, establishing robust standards and certification for DAC-derived Sustainable Aviation Fuel ensures the credibility and quality of carbon removal achieved, further supporting aviation sustainability.

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Introduction

1.1. Problem Background

The adverse impacts of climate change caused by human activities are increasing year on year. The extent of climate change and its consequences in the future will primarily rely on the global emissions of carbon dioxide (CO_2) and other greenhouse gases. By implementing substantial reductions in CO_2 emissions, it would be possible to control the rate of the annual average global temperature increase. As per the Intergovernmental Panel on Climate Change (IPCC), global temperatures can be brought back below the 2°C increase threshold by the end of the century only if deep emission cuts are paired with the rapid deployment of techniques to capture and store CO_2 such as reforesting lands and using carbon removal techniques such as Direct Air Capture of carbon dioxide from ambient air (Minx et al., 2018). However, there is a need to act fast and scale up technological carbon removal to around 75 Mt annually by 2030, compared to less than 1 Mt being captured and removed as of today (Fuss et al., 2018). Given the urgent awareness of the climate crisis, governments, investors, and companies are realizing the need to take definitive action.

There is a need to drastically cut carbon emissions across all sectors. Sectors such as industry, aviation, shipping, and agriculture are commonly seen as challenging to decarbonize. In sectors like these, achieving net-zero emissions by 2050 is expected to be very difficult. Hence these are referred to as 'hard to abate' sectors (PBL, 2022). To achieve the climate targets of the Paris Agreement (to hold the increase in the global average temperature to well below 2°C above pre-industrial levels), the remaining emissions in these sectors would need to be compensated via carbon dioxide removal (CDR) measures. The obstacles to emission reduction in these sectors stem from factors like high sectoral growth rates, the absence of affordable mitigation technologies, and the difficulties associated with implementation.

CDR can play a crucial role in complementing existing emission reduction efforts. CDR involves capturing CO_2 from the atmosphere and storing it durably on land, in the ocean, in geological formations or in products. Examples include reforestation, biochar, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS)(Budnis, 2022) as illustrated in the figure below. Nature-based approaches like planting trees and restoring forests are most widely deployed today. Novel technological methods like Direct Air Capture (DAC) are also being developed which can offer additional benefits as compared to nature-based carbon removal methods. Achieving high levels of carbon removal will take significant research and development to determine the most effective methods, minimize environmental impacts, and rapidly develop major projects across the world. Additionally, suitable policies play a crucial role in incentivizing the adoption of innovative technologies for carbon removal.

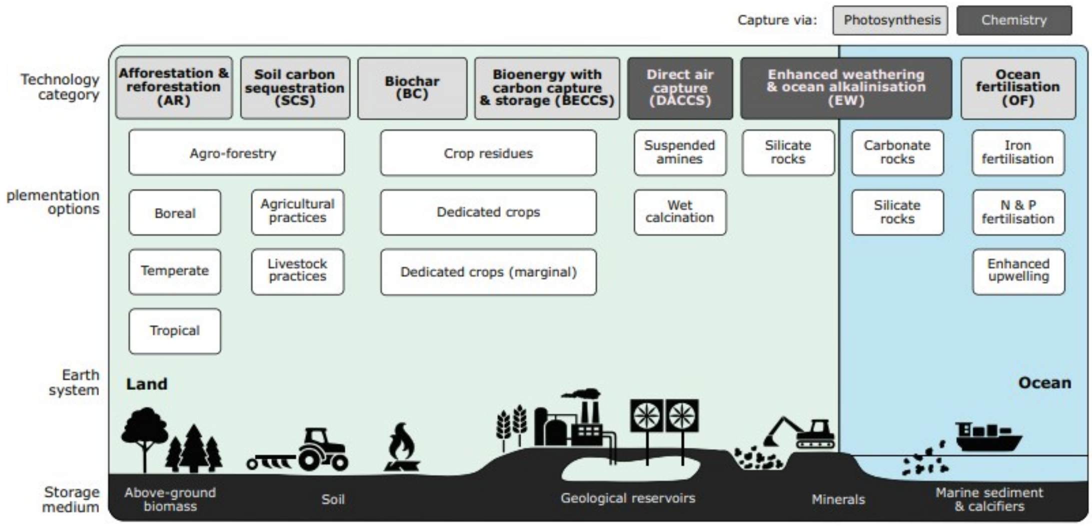

Figure 1.1: Negative Emission Technologies
(Minx et al., 2018)

1.1.1. Case for Aviation Sector

One such important hard-to-abate sector is the aviation industry. The aviation industry is one of the fastest-growing sources of greenhouse gas emissions and accounts for about 3% of global CO_2 emissions(van der, 2050). There are technical and structural challenges that make the aviation sector particularly hard to abate. In October 2021, the International Air Transport Association (IATA) set a target for carbon-neutral growth from 2020, and the aviation sector committed to achieving net-zero emissions by 2050(Larsson, Elofsson, Sterner, & Åkerman, 2019).

Multiple decarbonisation means such as technological innovation in aircraft design, new fuels like hydrogen and sustainable aviation fuel (SAF), efficiency improvements in airport operations and air traffic management, and market-based measures are already being implemented and further developed in various stages to achieve this goal. In addition to these innovations, the aviation sector is also implementing circularity measures in areas related to maintenance, repair and overhaul. There is also potential to further apply circular economy principles to aviation especially in the field of materials by taking a life-cycle approach which considers materials, production and manufacturing in addition to emissions during operations(van der, 2050). However, since aviation is a hard-to-abate sector, carbon removal is especially important because the current decarbonization drivers such as sustainable aviation fuel (SAF) and electrification alone may not be enough to achieve the industry's emissions reduction goals. Even with the adoption measures such as the use of SAF, hydrogen and electric aircraft, residual emissions will remain. Carbon removal technologies can help offset these residual emissions and help the aviation sector reach its net zero target. The captured CO_2 can also be valorized (given value) and used in products such as SAF, recycled carbon composites and plastics which can be reused, thus creating a circular system which can complement the existing decarbonization efforts.

The net-zero strategy for the industry envisions employing offsets and carbon removal technologies as a temporary measure until within-industry solutions become dominant (refer to the figures below). In the event that completely eliminating emissions directly at the source is unattainable, the industry is dedicated to addressing the residual emissions through offsetting methods, including technologies for capturing carbon.

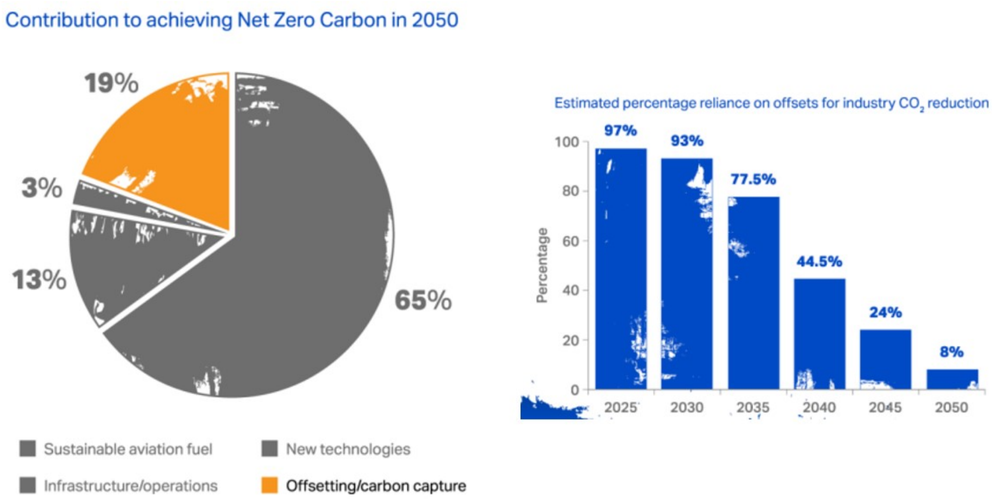

Figure 1.2: Reliance on carbon capture and offsets for 2050 net zero aviation (IATA, 2021)

1.1.2. Why Direct Air Capture?

Among the various carbon removal options, Direct Air Capture, a novel technology-based method for capturing CO_2 from the atmosphere can be seen as a potential solution to reduce emissions from aviation. This method involves the use of specialized sorbents that selectively adsorb CO_2 molecules from the ambient air. Once saturated, these sorbents release the captured CO_2 through a desorption process. The separated CO_2 can be stored underground in geological formations or utilized for various purposes, such as enhanced oil recovery or synthetic fuel production (Tamme, 2021).

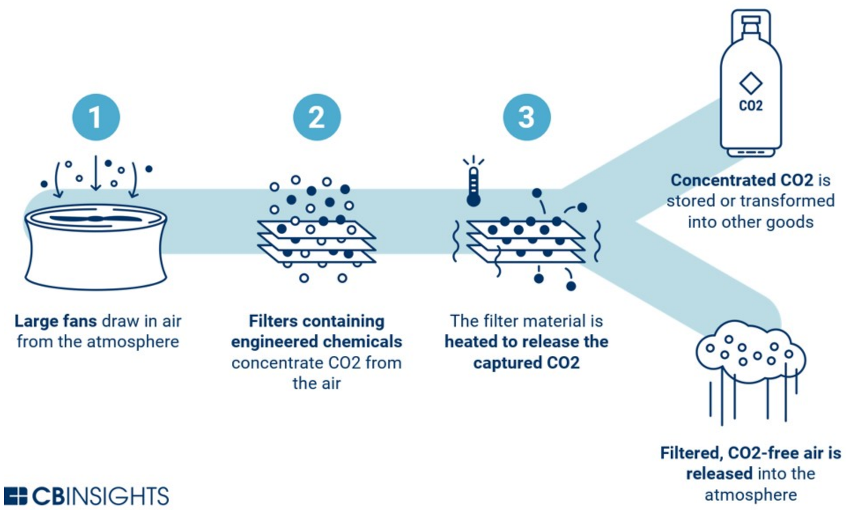

Figure 1.3: Principle of Direct Air Capture (CBInsight, 2021)

There has been growing consensus that CO_2 removal and DAC are expected to play a key role in the decarbonization of aviation. In a report endorsed by major global aviation leaders and signatories including more than one-third of the global airline industry,(MPP & CST, 2022), DAC was highlighted as a key solution for decarbonizing aviation through both CO_2 removal and power-to-liquids sustainable aviation fuels. There are two potential approaches for utilizing DAC-captured CO_2 to reduce carbon emissions in the aviation industry. The first approach involves combining DAC-captured CO_2 with carbon capture and storage where the CO_2 is collected and stored underground while conventional fossil kerosene is still used in aviation. This relates to carbon offsetting on the airlines' side. The second approach involves utilizing DAC-captured CO_2 and green hydrogen to produce e-kerosene, a nearly emissions-free alternative fuel. E-kerosene can serve as a replacement for fossil jet fuel or other aviation-related products.

Airbus and several prominent airlines, including Air Canada, Air France-KLM, easyJet, International Airlines Group, LATAM Airlines Group, Lufthansa Group, and Virgin Atlantic, have recently signed letters of intent to investigate the potential supply of carbon removal credits from DAC (Airbus, 2022). These airlines have expressed their willingness to engage in discussions and potentially pre-purchase verified and long-lasting carbon removal credits from 2025 to 2028. This collaborative effort aims to explore opportunities for reducing carbon emissions and promoting sustainability within the aviation industry. These efforts and initiatives recognize the role of DAC in the pathway towards aviation sustainability.

As part of its global climate strategy, Airbus is interested in the development and deployment of DAC technology, among several technological pathways in support of the aviation industry's decarbonisation ambitions(Airbus, 2022). As the aviation industry cannot capture all CO_2 emissions released into the atmosphere at source, captured atmospheric CO_2 can also be safely and permanently stored in geologic reservoirs or be used as feedstock in the production of SAF, polymers, construction materials and other products. This would allow the sector to extract the equivalent amount of emissions from its operations directly from the air, thereby counterbalancing residual emissions. Airbus is partnering with airlines and CDR companies to secure carbon removal credits, while also exploring the potential to incorporate the captured CO_2 with SAF production or other products in a circular fashion for the aviation industry at large. However, given the nascent stage of DAC technology, the techno-economics, institutional setup and policies related to DACCS for aviation are still a topic for further research.

In this context, a review of the existing scientific articles and grey literature was conducted to identify key themes related to Direct Air Capture as an additional tool in climate change mitigation and its potential to reduce aviation's negative impact on the environment. Typically, studies related to carbon removal technologies have focussed on the technology assessment, method efficiency and techno-economic feasibility. Studies related to non-technical dimensions of carbon removal are few and those which do are usually focused on low-carbon transitions or comparative studies among the various carbon removal options. There are few studies which incorporate an interdisciplinary approach to analyze the socio-technical dynamics of carbon removal, especially in the case of aviation. Hence, the literature review helped identify knowledge gaps and narrow down the focus area for the study.

1.2. Literature Review

This section presents a review of the scientific articles and grey literature related to DAC technology, its key considerations and its application to aviation. The section begins with a description of the search strategy, key search phrases and academic databases used. The key findings from the literature study are presented. The identified knowledge gap and the derived research questions are presented in the next section.

1.2.1. Search Strategy

Standard academic databases such as Scopus, ScienceDirect, ResearchGate, Emerald Insight and Google Scholar were used for the initial exploratory search to identify relevant articles. These databases were chosen as they are recognized as reliable online repositories containing peer-reviewed articles from several publishers across disciplines and sources. These articles were then analyzed using Connected Papers, a visual tool that helps researchers explore related papers in their field of study. The process helped map out related papers and the list was refined by narrowing down the scope. The selected articles were also checked for cited sources.

Some examples of the main keyword search strings used were:

(”direct air capture” OR ”Atmospheric Carbon Capture” OR ”Carbon Removal from Atmosphere” OR ”Atmospheric Carbon Sequestration”) AND (”aviation” OR ”aerospace”)

(”Direct Air Capture Technology” AND ”Aviation” AND ”sustainability”)

(”Efficiency” AND ”Direct Air Capture” AND ”aviation”)

(”Scalability” AND ”Direct Air Capture” AND ”aviation”)

(”Cost-effectiveness” AND ”Direct Air Capture”)

(”Stakeholder attitudes” AND ”Direct Air Capture”)

(” Government support” OR ”Policies” OR ”Regulations” AND ”Direct Air Capture”)

(”Institutional Analysis” AND ” Carbon Removal”)

(”Institutional Analysis” AND ” Aviation”)

The articles selected related to the broader theme of decarbonizing the aviation sector. Specific themes of interest such as carbon capture technology, carbon offsetting, and policy initiatives were included in the scope. Articles with a specific focus only on commercial aviation and related emissions were excluded. Additional criteria points included non-country-specific insights and English as the language of chosen literature.

After eliminating duplicate search results, the articles underwent a screening process to include only papers that were relevant. This methodology also ensured alignment with the latest advancements and trends in the field. From the resulting list of articles, further screening excluded those that were inaccessible or unobtainable, contained only quantitative reports, lacked insights into data collection, and focused solely on process enhancement or chemical engineering aspects of the technology. The eligibility criteria for the title screening of the papers were centred on articles discussing policy aspects of DAC adoption, the institutional framework of the aviation sector, and the supply-demand dynamics of DAC. Subsequent to the abstract screening, a more refined selection was made. This, combined with recommended articles from supervisors and other citations, formed the basis of the literature review aimed at identifying the knowledge gap.

1.2.2. Findings from Literature

The primary topics reviewed from the literature can be categorized as:

- Carbon Direct Removal (CDR) Landscape
- Direct Air Capture (DAC) key technology aspects
- Supply Demand dynamics of DAC
- Technology innovation niches in aviation
- Policy aspects of DAC
- Ethical considerations of scaling DAC
- Carbon Removal for aviation

The important concepts and key findings from each theme are identified and discussed below.

DAC Technology and Supply-side Aspects

The literature on DAC is nested under the body of literature related to CCUS and primarily focuses on the technological aspects and supply-side considerations. This includes R&D activities that compare different methods of capturing CO_2 from ambient air and the mechanisms to sustain the process (Lackner, 2013). There is extensive literature on the formative phases, involving experimentation and optimization of designs and configurations of DAC technology. The economic costs of DAC and the financial comparisons are extensively discussed, and there is a growing interest in scaling up DAC technologies for mass production (Sinha, Darunte, Jones, Realff, & Kawajiri, 2017). Detailed information on costs and potentials can be found in studies which highlight the importance of policy support, innovation, and collaboration in accelerating the development and commercial deployment of CCUS. (Fuss et al., 2018)

Technology Niche Innovation and Markets

DAC has received significant attention from entrepreneurial firms due to its main barrier being direct costs rather than side effects or social concerns. Startups explore niche markets and applications for DAC, such as greenhouse fertilization, industrial use, or enhanced oil recovery (Budnis, 2022). These niche markets offer opportunities for early adoption and innovation, as well as potential co-benefits beyond carbon removal. To transition from niche markets to broader commercial adoption, carbon removal technologies need to prove their reliability and demonstrate performance in real-world environments. Building examples and successful demonstrations are critical to reducing the risk associated with these technologies and attracting private investment (Krysta Biniek, Phil De Luna, Luciano Di Fiori, Alastair Hamilton, & Brandon Stackhouse, 2022). However, the technology ”valley of death” poses a challenge, as it may be difficult to secure sufficient investment for large-scale demonstrations (Nemet et al., 2018). So it may be essential to prioritize knowledge generation through demonstrations rather than focusing solely on production metrics. Regarding markets, niche markets provide initial opportunities for carbon removal technologies, including those relevant to aviation. Early adopters in these markets, with a higher willingness to pay, can provide insulation from the competition and help launch technologies with high initial costs (Rogge & Reichardt, 2016).

Scaling Up

Scaling up carbon removal technologies to commercially viable levels is a complex process that requires time and integration with existing infrastructures (Geels, 2002). Factors such as access to CO_2 pipeline systems or the development of mining and transportation infrastructures may influence the deployment speed of different carbon removal technologies. Additionally, the integration of DAC with aviation infrastructure requires considerations of unit scale increases and mass manufacturing of DAC systems (Lackner, 2013).

Supply- Demand Dynamics and Policy Influence

Innovation in carbon removal technologies involves both supply-side activities, focused on improving costs and performance, and demand-side activities, concerned with market dynamics and public acceptance. Performance improvements and cost reductions are key drivers of innovation, with performance encompassing various characteristics beyond efficiency (Nemet et al., 2018). The demand for carbon removal technologies is influenced by policy, market dynamics, and public acceptance, which create inter-dependencies between supply and demand. The demand for carbon removal technologies, including those applicable to aviation, is heavily influenced by policy mechanisms such as carbon pricing, subsidies, and technology mandates. Policy uncertainty and credibility play a significant role in shaping the demand for these technologies (Tamme & Beck, 2021). Furthermore, co-benefits beyond carbon removal, as well as expectations of future demand, can impact investment decisions and the need for early subsidies to achieve scale and cost reductions over time.

Ethical Considerations and Public Acceptability

The pursuit of carbon removal technologies also raises ethical concerns, as it may postpone immediate emissions reductions and shift the burden to future generations. Issues of procedural and distributive justice significantly impact the public acceptability of these technologies (Anderson & Peters, 2016). The acceptability of individual carbon removal technologies and the broader strategy of carbon removal are influenced by these ethical considerations. This is especially important in sectors like aviation.

Carbon Removal for Aviation

The aviation sector is dependent on carbon-intensive petroleum fuels, such as kerosene, kerosene-petrol mixture or aviation fuel and this dependence will likely remain in the near future due to the early development stage and limitations of alternatives (Gray, McDonagh, O'Shea, Smyth, & Murphy, 2021). A major barrier to large-scale biofuel use is the required large amounts of land and water (Peeters, 2017) and there are many technical challenges in the development of electric aircraft and the requirement for battery-specific energies (Viswanathan & Knapp, 2019). A challenge regarding the introduction of new less carbon-intensive aircraft is the high life expectancy of aircraft, resulting in a longer turnover time (Hasan et al., 2021). From a policy perspective, the international character of the aviation sector forms a barrier for policymakers to set certain standards, due to fear of carbon leakage, and to implement an efficient carbon price mechanism. Apart from the European Union, international aviation emissions are not part of the Nationally Determined Commitments (NDCs) (PBL, 2022). The international character of the sector and an associated favourable taxation regime make it difficult to implement substantial policies to reduce emissions.

The aviation sector can attain net-zero emissions through three primary methods: electric aircraft, alternative fuels, and carbon offsetting, which involves removing emissions from the atmosphere. While electric planes are already operational, their potential to reduce emissions from commercial long-haul flights is projected to be constrained by 2050. The International Civil Aviation Organization (ICAO) has introduced the Carbon Offsetting and Reduction Scheme for International Aviation, aiming to achieve carbon-neutral growth beyond 2020 through various mitigation measures(Lawson, 2012).

Emphasizing the use of alternative fuels and the acquisition of carbon offsets are seen as crucial steps in reaching this ambitious objective. If the CO_2 feedstock is obtained through DAC and hydrogen is produced with carbon-free electricity, the synthesized fuel would have net-zero CO_2 emissions. e-fuels are compatible with existing infrastructures and engines, but currently, their lack of aromatics does not allow for blending shares of the above 50% with conventional jet fuel. One of the main barriers to the use of synthetic fuels is their high cost with respect to that conventional fuels(Becattini, Gabrielli, & Mazzotti, 2021).

To summarize the findings in a concise manner:

Theme	Key Points
Technological Aspects and Supply-Side Factors	DAC literature falls within CCUS (Carbon Capture, Utilization, and Storage) discussions. The research covers various air carbon dioxide capture methods and sustaining the process. Economic costs, financial comparisons, and scaling up DAC technologies are central themes.
Market Exploration and Early Adoption	Startups explore DAC applications in niche markets like greenhouse fertilization and industrial use. Niche markets offer early adoption chances and co-benefits beyond carbon removal. Successful demonstrations are vital for attracting private investment and transitioning to broader markets.
Integration with Existing Infrastructures	Scaling carbon removal tech requires integration with existing infrastructures. Access to carbon dioxide pipeline systems and transportation infrastructure affects deployment speed. DAC's integration with aviation infrastructure involves unit scale increases and mass manufacturing.
Ethical Considerations and Public Acceptance	Carbon removal raises ethical issues and impacts immediate emissions reduction efforts. Public acceptance is influenced by procedural and distributive justice considerations.
Aviation Sector Challenges	The aviation sector relies on carbon-intensive petroleum fuels, with limitations on alternatives due to technical challenges and the long lifespan of aircraft. The international nature of aviation poses challenges for setting standards and implementing effective carbon pricing mechanisms.
Synthesized Fuels for Net-Zero Emissions	Utilizing Direct Air Capture (DAC) with carbon-free electricity to produce synthesized fuels is a promising pathway towards net-zero carbon emissions.

Table 1.1: Summary of literature review

From the literature, it is clear that the focus is more on the technological aspects and economic considerations of direct air capture. It is seen that DAC has potential in niche applications and markets which can allow it to grow. The importance of integration with existing infrastructure is also highlighted. However, there was a gap in bringing together the potential application of DAC for the cause of sustainable aviation. While the challenges of the aviation sector were outlined, including its institutional and structural setup, an understanding of how technologies like DAC can be adopted is unclear. There is a notable absence of an institutional analysis perspective. Institutional factors, such as policy frameworks, regulations, governance structures, and stakeholder dynamics, play a crucial role in shaping the adoption, implementation, and effectiveness of carbon removal technologies. Institutional analysis can provide insights into the social, political, and cultural contexts within which carbon removal technologies operate. It can help uncover the barriers and facilitators that emerge from institutional arrangements and shed light on the interactions between various stakeholders involved in the adoption and deployment of these technologies. Understanding the institutional landscape is essential for identifying opportunities for policy interventions, addressing governance challenges, and ensuring the societal acceptance of carbon removal technologies. Moreover, it aids in understanding how something comes about, rather than who is doing it, thus helping in revealing systemic problems and giving recommendations for more permanent and effective change.

By incorporating an institutional analysis perspective, questions related to the institutional barriers and enablers for the adoption of DAC in the aviation sector can be examined. This includes examining the role of governments, regulatory agencies, industry associations, and other relevant actors in creating supportive policy environments and overcoming hurdles in scaling up these technologies. Additionally, studying the social acceptance, public perception, and stakeholder engagement aspects can provide valuable insights into the dynamics of deploying carbon removal technologies in aviation. Thus integrating institutional perspectives can help identify strategies for effective policy-making, collaborative governance frameworks, and mechanisms for ensuring sustainable deployment of DAC technologies for the aviation sector.

1.3. Research Questions

This leads to the main research theme which is as follows:

What are the institutional enablers and barriers to the adoption of Direct Air Capture in the context of aviation sustainability?

To understand the institutional enablers and barriers for DAC in aviation, a systematic approach is needed that considers all the key contributing factors. To begin with, an overview of the current landscape of decarbonization efforts in the aviation sector is useful as it helps position the role of direct air capture and identify co-developing technologies. This leads to the first sub-research question:

1. What is the current landscape of decarbonization efforts in the aviation sector?

Beginning the institutional analysis, it is important to first understand the current state of the technology of DAC. This includes high-level functional understanding, requirements in terms of energy, land use, cost and the potential use cases of the captured carbon, specifically for the aviation sector. Next, an understanding of the current state of technology with respect to technology readiness and the required scale is needed. This acts as an input for the institutional analysis. This results in the second sub-research question:

2. What are the key factors defining the current state of Direct Air Capture technology?

The required scale-up needed for DAC can be facilitated by suitable policy action and frameworks. This required a study of the existing policy landscape (primarily EU), in the context of DAC for aviation. This leads to the third sub-research question:

3. What are the current policies and regulations that relate to DAC, specifically to the aviation sector?

Bringing together the technological and policy aspects of DAC, a stakeholder analysis is required which helps identify the key actors, their interests, influence and coordination. Further, it can answer important questions on who is removing carbon, who is ultimately benefiting, coalitions, and responsibility sharing. This leads to the fourth sub-research question:

4. Who are the relevant actors involved in the development and potential adoption of Direct Air Capture in the aviation context?

Insights from the above four questions help answer the broader question and identify institutional enablers and barriers to the adoption of DAC for aviation. Based on the above, relevant themes or use cases are identified as action situations for institutional analysis of the problem. This leads to the final sub-research question:

5. How can the institutional arrangements within the aviation sector influence the adoption and implementation of Direct Air Capture, for the relevant use case identified?

The identified use case is analysed using an institutional analysis framework and recommendations are provided for each actor category. Broader sectoral and societal implications are drawn from this. Finally, insights from all the sub-questions are tied up to present the institutional enablers and barriers to the adoption of direct air capture toward aviation sustainability.

The following section presents the research methodology and report structure.

1.4. Research Methodology

This section describes the research methodology, frameworks and data used for the study. Based on the nature of the research problem, a qualitative research approach was followed. An inductive method was preferred because it is guided by a theoretical foundation(Jebb, Parrigon, & Woo, 2017). It involves generalizing results beyond the observations made by looking for patterns in the data collected, such as relationships among stakeholders, power interests and conflict. In the context of examining the adoption of DAC for aviation sustainability through the lens of institutional analysis and IAD framework, the research methodology employed can be characterized as a qualitative approach. To begin with, a technology transition framework was used for the descriptive analysis of the problem context. Next, the institutional analysis was carried out using qualitative data from policy documents, grey literature and interviews. This helped to understand the institutional arrangements, policy frameworks, and incentives influencing the adoption of DAC in the aviation industry.

1.4.1. Data Sources

The below table summarizes the data sources used:

Data Source	Description
Scientific Literature	CDR landscape, DAC technical aspects, Policy status and challenges
Grey Literature	Industry reports related to state of CDR , DAC. EU policy documents related to carbon capture and DAC.
Interviews	With stakeholders working towards sustainable aviation initiatives.
In-person interactions	With aviation sector professionals at LDE Thesis Labs to gain sectoral knowledge and insights.

Table 1.2: Data Sources

Scientific and Grey Literature

The primary data source for this study was grey literature and EU policy documents. The study involved document analysis of EU policy documents and proposals related to carbon capture, both from a standalone viewpoint and from an aviation perspective. The data collection approach included a systematic search and review of policy documents, reports, industry publications, conference proceedings, and other relevant sources related to aviation sustainability, DAC technology, carbon offsetting programs, and institutional frameworks within the aviation sector. Industry benchmark publications like IEA, IPCC, NLR, Transport & Environment were preferred. This analysis provided valuable insights into the historical context and policy dynamics surrounding DAC and its potential adoption in aviation. Grey literature was studied to understand the position of key stakeholders in the aviation industry, including representatives from airlines, DAC technology developers, SAF producers, government policymakers, and environmental organizations. Additionally, scientific literature related to technological efficiency and key aspects of direct air capture were also studied.

However, it also posed challenges in terms of data quality and potential bias, which were addressed by critically evaluating the credibility and relevance of each source. For instance, reports on carbon capture backed by fossil fuel majors had to be evaluated because they could be promoting carbon capture as a free pass to continue emitting instead of prioritizing decarbonization. The data collection also focussed on the EU policy documents. These documents provided essential insights into the historical development of aviation policies, the current state of sustainability initiatives, and the emerging institutional arrangements influencing the application of DAC within the aviation industry.

The list of key policy documents and industry reports is listed in **Appendix B**

Interviews

Interviews provide a rich source of data as they allow for a detailed exploration of the experiences, perspectives and attitudes of participants. Semi-structured interviews were conducted as they provide flexibility to allow the interviewee to elaborate and discuss the topics more in-depth apart from the set of pre-determined questions. The objective of the interviews was to aid in contextual understanding of the aviation sector and challenges in adopting new technologies and processes such as direct air capture. They helped uncover practical challenges from stakeholders' perspectives, decision-making processes, and considerations regarding DAC adoption in aviation sustainability.

Due process was followed and approval from the Human Research Ethics Committee (HREC) was obtained before the interviews. An informed consent form was created and the interviewees were informed about the purpose of the study and the usage of the collected data. Interviews were conducted online using MS Teams. The interviews were recorded and transcribed after the due consent of the interviewees. This was then anonymized and used to derive insights for the study. The anonymized transcripts are available for reference in **Appendix A**, along with the informed consent form. In the following chapters, the statements from interviewees will be cited in relevant sections.

The interviews were conducted for the purpose of expanding the knowledge of actor motivations and behaviour in the system and not to draw direct insights. Open-ended questions were asked at the beginning of the interview to acquire a general understanding of the issue and create some initial impressions. Notes were made based on important observations mentioned and other questions that were increasingly more targeted were asked based on the answers to the broader topic using the funnelling approach (Dicicco-Bloom & Crabtree, 2006). As this was qualitative research, the sample size was not determined by statistical calculations but rather by the principle of data saturation, which is the point at which collecting more data no longer leads to new insights or themes. Additionally, interactions at the LDE Thesis Labs helped in asking questions to Airbus stakeholders regarding their viewpoints on aviation sustainability and the path ahead.

The below table highlights the interviewees' information in the anonymized form:

Participant ID	Role	Industry
1	Project Lead	Sustainable Aviation Fuel company
2	Business Developer	Airport
3	Policy Associate	Climate think-tank
4	Aviation Consultant	Sustainable aviation consultancy
5	Researcher	Aviation Policy & Law

Table 1.3: Interview Information

The combination of data from interviews and documents/grey literature analysis helped uncover an understanding of the institutional factors influencing DAC adoption for aviation sustainability. Through this qualitative approach, the study identified key challenges, incentives, and trade-offs faced by different actors, and consequently, helped formulate meaningful recommendations for different actor categories to aid in DAC adoption in the aviation sector.

The following section presents the research flow diagram

1.4.2. Research Flow Diagram

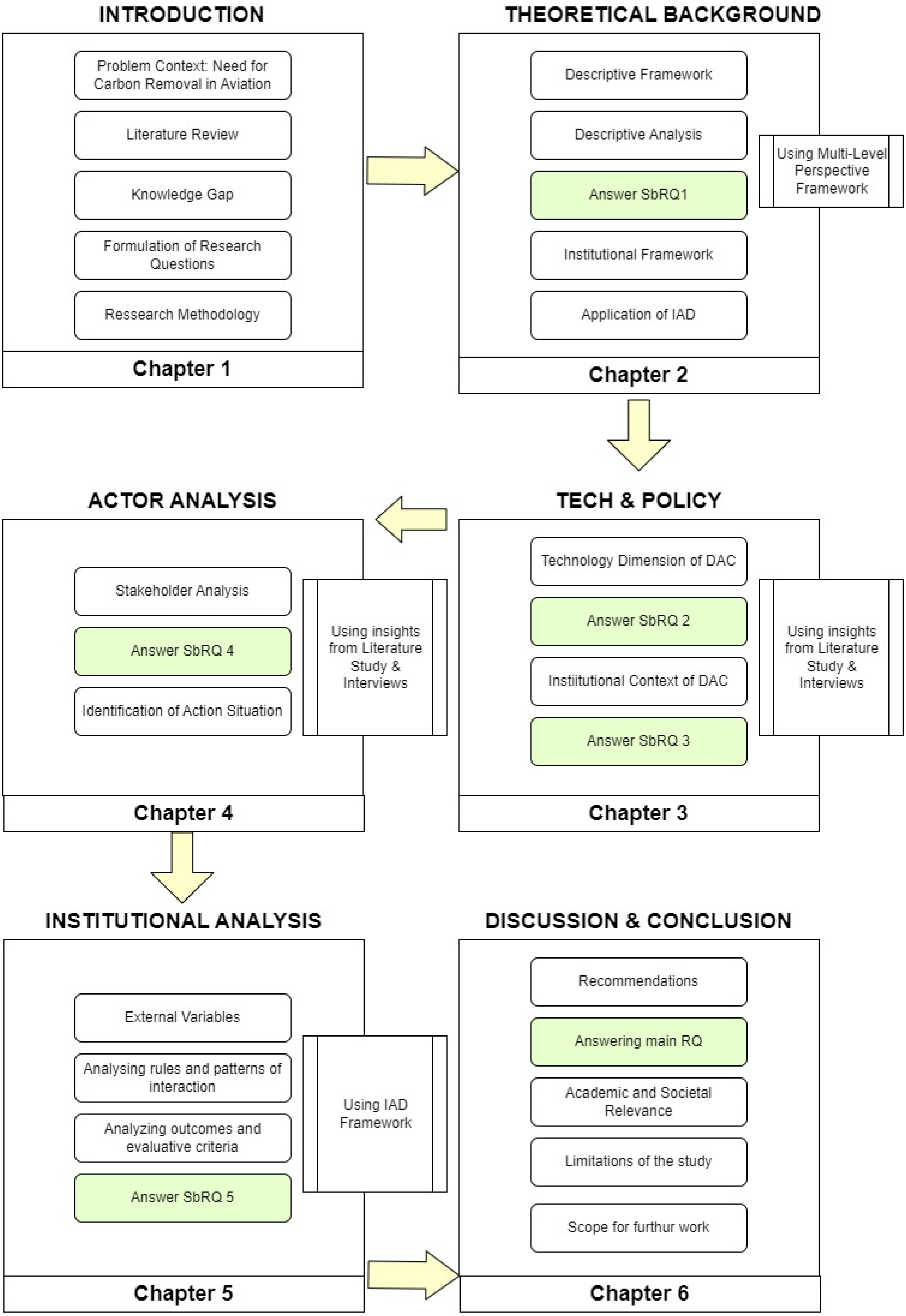

Figure 1.4: Research Flow Diagram

2

Theoretical Background

This chapter presents the theoretical background for the analysis methods used in this thesis. This is useful as it provides a conceptual framework for understanding and analyzing the topic in the required direction. In this case, it helps contextualize the research and offers a structured way to organize the problem statement. In the first part, a descriptive framework for understanding how technology transitions come into being and its application to the problem context is presented. Based on this descriptive analysis, the first sub-research question is answered. Next, the link between the transition framework and institutional analysis is highlighted. Finally, the institutional analysis framework and its various components are described in the context of the given problem.

2.1. Framework for Descriptive Analysis

The role of Direct Air Capture and other carbon removal methods in the context of aviation is multi-faceted due to the complex interplay of various factors, considerations, and challenges. To get a clear understanding of the current landscape of decarbonization efforts in the aviation sector (*sub-research question 1*), a suitable technology transition framework is used.

A technology transition framework was considered because :

- it can help understand the dynamics and drivers behind technology shifts. They can help explain why and how certain technologies gain momentum and eventually replace existing ones.
- it becomes easier to identify barriers that hinder the adoption of new technologies as well as enablers that facilitate the transition process
- these frameworks take a long-term view, accounting for the various stages a technology goes through from emergence to full adoption
- they emphasize the roles of different actors, stakeholders, and networks in driving or impeding transitions
- they consider the broader societal, economic, and environmental contexts within which transitions occur and allow for comparisons across different cases or sectors.

The following transition frameworks and theories were considered in this regard:

- Technological Innovation Systems (TIS): The TIS framework, explores how technological innovations emerge, develop, and diffuse within a broader social context. It emphasizes the interplay of various actors, institutions, and networks in shaping technological change and transition processes (Markard, Raven, & Truffer, 2012).
- Multi-Level Perspective developed by Frank Geels, provides a comprehensive and structured approach for understanding how socio-technical systems undergo transformative change. At its core, the MLP suggests that socio-technical systems consist of three interconnected levels: niche innovations, socio-technical regimes, and the broader socio-technical landscape. (Geels, 2002).
- Diffusion of Innovations Theory: This theory focuses on how new ideas, products, or technologies spread and are adopted within a social system. It explores factors such as the attributes of the innovation, the characteristics of adopters, communication channels, social norms, and the adoption process itself (Dearing & Cox, 2018).
- Transition Management: This approach focuses on managing and facilitating sustainability transitions by actively engaging multiple stakeholders. Transition management emphasizes the importance of experimentation, learning, and collaboration across different levels and sectors to achieve transformative change. It recognizes the need for systemic innovation and governance changes to address complex sustainability challenges (Rotmans, Kemp, & van Asselt, 2001) (Hunsucker & Loos, 1989).
- Strategic niche Management (SNM) which is used to study the development and diffusion of innovative and sustainable technologies. It focuses on creating favourable conditions and supportive environments for niche innovations to emerge, evolve, and eventually transition into mainstream markets or societal practices. However, Strategic Niche Management has been used primarily for ex-post evaluations of case studies. It has not been applied prescriptively in ongoing processes (Scott & Geden, 2018).

From the above options, it was seen that the MLP framework clearly emphasizes the interplay between technological, social, and institutional factors that shape the emergence, growth, and transformation of socio-technical systems(Geels, 2002). The technology transitions are characterized by multi-dimensional changes in various aspects, including technology, market dynamics, user practices, policy support, and cultural norms. Transitions occur when a new technology challenges and eventually replaces the dominant technology in a particular sector or system. In this case, we consider DAC as a new technology in the domain of negative emission technologies and see how it can find a place in the existing practices towards emission reductions, particularly in the domain of aviation (Foxon, 2011). Thus, MLP is chosen as the theoretical frame to describe the problem from a multi-level perspective.

2.1.1. Multi Level Perspective on Transitions

The multilevel perspective (MLP) of transitions was developed by Frank Geels as a heuristic to better understand sociotechnical change. The MLP views transitions as non-linear processes that result from the interplay of developments at three analytical levels. The three levels named: micro, meso and macro, relate to analytical and heuristic concepts to understand system innovations (Geels, 2002)

Geels defines systems innovations with distinct characteristics. These characteristics include the co-evolution of interconnected elements, transformations in both supply and demand aspects, the active involvement of diverse actors, and their extended duration. Analyzing the progression of ongoing transitions amidst policy actions is complex due to these multifaceted aspects of system innovations. The benefit of using MLP to describe the problem context is its broad scope and applicability. It has the capacity to integrate insights from various fields, including sociological, economic, and socio-technical theories, offering a comprehensive perspective.

The below figure is an illustration of the dynamic multi-level perspective on system innovations (Geels, 2002)

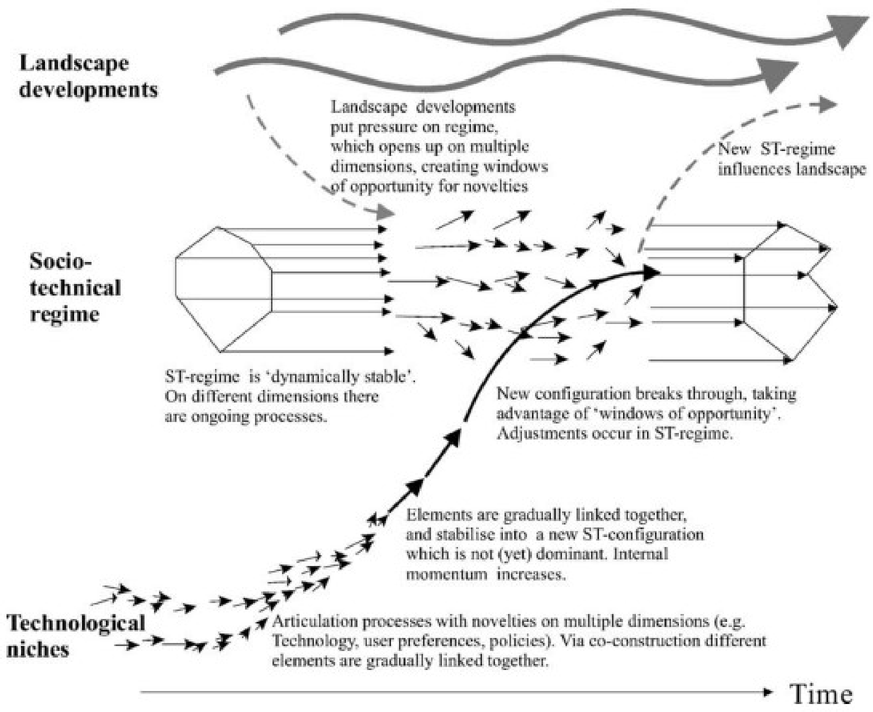

Figure 2.1: Multi-Level Perspective on Transitions

The three levels of the MLP are briefly described:

Micro Level- Technology Niche

The micro-level is consists of technological niches which refer to emerging technologies or processes. Since these are nascent in nature, they develop in 'protected spaces' to shield them from mainstream market selection and act as incubation rooms for radical novelties (Schot, 2008). Governments may also add to the protection through R&D subsidies or subsidized demo projects. Also, the rules in technological niches are not as well defined. There may be uncertainty about technical design rules, user preferences or infrastructure requirements. This leads to the 'windows of opportunity' in the existing socio-technical regime. Niche innovations that are supported by more actors and receive more resources have higher degrees of momentum.

Meso Level- Existing Socio-Technical Regime

The meso level refers to the complex engineering practices, production process technologies, product characteristics, skills and procedures, all of which are embedded in institutions and infrastructures of an existing system. Interdependence and linkage between sub-systems occur which are coordinated and aligned with each other. This is represented by the concept of socio-technical regimes. Socio-technical regimes account for the dynamic stability of sociotechnical systems. It is dynamic because innovation still occurs, but it is stable because innovations are of an incremental nature, going in predictable directions. Socio-technical regimes impose logic and direction for incremental socio-technical change alongside established pathways of development that are translated in path dependency and occasional lock-ins (Markard et al., 2012).

Macro Level- Socio-Technical Landscape

The macro-level is formed by the socio-technical landscape, which refers to aspects of the wider exogenous environment, which affect socio-technical development such as globalisation, environmental problems, and cultural changes.

The relationship among the three levels can be visualized as a nested hierarchy, meaning that regimes are embedded within landscapes and niches within regimes, The work in niches is often geared to the problems of existing regimes. Actors support the niche hoping that novelties will eventually be used in the regime or even replace it. This is not easy, because the existing regime is entrenched in many ways. This could be institutionally, organisationally, economically or culturally.

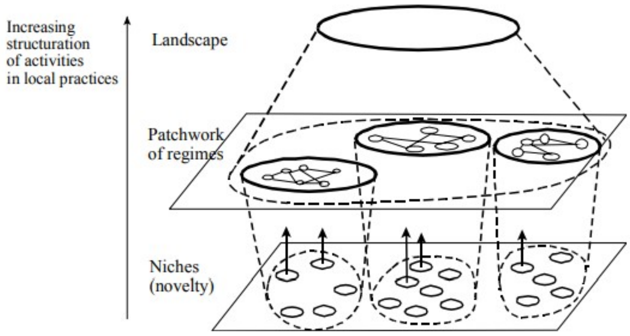

Figure 2.2: Nested Hierarchy in MLP
(Geels, 2002)

2.1.2. Application of MLP to given case

The core notion of the MLP is that transitions come about through interactions between processes at different levels: (a) niche innovations build up internal momentum, (b) changes at the landscape level create pressure on the regime, (c) destabilisation of the regime creates windows of opportunity for niche innovations(Geels, 2002). DAC technological innovation with respect to carbon capture efficiency, energy usage and subsequent cost of capture has been happening in niches which are protected or insulated from a normal market selection. They have relatively low technical performance, and low technology readiness levels and are often cumbersome and expensive. Such novelties emerge in niches, which offer some protection because the selection criteria are very different from the regime(Geels, 2002). However, the success or adoption of DAC is not only governed by processes within the niche of innovation but also by developments at the socio-technical regime and landscape developments.

To begin with, the position of direct air capture among the various sustainability-oriented solutions in aviation is visualized below:

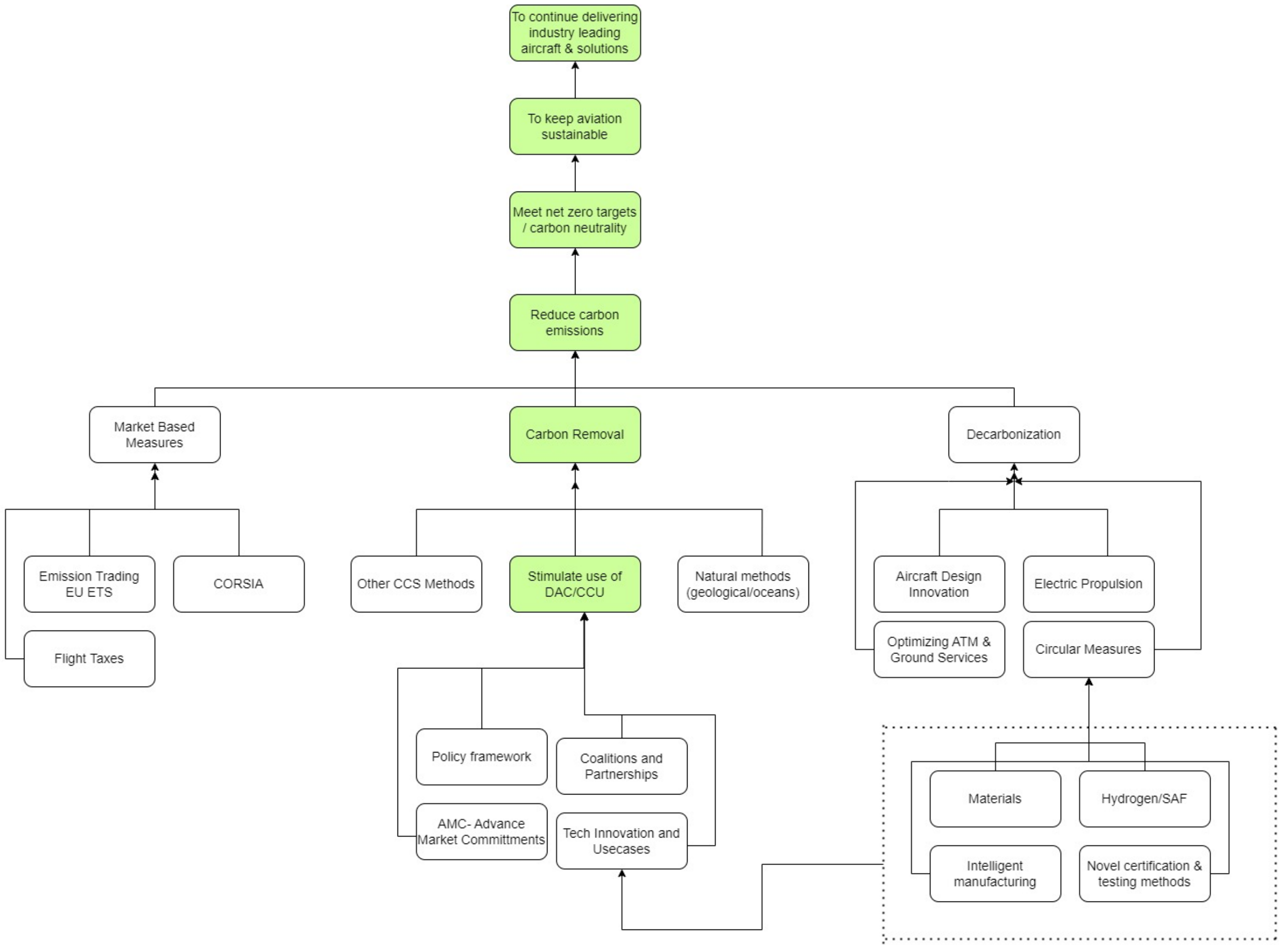

Figure 2.3: Relative position of DAC in the system context

Next, the following figure shows the adaptation of the MLP for the given problem.

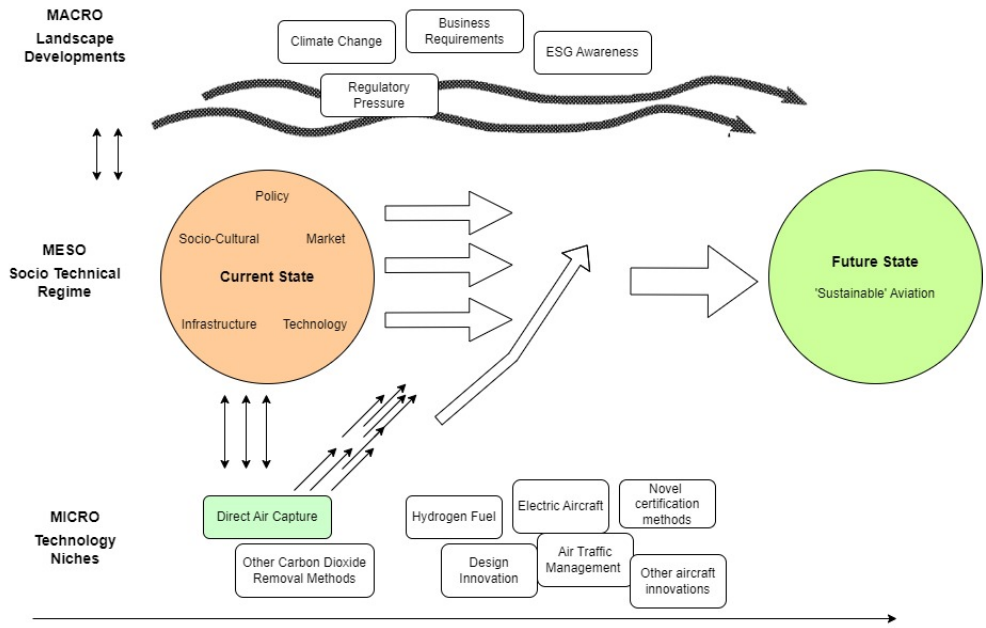

Figure 2.4: Adaptation of MLP for aviation

Technology Innovations in Aviation Sustainability

Aviation needs technological innovation to move beyond its current standard aircraft technologies. Various factors, like existing fleet longevity, the substantial resources needed for change, safety and security concerns, and the complex interdependencies of incremental changes, indicate that coordinated efforts are necessary for this innovation. The technology niche in relation to the larger aviation sustainability system includes a range of different technologies and industry players. DAC, other CDR technologies, electric aircraft, hydrogen fuel, aircraft design improvements, circular materials, and novel certification methods are all innovation niches. There is interaction between these innovation niches which could lead to co-development. For instance, the development of SAF using green hydrogen and DAC-derived CO_2 (Fuss et al., 2018).

Given that DAC technology development is still in the early stages, there is much uncertainty about precise technical characteristics, functional dimensions, markets and user preferences. Gradually, these dimensions will become aligned and stabilised, leading to dominant designs and normal markets. Technologies, markets, user preferences, etc., are thus seen as the outcome of articulation processes, learning and interaction. (Olsthoorn & Wieczorek, n.d.)

Existing Aviation Regime

The meso level is the existing socio-technical regime. This refers to the transitioning system- from fossil fuel towards renewable energy. Key actors in the aviation case include aircraft manufacturers, carbon removal technology providers, offset facilitators (including DAC), airlines, airports, policymakers and investors. Socio-Technical regimes are shaped by the relationships between actors, institutions and technology. In the socio-technical regime, According to the MLP. there are seven characteristics which are: technology, user practices and application domains (markets), the symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge (Geels, 2002). In the current regime, technology innovation and market-based measures have developed which have been dynamically stable. In this case, the focus is on path dependency and technology lock-in for the aviation sector.

A system locked into a particular trajectory of development would find it very difficult to reduce aviation emissions. Examining the context of emission trading, an underlying assumption is the equivalence of all emissions. The challenge addressed by emissions trading lies in the presence of gaps within markets. The remedy to this challenge involves establishing suitable market mechanisms that can efficiently allocate emissions reductions, thereby addressing concerns related to varying cost considerations.(Lawson, 2012). However, a real problem is one of how to break out of a system of inter-dependencies in which there is a need to increase demand for travel to remain profitable and the lack of technological fixes which play driving roles. One of the key reasons for the existing lock-in in the aviation sector is because flights are the least taxed and the most subsidized (Gössling & Cohen, 2014). This exemption costs EU governments around $10 billion and, because VAT is (or would be) proportional to the ticket price, those who travel the most often, the furthest distances, or fly first/business class are the most subsidized. In addition, the air industry receives subsidies and preferential treatment which other industries can only dream of. As a result of tax breaks and subsidies, as well as significant economies of scale enabled by the rapid growth of low-cost carriers, airfares have become, on average, 1.3 % cheaper every year since 1979 – a third cheaper in real terms than they were twenty years ago according to industry figures. In contrast, railway fares have risen, on average, by 1.2% since 1995 (Gössling & Cohen, 2014).

In addition to looking at the meso level solely in terms of lock-in and path dependence, existing regime actors can also be looked at as actively resisting fundamental change, rather than as locked-in and inert. This is related to power and politics at the regime level(Geels, 2002). The aviation sector has used its lobbying power over the years to remain tax-free and get subsidized. This could also be a symbol of broader institutional power, which is embedded in political cultures, ideology and governance structures. These wider institutional contexts facilitate the strategies of incumbent actors and thus assist regime resistance.

Landscape Forces Driving the Change

At the macro level, the landscape developments put pressure on the existing socio-technical regime to allow new technology configurations to break through, which in turn eventually influence the landscape (Geels, 2002). In this case, the landscape refers to the prevailing socio-political environment concerning climate change. This is not specific to aviation. There is an imminent need to reduce emissions and an increasing awareness to do so. The Paris climate agreement is one of the guiding forces in the pursuit to limit global temperature rise to below 2 deg Celsius. The subsequent studies based on this agreed target have revealed the need for increased decarbonization and inclusion of carbon removal. Governments and independent institutions recognize this and are taking steps in terms of policy incentives, R&D funding and market-based mechanisms. For the aviation sector, this includes ICAO net zero commitments, market-based mechanisms like CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) and a push towards circularity measures. Also, the aviation industry is frequently regarded as a prominent symbol of conspicuous and inefficient consumption. In fact, the industry's external marketing efforts often unintentionally reinforce this perception(Higham et al., 2021). But there is a growing change in perception about air travel, both from the industry and passengers. This is part of the landscape changes occurring in the sector.

Windows of Opportunity for Direct Air Capture

The breakthrough of new technology can be caused by external circumstances or internal drivers. The breakthrough of DAC from the niche level depends on niche-external circumstances at the regime and landscape levels. Only if conditions in the aviation regime and broader landscapes are simultaneously favourable will wide diffusion of the DAC occur. Such situations are called windows of opportunity (Geels, 2011).

The following circumstances are important for windows of opportunity to arise:

- internal technical problems in the current aviation innovation, which cannot be met with the available technology
- problems external to the aviation system i.e negative externalities
- stricter regulations, often in reaction to negative externalities
- changing user preferences, which may lead to new markets in which new technologies may link
- landscape changes that put pressure on the regime

Besides such external circumstances at the regime level, there are also internal 'drivers' that stimulate the diffusion of innovations such as economic improvements in cost/performance ratios stimulate wider diffusion. The performance of the new technology may be improved, as producers gain experience,

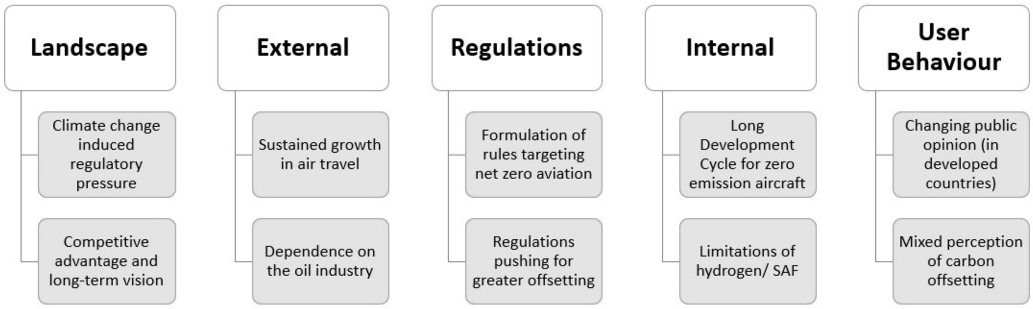

Figure 2.5: Drivers for innovation

- **Internal Technical Challenges**: This refers to challenges and limitations within the aviation industry's current technological landscape that cannot be adequately addressed with the existing technology. These challenges might include the need for improved fuel efficiency, reduced emissions, enhanced safety measures, and better passenger experiences. As aviation seeks to evolve and meet emerging demands, internal technical problems become drivers for innovation, spurring research and development efforts to overcome these limitations.
- **Negative Externalities**: Negative externalities refer to the adverse effects of aviation operations that extend beyond the direct participants in the industry. These externalities include environmental impacts like carbon emissions, air and noise pollution, and resource consumption. These negative effects are not fully priced into the cost of air travel, leading to societal costs that are not adequately accounted for. Addressing negative externalities requires innovation in sustainability practices, including the development of cleaner technologies and the implementation of regulatory measures
- **Stricter Regulations in Reaction to Negative Externalities**: As negative externalities become more evident and concerning, regulatory bodies often respond by imposing stricter regulations on the aviation industry. These regulations are designed to mitigate the negative impacts and promote sustainable practices. They can encompass emissions standards, noise reduction requirements, safety regulations, and operational guidelines. The need to adhere to these regulations drives innovation as aviation stakeholders work to comply with and exceed these standards
- **Changing User Preferences and New Markets**: As user preferences evolve, such as growing demand for environmentally friendly travel options, the aviation industry must adapt to these changing market dynamics. This can lead to the emergence of new markets for technologies that align with these preferences. For instance, the shift towards electric or hybrid aircraft is driven by the increasing demand for more sustainable modes of transportation. Innovations that cater to changing user preferences have the potential to disrupt the traditional aviation landscape
- **Landscape Changes Putting Pressure on the Regime**: The broader context in which aviation operates is subject to landscape changes, such as geopolitical shifts, economic fluctuations, and global events like pandemics. These changes can exert pressure on the existing regime of aviation operations and prompt the industry to reevaluate its strategies and practices. Landscape changes can lead to challenges, but they also create opportunities for innovative solutions that address emerging needs and navigate uncertainties

By using the Multi-Level Perspective, it was possible to understand how DAC adoption can potentially unfold across multiple levels, from individual actors and organizations to the wider aviation system and sustainability landscape. This multi-dimensional approach provides a comprehensive understanding of the challenges and opportunities for DAC integration in aviation sustainability and offers valuable insights for formulating effective policy recommendations and developing a roadmap for successful implementation. The breakthrough of radical innovations depends both on internal drivers and niche processes and on external developments in regimes and landscapes. The key insight of the multi-level perspective is that system innovations come about because developments at multiple levels link together and reinforce each other. This means that system innovations are not caused by a change in a single factor but are the result of the interplay of many processes and actors.

The combination of the IAD framework and the MLP enriches the research methodology by capturing both the institutional dynamics within the aviation sector and the broader systemic changes required for a sustainable aviation future.

2.2. Link between MLP and Institutional Analysis

The Multi-Level Perspective theory is useful in comprehending the intricate dynamics of adopting Direct Air Capture (DAC) technology within the aviation sector. DAC represents the technological niche, while the established aviation system serves as the regime. The MLP lens assists in grasping how landscape-level policy changes can create openings for niche innovations, such as DAC, to influence and potentially disrupt the existing aviation regime. Applying Institutional Analysis methods can enhance the understanding of the specific policy instruments and their implementation that affect collective actions and technological choices in the context of DAC adoption.

Both approaches recognize nested levels within the broader system. MLP identifies the niche, regime, and landscape levels, while Institutional Analysis spans from individual to collective to institutional levels. Aligning these levels offers a holistic view of how institutions across different scales interact with innovations at varying developmental stages. These interactions play a crucial role in either facilitating or impeding the transition to new technologies. Institutional Analysis underscores institutions' impact on collective actions, decision-making, and policy formulation, which can be explored in the context of MLP by investigating how institutions within the aviation regime either support or resist the integration of DAC technology. The rules and power structures of institutions play a pivotal role in determining whether novel solutions gain acceptance and challenge established practices.

Furthermore, Institutional Analysis provides an enriched context for understanding how institutions interplay within specific sectors, such as aviation. By weaving it into MLP, the focus can extend to how institutional arrangements and governance structures within the aviation regime shape the emergence and diffusion of DAC innovations. This might delve into how institutions influence transitions, either enabling or constraining the adoption of DAC and how they adapt to accommodate new technological advancements.

Regarding transition dynamics, the concept of path dependency highlighted by MLP underscores how existing technologies and practices influence future trajectories. Integrating Institutional Analysis into this perspective allows for an exploration of how institutions reinforce or disrupt these established paths. This interplay between path dependency and institutional dynamics provides insights into why certain transitions, like DAC adoption, face resistance or gather momentum within the aviation sector.

2.3. Framework for Institutional Analysis

Institutions are the foundation of any social system which contains the rules that govern social behaviour (Ostrom, 2011). Institutional analysis can help assess current concepts, theories, practices, policies, and initiatives and serve as an organizing tool to improve coordination, working relationships and mobilize joint action among intervening actors and the communities they serve. Using institutional analysis, it is possible to examine institutional policies and practices and the assumptions that support them. By asking how something comes about, rather than who is doing it, the analysis can reveal systemic problems and produces recommendations for more permanent and effective change. In this case, a suitable institutional analysis framework is used to describe the problem context and identify the institutional enablers and barriers.

2.3.1. Institutional Analysis and Development Framework

The Institutional Analysis and Development (IAD) framework was designed by Elinor Ostrom and her colleagues from the Ostrom Workshop in 2005 to facilitate analysis of institution processes through which individual and collective choices occur (Mcginnis, 2011). The IAD framework includes analyzing actors, norms, institutional settings, incentive structures and rules. IAD framework divides situations into ”action arena”, which includes ”actors” and ”action situations”. ”Actors” are influenced by ”Exogenous Variables”, making choices within existing ”rules”, and engaging in “interactions”. Both the Exogenous Variables and “participants” interactions result in outcomes, which are evaluated by the “participants”. Such evaluation influences other components in the framework.

Social scientists have widely adopted the IAD framework to study institutional arrangements and the emergence and changes of institutions over time. Typically, it has been widely employed in research aimed at studying local management of common resources.

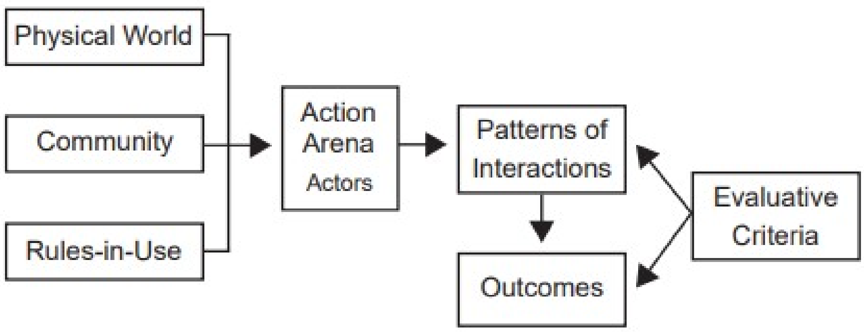

Figure 2.6: Institutional Analysis and Development Framework
(Ostrom, 2010)

Components of the IAD framework are briefly described below (Mcginnis, 2011):

- The input includes contextual elements comprising attributes of the community, characteristics of the goods or biophysical conditions, and the prevailing rules in use. These elements collectively encompass all dimensions of the social, cultural, institutional, and physical environment, providing the backdrop against which an action situation unfolds.
- The action situation is where policy choices are made. It is the core component of the IAD Framework, in which actors (acting on their own or as agents of organizations) observe information, select actions, engage in patterns of interaction, and realize outcomes from their interaction
- Outcomes are shaped by both the outputs of the action situation and by exogenous factors.
- Actors evaluate actions, outputs, and outcomes, and these evaluations may affect any stage of the process.
- Feedback and adaptive learning may affect inputs and processes within the action situation.

A detailed description and analysis using each of the components is presented in the following chapters

Adopting this to the given case, it is possible to identify factors that influence the behaviour of actors in the aviation carbon removal policy situation, namely in the domains of physical and material conditions, community attributes, and rules in use. It can also be used to identify and evaluate patterns of interaction that are logically associated with behavior in the action arena, and outcomes from these interactions. Many of these factors would be overlooked by technical analyses that consider a relatively narrow range of closely related factors. By using IAD, there is a means to incorporate diverse participants in policy analysis and design. The policies related to aviation sustainability and carbon capture in the EU can be viewed from the lens of institutions and rules. Applying the IAD framework to analyze how DAC can be adopted for aviation sustainability involves understanding the actors, rules, incentives, and information flows and proposing institutional changes.

2.3.2. Relevance of IAD to given problem

- **Identifying the Actors**

  Key actors: airlines, governments, regulatory agencies, airports, aircraft manufacturers, environmental organizations, DAC providers, CO_2 transport and storage providers, researchers, and the public.

- **Identifying the rules and institutions**

  The approach to addressing aviation emissions involves multiple aspects. Firstly, there are existing policies and regulations established by international bodies like ICAO, national governments, and regional aviation authorities. These policies set emission standards to mitigate the environmental impact of aviation. Secondly, market mechanisms play a significant role, including carbon offset programs, carbon trading systems, and initiatives promoting SAF. These mechanisms aim to incentivize emission reduction and sustainability practices within the industry. Lastly, research and development institutions are actively engaged in studying DAC technology and its potential applications, seeking innovative ways to further reduce aviation emissions and create a more environmentally friendly future for air travel.

- **Analyzing Incentives and Disincentives**

  There are various incentives and disincentives associated with the adoption of DAC technology. For airlines, getting involved in DAC projects offers the opportunity to significantly reduce carbon emissions, leading to improved environmental credibility and alignment with sustainability goals. Governments find incentives in achieving their emission reduction targets through the adoption of green technology like DAC, promoting a more sustainable aviation industry. Research institutions benefit from securing funding and support for their studies on DAC and exploring its potential benefits for the environment and aviation sector. However, airlines face disincentives due to the high initial implementation costs of DAC technology, which could pose financial challenges. Governments might hesitate to fully embrace DAC due to concerns about its scalability and reliability, as well as potential economic impacts. Additionally, there may be conflicting interests from other industries, which could influence the decision-making process. Research institutions may encounter disincentives in the form of limited funding and resources dedicated to DAC research, making it difficult to conduct comprehensive studies and evaluations.

- **Understanding Information Flows**

  Primarily, governments and regulatory bodies drive information on policy updates and incentives for adopting sustainable practices, including DAC. Secondly, research institutions and environmental organizations disseminate information on DAC's effectiveness in carbon removal and aviation sustainability.

- **Examining power dynamics**

  Significant influence in the aviation industry often lies with powerful actors like major airlines, who can sway policy decisions and investments towards sustainable technologies like DAC. Additionally, the pivotal role of governments and regulatory bodies cannot be understated, as they hold the authority to establish standards and regulations that greatly impact the adoption and implementation of DAC in the aviation sector.

- **Recommending Institutional Changes**

  To foster the adoption of DAC technology in the aviation industry, several key strategies can be employed. Firstly, governments could establish financial incentives, such as tax breaks or subsidies, to support airlines willing to invest in DAC and offset the initial high implementation costs. Secondly, promoting collaboration among airlines, research institutions, and governments is vital, as it allows for the sharing of knowledge and resources, accelerating DAC research and implementation efforts. Lastly, strengthening regulations by setting ambitious emission reduction targets that encourage airlines to integrate DAC into their sustainability strategies would further drive the industry towards more environmentally responsible practices.

- **Evaluating Trade-offs and Impacts**

  When considering the adoption of DAC technology for aviation, it is essential to take into account its significant environmental advantages, including carbon removal and the potential for reduced aviation emissions. However, a comprehensive assessment of the economic feasibility is equally crucial, along with identifying potential challenges that may arise within the existing aviation industry for the adoption of DAC. Another critical aspect to evaluate is the scalability of DAC and how it aligns with other sustainable practices, such as the adoption of SAF. Understanding the compatibility of DAC with existing sustainability initiatives can help create a more holistic and effective approach to mitigate the environmental impact of aviation. By carefully considering the environmental benefits, economic feasibility, potential disruptions, scalability, and compatibility of DAC, stakeholders can make informed decisions regarding its integration into the aviation industry's sustainability efforts. This approach ensures a balanced and well-informed strategy towards a greener and more sustainable future for aviation.

By systematically analyzing the applicable action situations within the IAD framework, stakeholders can better understand the opportunities and challenges associated with adopting DAC in aviation sustainability. This analysis can guide the formulation of effective policies and institutional changes to promote the successful integration of DAC technology in the aviation industry's efforts to combat climate change.

In the following chapters, the IAD Framework is used to analyze the context of DAC adoption for aviation. The below figure illustrates where the different elements of the framework are used.

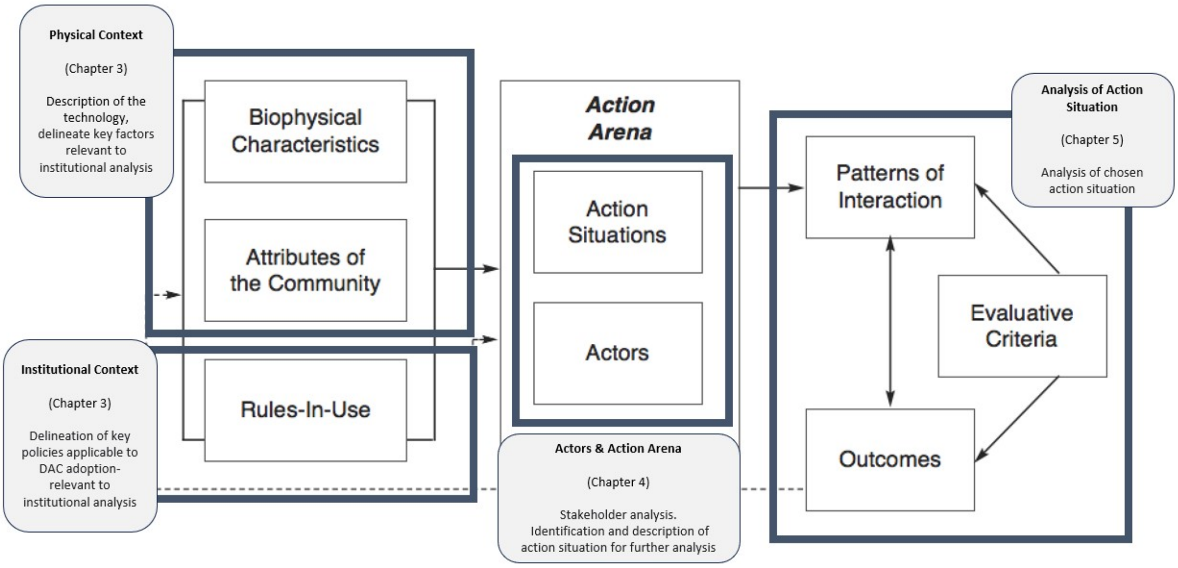

Figure 2.7: Research Breakdown using IAD Framework

3

Physical and Institutional Context

Using the IAD framework as a reference, this chapter describes the technology overview and institutional context of DAC. According to the IAD framework, the action arena (consisting of action situations) is affected by three sets of exogenous variables that jointly combine to structure it, namely the material conditions, community attributes and rules in use (Ostrom, 2010). In the context of using DAC for aviation, the technical aspects and requirements of DAC can be referred to as the material conditions. Community attributes related to monitoring and enforcement involve mechanisms for monitoring the implementation of DAC projects, ensuring compliance with relevant regulations and standards, and addressing any potential environmental or social impacts. Finally, the policies related to the development, use and monitoring of carbon removal including DAC are considered as the rules in use. Since DAC is a nascent technology, policy proposals are also considered as rules in use. The below figure highlights the elements described by the IAD framework.

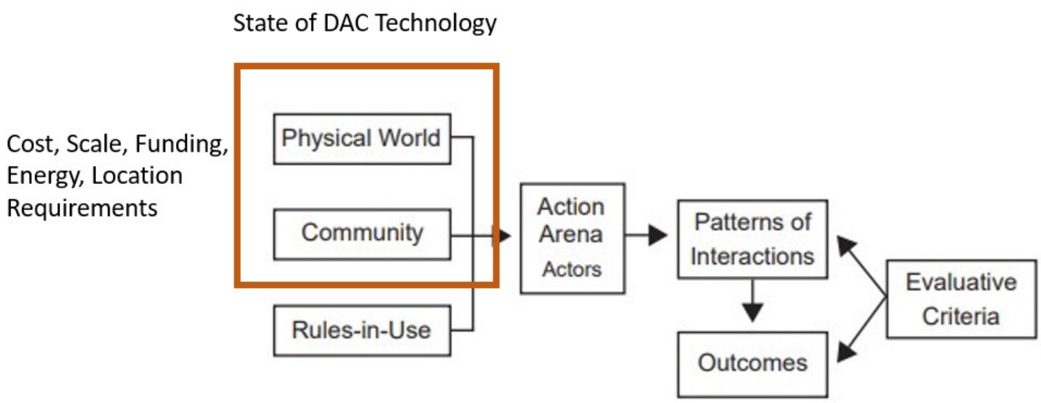

Figure 3.1: Physical and Institutional Elements-IAD
(Ostrom, 2010)

Physical and material conditions often influence policy action situations and constrain institutional arrangements in important ways. It is important to understand these conditions because they have significant implications for policy design. The following questions were adapted to get a general direction for the examination of the material conditions(Polski & Ostrom, 1999):

- What is the economic nature of the activity?
- How is this service provided?
- What physical resources are required to provide this service?
- What technologies and processes are required for this?
- What is the scale and scope of the activity?

A delineation of the key factors for DAC adoption, its commercial status and key requirements were done to answer these questions, which are presented in the following sections. In this first part of the chapter, a functional understanding of the technology and the current maturity state is described. Key players involved in the development and deployment of this technology are highlighted.

The core requirements of DAC were categorized into the following themes based on the literature:

- Cost
- Scalability
- Energy Requirements
- Funding and Investments

The cost overview includes net & gross costs of operation, existing cost of captured carbon and project costs in 2030 & 2050. Scalability includes the existing scale of DAC operations, limitations and projected growth in captured carbon capacity. The energy requirements of DAC are reviewed along with the choice problem of allocating sufficient renewable energy to it and the potential geo-restrictions based on the availability of renewable energy. The current investment sources for DAC from both public and private domains are reviewed. The Public domain investments such as the EU Investment Fund and other govt funding/subsidies are discussed in the chapter on policy analysis.

Finally, the existing and potential use cases of DAC, including those related to aviation are reviewed. The non-product use cases of DAC are also described namely carbon offsetting.

3.1. Technology Dimension of DAC for sustainable aviation

DAC is a novel carbon removal technology that separates CO_2 directly from the ambient air using an engineered chemical system. It is one of the several existing methods to extract carbon dioxide from the atmosphere. These methods collectively form the negative emissions technology suite as shown in the below figure (Cowie & Mohan, 2023).

Natural methods like afforestation, reforestation and existing forest reserves account for 99% of the total annual carbon removal of 2 Gt per year. Novel methods like BECCS, Bio-Char and DAC account for the remaining 0.002 Gt CO_2year 2 Mt of CO_2 year (Smith et al., n.d.). This illustrates the nascent nature of the technology and the current low-scale and low-impact state. However, this contrasts with the high commercial intent to invest in this technology and the policy incentives being devised and implemented to give this a boost.

3.1.1. Working Principle of DAC

There are currently two most commonly used methods employed for capturing CO_2 from the atmosphere: solid DAC (S-DAC) and liquid DAC (L-DAC). S-DAC employs solid adsorbents at ambient to low-pressure conditions (such as operating under a vacuum) and medium temperatures ranging from 80 to 120 degrees Celsius. On the other hand, L-DAC relies on an aqueous basic solution, typically potassium hydroxide, to capture CO_2 The captured CO_2 is subsequently released through a sequence of units operating at high temperatures between 300 and 900 degrees Celsius (McQueen et al., 2021). The key difference is that S-DAC could be powered by a variety of low-carbon energy sources (e.g.heat pumps, geothermal, solar thermal and biomass-based fuels) whereas the current high-temperature needs of today's L-DAC configuration do not allow that level of flexibility and could at best operate using low-carbon fuels such as bio-methane or renewables-based electrolytic hydrogen. Large-scale L-DAC plants have been designed to use natural gas for heat and to co-capture the CO_2 produced during the combustion of the gas without the need for additional capture equipment. This integration substantially reduces the L-DAC plant's overall emissions and can still enable carbon removal. However, any future ability of renewable energy to supply high-temperature heat could reduce the process emissions to near zero, maximising the potential for carbon removal and associated revenue streams.

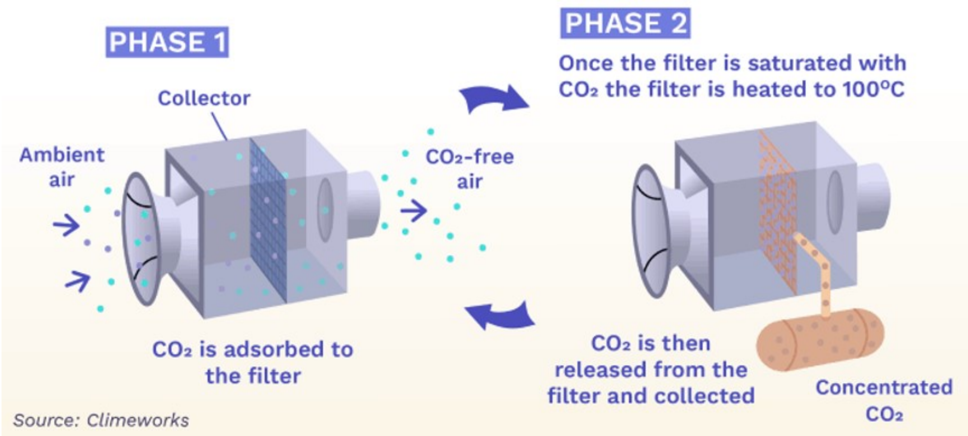

Figure 3.2: Solid DAC Working Principle

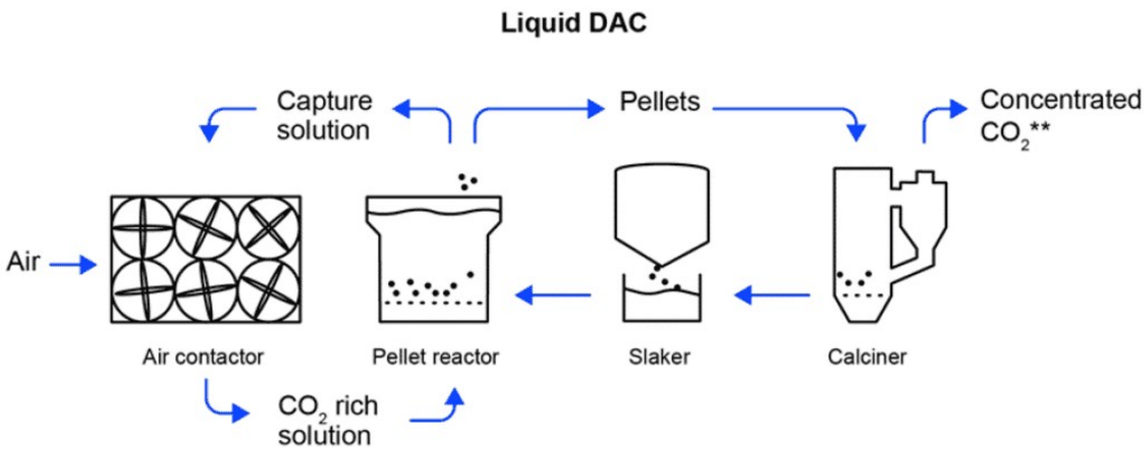

Figure 3.3: Liquid DAC Working Principle

3.1.2. Key Factors determining the state of DAC

DAC is a technically challenging process as CO_2 is present at a concentration of 0.04% in the ambient air. This is 2–3 orders of magnitude lower in concentration than other commonly targeted point sources for capturing CO_2 thus requiring more energy (McQueen et al., 2021). Nonetheless, DAC has received an increasing amount of attention due largely to development and deployment by a limited number of start-ups. There is also a growing body of research on new materials and processes for DAC, and a need to understand the financial costs and environmental impacts associated with DAC. Moreover, there are emerging questions related to public acceptance, policy requirements, and integration of DAC in the energy system, particularly as related to the energy transition and climate change mitigation. The usage of the captured CO_2 whether it is stored, reused, or utilized, along with choices related to the energy and materials inputs for a DAC process, decides whether or not the overall process results in negative emissions. If the captured CO_2 is stored, then it results in negative emissions, if it is utilized then it results in neutrality or circularity in the carbon cycle.

Cost of Capture

The costs associated with DAC infrastructure, energy generation, transport, storage, monitoring and maintenance as DAC is significantly more expensive than other leading CDR and mitigation options. Although economies of scale can be expected with upscaling, at present, the limited number of large-scale demonstrations in the technology niche and uncertainties in cost estimates pose as disincentives for potential investors.DAC is currently very expensive, with cost estimates ranging from between $100 and $600 to potentially as high as $1000/ton of carbon removed (McQueen et al., 2021). A carbon price in that range would be significantly higher than the vast majority of carbon prices globally, many of which only cover a fraction of total greenhouse gas emissions.

Scalability

The expected scale-up of DAC requires not only policy incentives but also funding from government and private investors, for it to move beyond the niche stage. Many early start-ups had to rely on funding from private sources including, the oil and gas industry. As its potential importance to climate action has risen, there have been calls for more public funding. Only a handful of governments including the EU, USA and UK) have committed funding for DAC. Most existing policy incentives are available through schemes that support CDR or CCS more broadly rather than DAC specifically.

The speed of DAC scale-up is one of the biggest challenge in its ability to remove CO_2A failure to achieve this scale-up risks locking the energy system into fossil fuels and making the long-term temperature goal much more costly and less feasible. Therefore, it is important to include DACCS within a diversified mitigation portfolio in low-carbon scenarios, together with other CDR strategies. The scale-up of DACCS indicated would only be possible with an appropriate CO_2 transport and storage infrastructure, as well as a strong regulatory and planning framework and public acceptability. In the event of the above conditions not being met, DAC could in fact lead to up to 0.8°C of warming overshoot(Realmonte et al., 2019).

Many predictions related to large-scale CO_2 removal assume that a significantly higher carbon price will be necessary to account for the impact of CO_2 on the climate system. Imposing taxes on carbon emissions could essentially function as financial support for negative emissions. However, implementing such a system at a scale relevant to climate change would demand substantial financial resources, potentially reaching up to a third of overall government spending in advanced economies. The political response to taxes and subsidies for renewable energy sources indicates that relying solely on carbon taxes or subsidies for negative emissions will become progressively more difficult as DAC expands. Additionally, carbon pricing alone would not be sufficient to drive the global transition away from fossil fuels and effectively deploy optimal CDR strategies, as different pricing mechanisms would likely be required for each of these goals. The fundamental issue facing all of these policy options is that, currently, carbon pricing does not reward CDR, which renders alternative decarbonization options significantly cheaper than NETs in general and DAC in particular(Buck, 2018).

Energy and Location Requirements

The advantage of DAC over the other CCS options is that it can be deployed close to storage and renewable energy facilities, significantly reducing transport costs. DAC offers significant advantages in terms of siting flexibility. In theory, DAC plants can be located in various regions, provided they have access to low-carbon energy sources and opportunities for CO_2 storage or utilization. However, certain limitations to this flexibility exist. Presently, DAC plants have demonstrated successful operation in diverse climatic conditions, primarily in Europe and North America. Nonetheless, additional testing is necessary in locations characterized by extreme dryness, high humidity, or air pollution(Budnis, 2022)

Funding

DAC could be more viable when it is associated with job creation and infrastructural investment. Relatedly, attitudes towards DAC may be influenced by whether the captured CO_2 is utilised in another industry and, therefore, linked to greater revenue streams than storage. Public sentiment may be more supportive if DAC is incentivised by a socially acceptable policy instrument, although what that instrument is will vary by country. Ultimately, all negative emissions technologies are likely to elicit higher support if presented as transitional measures complementary to, rather than in conflict with, mitigation, just energy transitions and other CDR options.

An incentive for potential investors is the possibility of using or utilising the captured CO_2 in commercially viable end-use industries such as carbonated drinks, synthetic fuels and, most prominently, EOR. Although geological storage of CO_2 should be the primary aim for climate change mitigation strategies, CO_2 captured from the air can also be used directly or utilised as a feedstock in the production of valuable products such as chemicals or fuels. The use or utilisation of CO_2 in this way can lower the net costs of DAC technologies and recycle a useful material that otherwise would be stored in deep reservoirs.

3.1.3. Commercial Status of DAC

The prominent developers of DAC today are Carbon Engineering (Canada), Climeworks(Switzerland), and Global Thermostat (USA). (Budnis, 2022). These plants are small scale and a large majority of them capture CO_2 for utilisation purposes such as for soft drinks carbonation. Few of them are involved in storing the captured CO_2 in geological formations for removal. Only a few commercial agreements are in place to sell or store the captured CO_2 while the remaining plants are operated for testing and demonstration purposes.

As of now, a total of 27 DAC plants have been established in Europe, North America, Japan, and the Middle East (Budnis, 2022). These plants are generally of a small-scale nature, with only a few commercial agreements in place to either sell or store the captured CO_2The majority of these plants are being operated for testing and demonstration purposes. Additionally, six new DAC projects are currently in the construction phase. Among them, the two largest projects are anticipated to become operational in 2024 in Iceland (36 kt CO_2year) and in 2025 in the United States (500 kt CO_2year, with plans to potentially scale up to 1,000 kt CO_2year)(IEA, 2019). Plans for a total of 16 DAC facilities are now in advanced development or under construction. If all of these planned projects go ahead and steadily capture CO_2 at full capacity, DAC deployment would reach around 4.7 Mt CO_2 by 2030; this is more than 500 times today's capture rate, but less than 7% of the 75 Mt CO_2 needed to get on track with net zero requirements. All the remaining projects are still at a very early stage, with no funding committed, and, in certain cases, not even an identified location for deployment. A lot of projects are waiting for clear policy signals and the development of a market for carbon removals and use cases. For instance, in June 2022, 1PointFive and Carbon Engineering announced their intentions to establish 70 large-scale DAC facilities by 2035 (1PointFive, 2022). Each facility will have the capacity to capture up to 1 million tonnes of CO_2 per year. These plans are dependent upon existing policies and voluntary and compliant market conditions. Additionally, Climeworks is also constructing its largest facility to date which will have a capture capacity of up to 36,000 tonnes of CO_2 per year and is expected to become operational by 2024 (Climeworks, 2022).

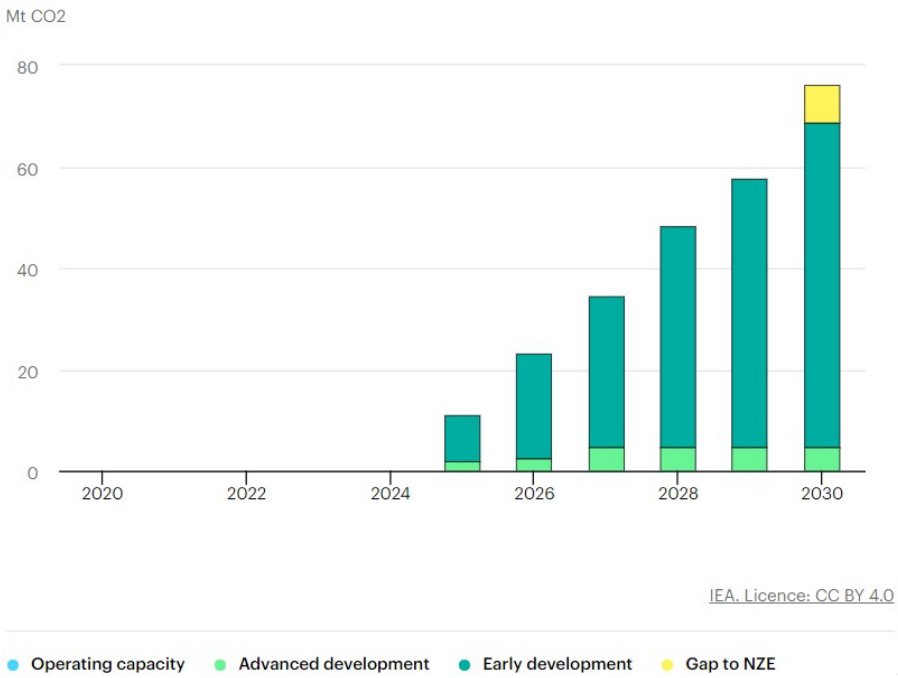

Figure 3.4: DAC Projected Capacity upto 2050
(Budnis, 2022)

Related to aviation, the Norsk e-Fuel AS consortium in Norway aims to produce synthetic fuels, with a volume of up to 3 million litres by 2024. These fuels will be created using various methods, including the capture of CO_2 from DAC but not limited to it (Norsk e-Fuel, 2023).

Next, unlike other lower-carbon technologies, such as renewable electricity and electric vehicles, DAC produces a primary product CO_2 for which there is currently limited market demand. That demand lies primarily in enhanced oil recovery. EOR can only support a small fraction of the total amount of carbon that must ultimately be removed from the atmosphere. Similarly, the potential for demand growth in industrial carbon utilization beyond EOR is projected to be limited to 0.5% of the CO_2 mitigation challenge by 2050. Market development for DAC thus relies even more on policy support than other low-carbon technologies

Although some industry-leading firms have taken an interest in DAC to meet internal commitments, market demand is unlikely to cover longer-term deployment costs, given the large gap between DAC costs and other options. Moreover, private actors are generally reluctant to provide the required investment without public intervention. On the other hand, countries with ample renewable and CO_2 storage capacity may look more positively on DAC because they can take advantage of relevant technical knowledge and infrastructure investments. Given the massive energy and heat demands, both the potential technology and the resulting geopolitics are important considerations for locating DAC plants. For instance, Iceland, with renewable resources was identified by Climeworks for its plant (Climeworks, 2022). Thus, we see a geographical distribution based on the availability of abundant and cheap renewable energy which can be diverted to these projects.

3.1.4. Challenges and Perceptions of the technology

As long as DAC projects continue to prioritise CCU over permanent storage, there could be concerns that CDR could detract from mitigation and give rise to negative perceptions among commercial stakeholders. A study even quantified "a risk of assuming that DACCS can be deployed at scale" contributing to an additional warming of up to 0.8°C if DAC was later found unfeasible. A related concern is that DAC is premised on accepting the inevitability of overshoot and in so doing accepts such an outcome (Eichner & Pethig, 2011).

In terms of politics, DAC is often appealing to those less inclined towards more traditional mitigation options. In countries more polarised on climate change, such as the United States of America, DAC commands wider bipartisan support as evidenced by the favourable laws, tax credits and subsidies. Of course, such support also creates suspicions of DAC among proponents of aggressive climate action.

The successful transition to low-carbon technologies requires careful sequencing of policies. Initial policies should focus on reducing technology costs and gaining broader political support, paving the way for more ambitious measures to promote global technology diffusion. The optimal policy approach involves a combination of financial incentives and deployment or performance mandates. Financial incentives, such as subsidies or tax rebates, have played a pivotal role in driving the deployment of renewable energy technologies and electric vehicles. These technology-specific policies have been more widely adopted compared to carbon pricing mechanisms. Given the significant costs associated with DAC, substantial government incentives will be necessary to make DAC economically viable. For example, the US government has introduced a tax credit (Section 45Q) for the geologic storage of CO_2 (Ozkan, Nayak, Ruiz, & Jiang, 2022).

In addition to financial incentives, deployment mandates could be important for the widespread adoption of carbon removal technologies. Mandates for direct electric vehicle deployment, as seen in China and California, and indirect mandates through progressively stringent fuel economy standards, such as in the EU and the US, have played a vital role in creating a nascent market for electric vehicles. Similarly, some jurisdictions have implemented deployment mandates like renewable portfolio standards for promoting renewable energy adoption, while others have relied solely on robust financing mechanisms like feed-in tariffs. However, relying solely on subsidies for DAC may pose political challenges as DAC scales up. The backlash against the costs of feed-in tariffs for renewables in Germany and Spain, despite the revenue generated from electricity sales, serves as an example. Mandates, on the other hand, tend to have lower political costs and can maintain public support for DAC deployment. Therefore, mandates are a crucial component in effectively scaling up DAC technology(Meckling, Kelsey, Biber, & Zysman, 2015).

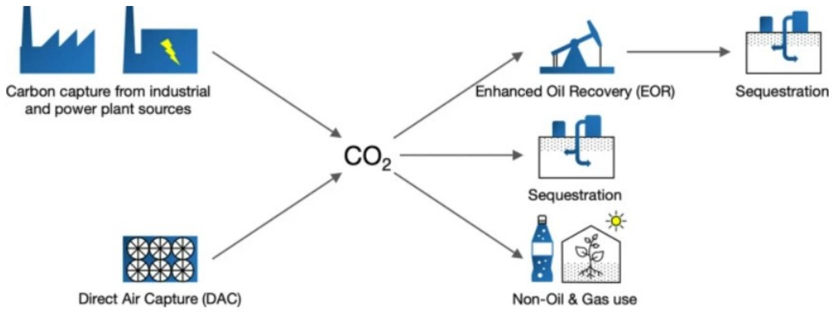

Figure 3.5: CO_2 Capture Pathways

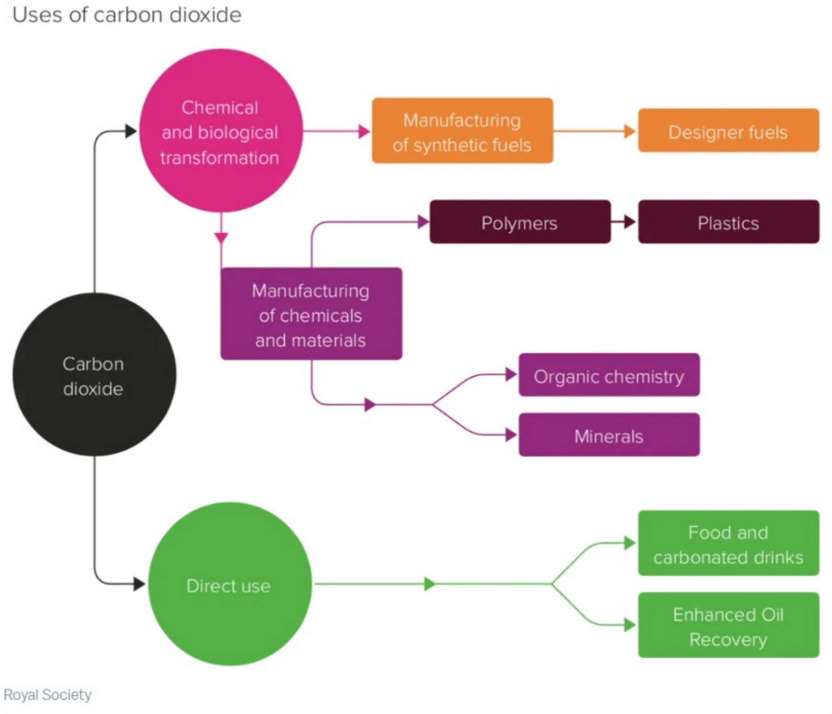

Figure 3.6: Captured Carbon Use Cases

The most relevant use case for aviation as of current readiness levels is for bio-fuels. In the case of fuels, current transport infrastructure can still be used and besides, they could help to decarbonize hard-to-abate sectors such as maritime transport and aviation. The use of captured CO_2 would generate an interesting synergy to aid decarbonization efforts: storing renewable energy, reducing CO_2 emissions, and obtaining fuels for transportation.

Another existing use case for DAC, which involves the fossil fuel industry is for enhanced oil recovery (EOR). Captured CO_2 is already being used to recover oil from semi-depleted oil fields through EOR, a type of tertiary oil recovery. EOR can recover up to 15–20% of the original field, with the US producing around 3.5% of their annual domestic oil output using EOR. However, it seems counter-intuitive to use captured CO_2 to extract more oil that will generate CO_2 via combustion, particularly if the CO_2 is captured from the air via DAC. Thus, the investments of oil and gas in DAC need to be studied to understand the intent and use of captured carbon, whether it would be for SAF or for EOR.

3.2. Institutional Context for DAC

This second part of this chapter describes the rules in use: namely the EU policies related to DAC, CDR and aviation sustainability policies at the EU and global levels. Using the institutional analysis framework as a reference, this chapter examines the policy landscape for carbon removal. The role of DAC as mentioned in these policies is highlighted. Next, the selection of policies for further analysis along with the rationale is provided. The key elements from the selected policies are described in the problem context and tied to the IAD framework.

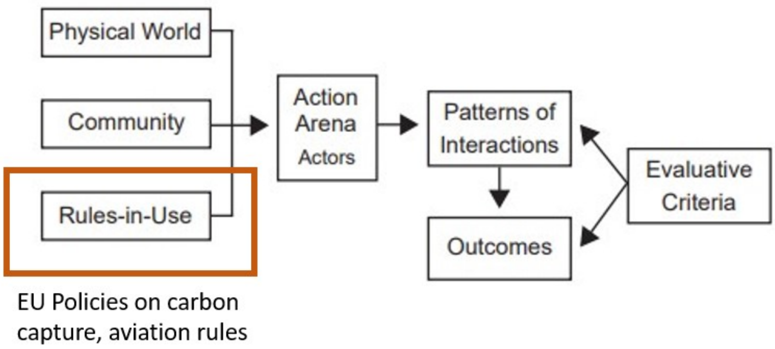

Figure 3.7: Institutional Elements-IAD

To begin with, the existing and proposed policies related to carbon capture and storage are identified from grey literature. A European perspective was taken, focusing primarily on EU Commission regulations, directives and proposals. From the aviation side, policies related to sustainable aviation fuel and airports are also examined. Within the context of institutional analysis, these policies and proposals can be considered as formal rules. In the case of DAC adoption in aviation sustainability, formal rules in the form of policies may include regulations related to carbon pricing, emission reduction targets, sustainability standards for DAC technologies, or incentives for the integration of DAC into aviation strategies. This includes communications that are not laws or policies but rather a baseline that the European Commission, European Parliament, and other EU institutions use as input while amending or developing laws and rules. The following figure presents an overview of all related rules identified from grey literature which relate to CCUS, SAF, carbon offsetting and airports.

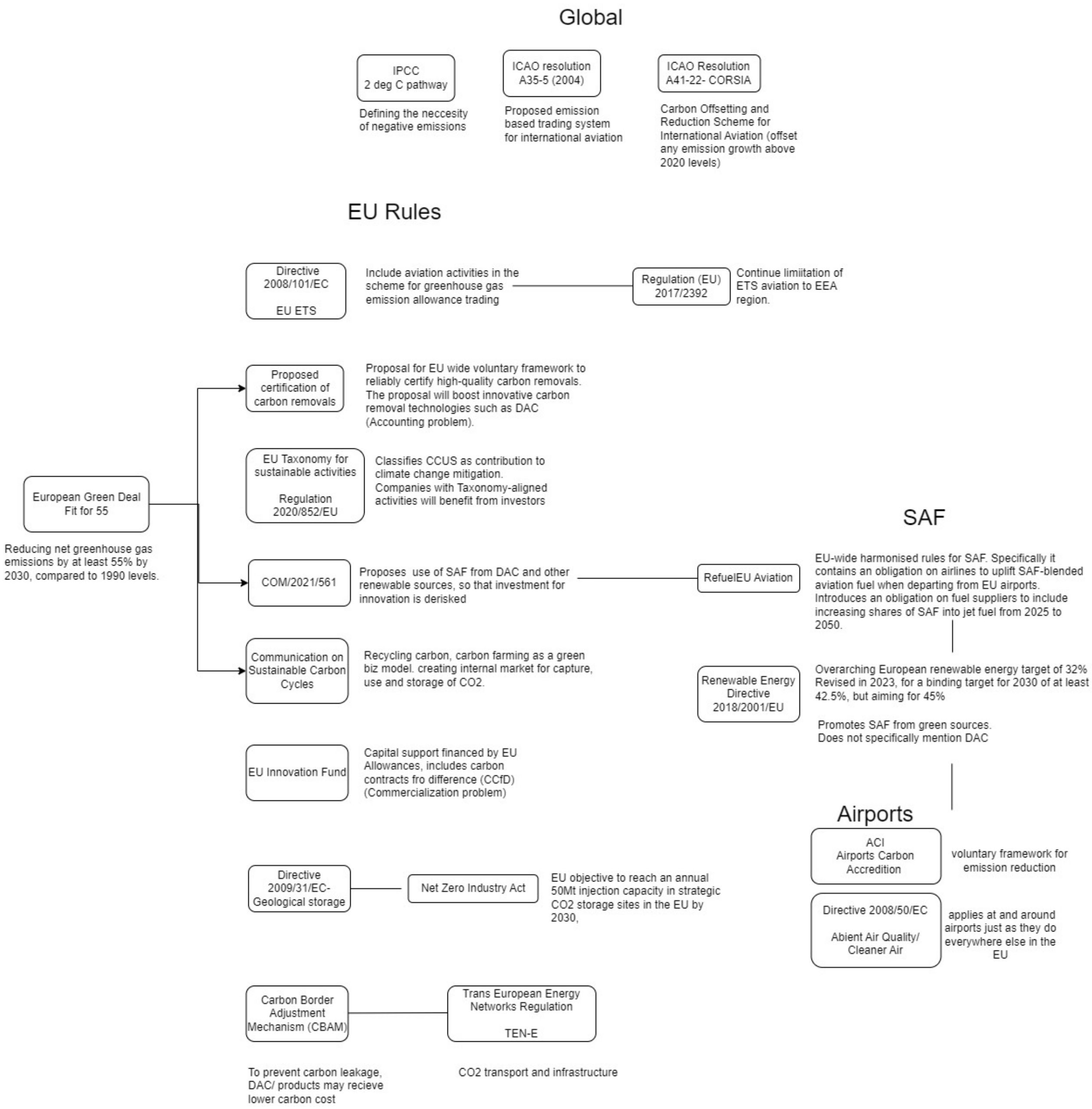

Figure 3.8: Policy Overview

A delineation of the relevant policies and their intended targets in the context of the given research is elaborated below.

3.2.1. Identification of Relevant Policies

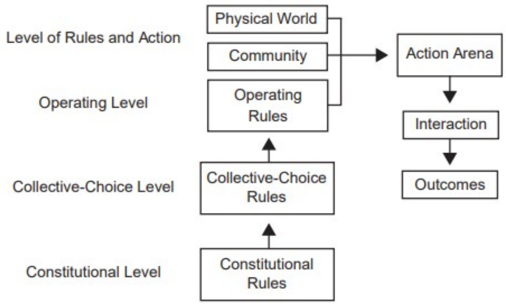

Figure 3.9: Level of Rules- IAD

As per the IAD framework, rules are frequently nested in other sets of rules (Polski & Ostrom, 1999). The first level is the operating level which involves rules regarding regular operations in specific economic settings. The second level is the collective-choice level which determines who is eligible to participate in an activity affecting the operating level, and how operating rules may be changed. Similarly, constitutional rules determine who is eligible to participate in crafting collective-choice rules, and how these rules may be changed. At each level of analysis, there can be one or more arenas. This concept is applied to the case of DAC adoption for aviation as described in the following sections.

High-Level Guiding Policies

Beginning at the landscape or constitutional choice level, the European Climate Law, signed in 2021, can be seen as the driving force making it legally binding for the EU to achieve a balance between greenhouse gas emissions and removals by 2050, and to achieve negative emissions thereafter. It also includes an ambitious 2030 climate target of at least 55% reduction of net emissions of greenhouse gases as compared to 1990 (Cifuentes-Faura, 2022). This acts as a guiding overarching policy which influences all new policies related to EU climate action. Building on the climate law is the European Green Deal (EGD) which aims for a net carbon-neutral European Union by 2050 and a decoupling of economic growth and resource use. The EGD is not a law in itself, but a general policy strategy, outlining the ambitions and goals of different policy sectors. For its implementation, existing regulations and standards will be revised over the next few years and new laws and directives will be developed and implemented (Fetting, 2020). Under the Green Deal, carbon removal-specific rules have been introduced. Based on the net zero targets, it is important for the EU to direct investments towards sustainable projects and activities. Fundamentally, it then becomes important to define what ”sustainable” activities are. This resulted in the creation of a common classification system for sustainable economic activities, or an “EU taxonomy” (European Commission, 2023). The EU taxonomy establishes a list of environmentally sustainable economic activities and provides companies, investors and policymakers with appropriate definitions for which economic activities can be considered environmentally sustainable. One of the six objectives of the Taxonomy regulation is the transition to a circular economy. This is where carbon capture and DAC fit into the picture.

Related to Carbon Capture and Storage

Next, it is worth examining the broader EU targets related to carbon capturing and storage, not limited to DAC. According to the communication on sustainable carbon cycles, the European Union (EU) has set ambitious targets to achieve climate neutrality by 2050 and to meet this goal, the EU aims to capture between 300 to 500 Mt of CO_2 from waste, sustainable biomass, and DAC by 2050 (Tamme, 2021). In addition, there is a target of achieving net removals of 310 Mt by 2030 under the proposed Land Use, Land Use Change and Forestry (LULUCF) regulation, with carbon farming playing a significant role. By 2030, the EU aims to remove 5 Mt of CO_2 annually from the atmosphere and store it permanently through projects like DAC and storage. Furthermore, there is a target for at least 20% of the carbon used in chemical and plastic products to come from sustainable non-fossil sources by 2030 (Tamme, 2021). These targets serve an important purpose in providing certainty for investors and guiding national policy design for governments. For DAC, this is a good starting point by setting a target that five Mt of carbon removal should be delivered by technological solutions annually by 2030. The communication further estimates that the EU will need to remove more than 100 Mt of CO_2 from the atmosphere using DAC (DAC) by 2050 (Energy, Mcquillen, Leishman, & Williams, 2022).

As seen in the technology overview, given the limited use cases of DAC, storage of carbon dioxide via injection in exchange for carbon removal credits is the primary pathway ahead for many operators. In this scenario, the EU's proposed Net Zero Industry Act has targets to reach an annual 50Mt injection capacity in strategic CO_2 storage sites in the EU by 2030. This 50Mt target will help to develop CO_2 capture and storage as an economically viable climate solution reducing emissions, but also for technological carbon removal methods that rely on geological storage like DACCS and BECCS. When DAC operators and offset providers sell carbon removal credits based on storage activities, the question arises regarding the quality of the removals. To ensure high-quality removals, the European Commission adopted a proposal for the first EU-wide voluntary framework to reliably certify high-quality carbon removals. The proposed regulation will significantly improve the EU's capacity to quantify, monitor and verify carbon removals and help reduce greenwashing. To ensure the transparency and credibility of the certification process, the proposal sets out rules for the independent verification of carbon removals, as well as rules to recognise certification schemes that can be used to demonstrate compliance with the EU framework. To ensure the quality and comparability of carbon removals, the proposed regulation establishes four quality criteria related to quantifiability, additionality, long-term storage and sustainability (European Commission, 2022)

Aviation Specific

With respect to aviation-specific rules, the ICAO's CORSIA scheme, the revisions to the EU ETS and the REFuelEU scheme are relevant. CORSIA stands for the Carbon Offsetting and Reduction Scheme for International Aviation. It is an initiative established by the ICAO to address greenhouse gas emissions from international aviation. CORSIA aims to achieve carbon-neutral growth in international aviation by requiring airlines to offset their emissions through the purchase of carbon credits from approved emission reduction projects in other sectors. Under CORSIA, participating airlines are required to monitor, report, and verify their CO_2 emissions annually. The scheme has a voluntary phase (from 2021 to 2026) and a mandatory phase (from 2027 onwards) for certain countries (Scheelhaase & Maertens, 2020). These emission reduction projects can include both natural and technological carbon removal processes such as DAC which have the potential to produce high-quality carbon offsets in the future.

Regarding the EU ETS, in its 2020 resolution on the European Green Deal, the EU Parliament supported phasing out free allowances for aviation under the ETS and strengthening the CORSIA scheme. Another aspect of the reform includes the proposal to reserve 20 million allowances, from January 2024 to December 2030, to support the purchase of SAF to assist operators in navigating the price difference between conventional jet fuel and SAF (Grimme, 2023). One of the policies within the EU ETS framework is the EU Innovation Fund, which serves as a capital support mechanism for innovative technologies. The fund is financed through auctions of EU allowances and currently has a value of 22 billion euros based on the current EU ETS allowance price (European Commisson, 2023). However, this amount is relatively small considering the overall ambition of the fund. The Fit for 55 packages proposes to double the fund's capacity and also introduce carbon contracts for difference (CCfDs). During the first round of applications, the Innovation Fund received an overwhelming response, with the number of applications being 20x the available funding, thus reflecting the pace of innovation happening in the space of CDR technologies (Tamme & Beck, 2021). The Innovation Fund holds promise in driving investments for CDR demonstration projects in Europe and can serve as a vital tool for mitigating risks and attracting additional private capital. It can provide financial support for demonstration projects, as well as technology-specific incentive mechanisms. First-mover demonstration projects also play a crucial role in identifying opportunities for cost reduction. However, due to its limited size and the need to allocate funds across various technologies, the Innovation Fund alone may not be sufficient for the large-scale commercialization efforts of DAC.

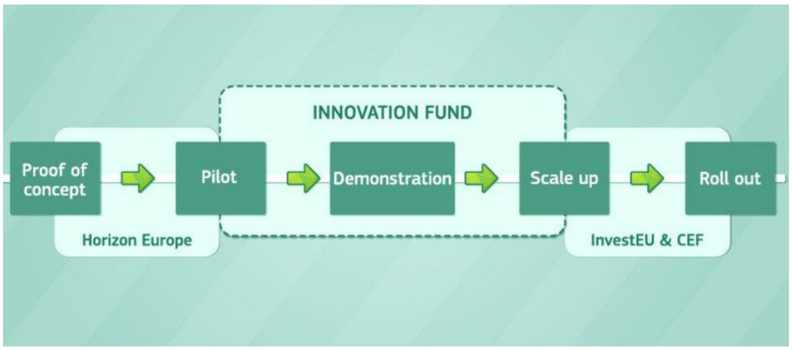

Figure 3.10: EU Innovation Fund

In addition to the Innovation fund, CCfDs (Contracts for Difference) are increasingly being adopted in Europe to incentivize the use of advanced clean energy technologies. The primary goal of CCfDs is to bridge the gap between the actual costs of decarbonization technologies and the price benchmark set by the EU ETS especially when combined with geologic storage of CO_2The underlying rationale for CCfDs is that the carbon price under the EU ETS alone is insufficient to encourage the widespread adoption of such technologies, hence the need for additional innovation policies. The revised proposal for the EU ETS includes the inclusion of CCfDs as a means to promote innovation in the decarbonization sector. This could prove vital in scaling up DAC. Finally, the REFuelEU proposal aims to increase the production and use of SAF. It puts forward obligations on fuel suppliers to distribute SAF when supplying fuel at EU airports. It sets mandates for minimum SAF uplift at EU airports of 2% by 2025, 6% by 2030 and 20% by 2035, up to a maximum of 70% by 2050. Of these amounts, 1.2% in 2030, and 5% in 2035 must be power to liquid (PtL) or E-Fuels, increasing to 35% by 2050 (Gonzalez Sanchez, Chatzipanagi, Kakoulaki, Buffi, & Szabo, 2023). DAC-derived SAF comes under the category of PtL fuels, thus providing a potential use case and market.

Based on the identified rules, they are categorized based on the IAD level of rules as follows:

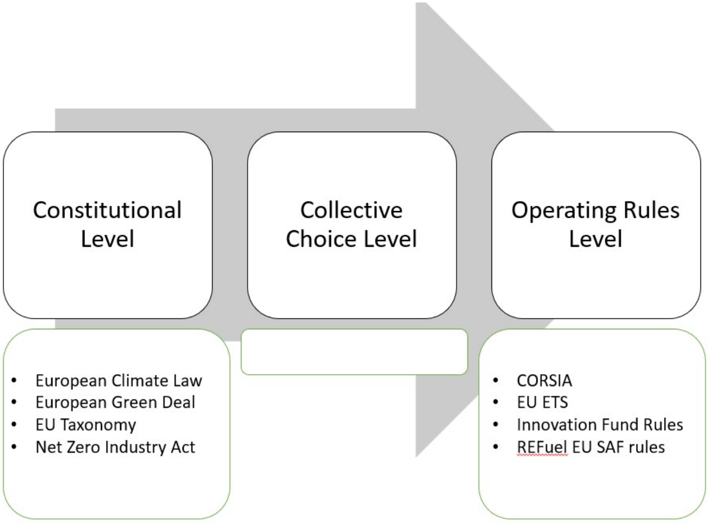

Figure 3.11: Levels of Rules- DAC for Aviation

Rule	Key Message and Relevance
REFuelEU	> Part of EU's Fit for 55 package > Setting of mandates for minimum SAF uplift at EU airports > Create a single EU SAF mandate and Book & Claim system to overcome supply discrepancies
Communication on Sustainable Carbon Cycles	> Need for both land-based and industrial removals to achieve the 2050 climate neutrality > Proposes regulatory framework and the certification of carbon removals > Scaling "technological" carbon removal such as Direct Air Capture and Storage (DACS) to 5 million tonnes CO2 per year by 2030.
Proposal for Certification of Carbon Removals	> The framework would cover nature-based solutions (carbon farming), technology-based solutions that enable permanent storage
Proposal for Net Zero Industry Act (NZIA)	> NZIA sets a target for storage in the EU of 50 million tonnes of CO2 in annual injection capacity by 2030 > Recognises a cross-border, single-market approach for EU member states > Assigns responsibility to oil and gas players > Fast tracking permits for CO2 storage sites
EU ETS Revision- Aviation	> Free EU ETS emissions allowances for aviation would be phased out, decreasing by 25% each year, starting in 2024 and reaching full auctioning in 2027. A new allowance cap would come into effect in 2024, and be subject to an annual linear reduction of 4.2%. Reserve allowances would be given to operators who increase their use of SAF > Also includes integrating ICAO's market-based CORSIA

Table 3.1: Summary of Key Policies

The identification of the relevant policies and deriving their potential role in the adoption of DAC is a step towards analysing the action situation.

4 Actors and Action Situation

This chapter presents the actor analysis. It includes a profile of the relevant stakeholders, their interests, level of involvement, influence and visual representation using a stakeholder map.

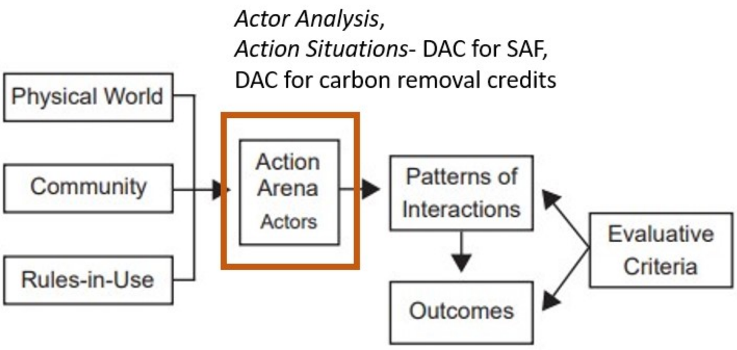

Figure 4.1: Action Situation-IAD

4.1. Key stakeholders

The below figure shows the actor diagram for the system. The stakeholders identified from desk research and literature are as follows:

1. Airbus (aircraft manufacturers)
2. Airlines
3. EU Commission (policy makers)
4. Direct Air Capture developers
5. Associated Transport & infrastructure actors
6. Carbon offset providers
7. Investors, both public and private (including consortium of tech companies)

8. Airports
9. Sustainable Aviation Fuel companies
10. Secondary stakeholders such as local communities, air travellers independent research analysts /advocates (think-tanks)

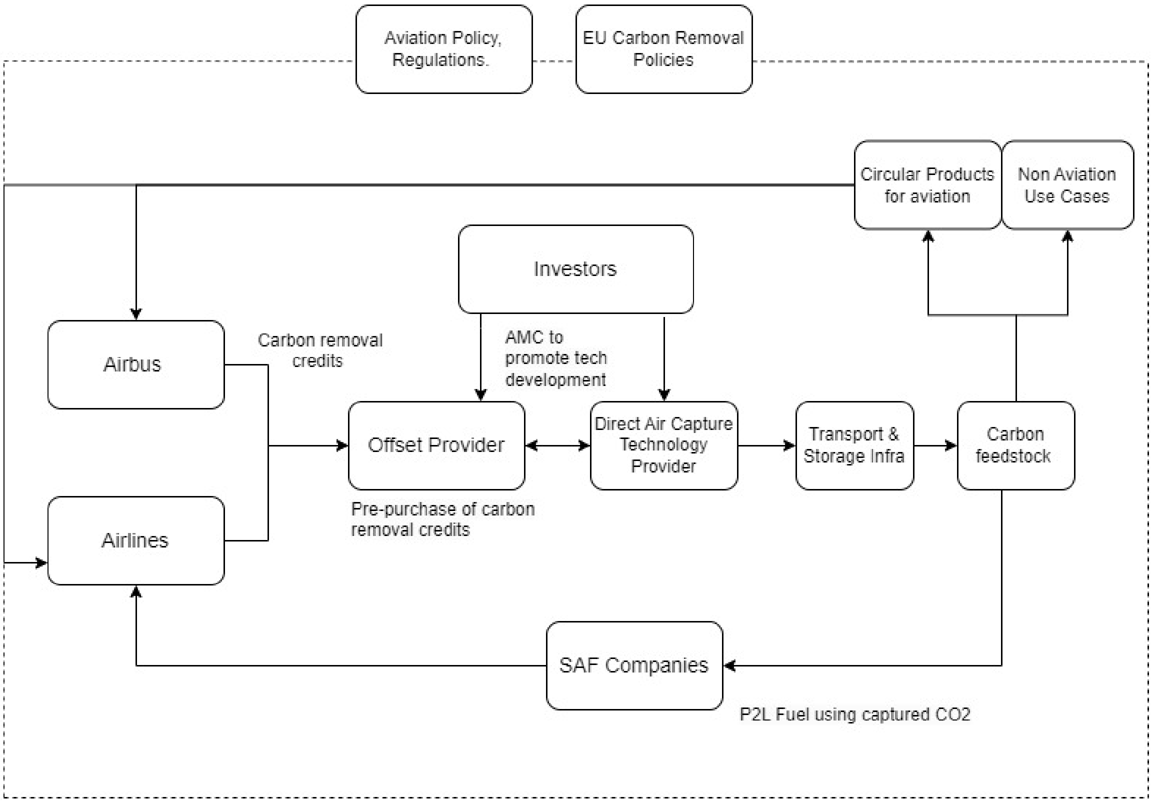

Figure 4.2: Actor Diagram

The role of Airbus (aircraft manufacturers), airlines and airports were investigated in detail. The key points are described below:

Airbus

As part of its next zero strategy, Airbus has announced its investment in Carbon Engineering Ltd., a company that specializes in developing technologies to remove CO_2 from the atmosphere (Airbus, 2022). This investment is a part of Airbus's efforts to support the development of sustainable aviation fuels and reduce the carbon footprint of its aircraft. The investment will help Carbon Engineering to scale up its DAC technology, which involves extracting CO_2 directly from the air. As part of this, Airbus has partnered with 1PointFive, a subsidiary of Carbon Engineering, to explore the potential of DAC and storage technologies for the aviation industry. The partnership will focus on assessing the technical and economic feasibility of using DAC technologies to produce sustainable aviation fuels and reduce the aviation industry's carbon footprint. Airbus has also announced a partnership with Clean Sky, a joint initiative between the European Commission and the European aviation industry, to develop new carbon capture technologies for the aviation sector. The initiative aims to support the European Union's goal of achieving net-zero carbon emissions by 2050(European Commisson, 2018). In a broader perspective, Airbus is seeking to form an alliance with airlines in order to pool investment towards securing carbon removal credits for the aviation sector.

Airlines

Airlines including Air Canada, Air France-KLM, EasyJet, International Airlines Group, LATAM Airlines Group, Lufthansa Group and Virgin Atlantic have committed to engage in “negotiations on the possible pre-purchase of verified and durable carbon removal credits starting in 2025” (Shepardson, 2022). The carbon removal credits will be issued by Airbus’ partner 1PointFive – a subsidiary of Occidental Petroleum Corp Low Carbon Ventures business, which plans to build a direct air carbon capture and storage facility in Texas for carbon removal that will be able to remove up to 1 million tons of CO_2 Airbus’ partnership with 1PointFive includes prepurchasing 400,000 tons of carbon removal credits over a four-year period(Shepardson, 2022). Airlines are also increasingly investing in DAC as a means to reduce emissions and gain the benefits of using DAC-derived SAF. United Airlines announced a $5 million investment into the carbon capture company Svante which provides materials and technology that has the potential to convert CO_2 removed from the atmosphere into sustainable aviation fuel(Foster, 2023). Airlines had until now focused primarily on the purchase of carbon offsets to reduce the environmental impact of flying. Now they hope to offset a sizable percentage (up to 10% for United) through carbon capture.

Airports

Airports are the interlink between airlines and aircraft. They are now in a unique position to become green energy power stations and house SAF facilities whose demand is only going to increase as per regulatory mandate. Based on a study conducted by Cranfield University, a combination of integrating renewable green hydrogen technology with DAC and SAF would help in the UK’s Net Zero ambitions (Miyoshi, 2022). Similarly in the Netherlands, Rotterdam The Hague Airport (part of Royal Schiphol Group), Rotterdam The Hague Innovation Airport, SkyNRG and Climeworks have setup a consortium called Zenid which entails a demonstration plant producing fully circular sustainable aviation fuel directly from air(SkyNRG, 2021).

Stakeholders	Power	Interest	Reason to support	Conflict of interest/ Reason to block
Airbus/ Aircraft Manufacturer	Medium	Medium	1) to secure share of carbon removal credits for the aviation industry 2) act of intent (for stakeholders) 3) potential funding to further develop/scale CDR 4) provides extra time until decarbonization tech (electric, H2) matures	High cost of DAC carbon, If carbon removal market does not scale. Cobenefits are not scalable
Airlines	High	Medium	1) Cobenefits- SAF from DAC/CCU 2) Additional method in net zero pathway 3) Inclusion of CCUS in ETS (?)	High cost of DAC derived fuel
Airports	Low	Medium	1) To reduce scope 3 emissions in airport radius 2) Become green energy 'power stations 3) Reach higher Airport Carbon Accredition Index score	1) Infeasibility based on land, energy requirements, non-availability of green energy sources, lack of support from local govt/communities 2) High costs, unfeasible techno-economics 3) Lack of agreement with airlines
DAC Technology	Medium	High	1) Ideal hard-to-abate market (aviation) 2) High potential usecase- PtL Fuel (SAF)	Lack of clear policy incentives for DAC in aviation. Could move to other markets such as construction, oil & gas
Offset Providers	Medium	High	1) Ideal hard-to-abate market (aviation) 2) High potential usecase- PtL Fuel (SAF) 3) High interest from corporate investors	Lack of clear policy incentives for DAC in aviation. Could move to other markets such as construction, oil & gas
Investors	High	Low	1) Additional lever for emission reduction. 2) act of intent (for stakeholders) 3) tangible impact compared to offsetting	1) High Price of DAC Carbon 2) Low number of credits available
Transport, Storage Infrastructure	Medium	High	Smaller area requirements, relatively mobile	Dependence on availability of abundant renewable energy source

Table 4.1: Stakeholder Analysis Overview-1

4.2. Stakeholder mapping

Stakeholders	Power	Interest	Reason to support	Conflict of interest/ Reason to block
Sustainable Aviation Fuel	Medium	High	"more" sustainable/circular carbon fuel Cater to rising demand for SAF- stipulated by policy	High cost of DAC derived fuel Unfavorable policy incentives/subsidies
Oil & Gas Industry	Medium	Medium	1) High potential use for EOR (Enhanced Oil Recovery) 2) Aids in low carbon H2 generation, ethanol production and other chemical processes 3) Improves ESG performance and regulatory compliance	-
EU Commission	High	High	To achieve target of climate neutrality as written into law by the European Climate Law	If economic feasibility/market creation is not successful even after providing financial incentives
Aviation Policy Makers (ICAO)	Medium	Medium	To meet long-term aspirational goal (LTAG) of net-zero carbon dioxide (CO2) emissions from aviation by 2050. CORSIA	Unfeasible costs/techno-economics for SAF
Independent research groups	Low	High	Potential co-benefits, complementary option in NZ pathways	Low TRL, High resource usage at scale, undeveloped revenue model, policy uncertainity
Local communities	Low	Low	Availability of cobenefits- industry, jobs, positive local governance	NYIMB (Not in my backyard) Diversion of renewable energy from other needs
Air Passengers	Low	Low	Environmentally conscious	High cost passed on to them

Table 4.2: Stakeholder Analysis Overview-2

Figure 4.3: Power-Interest Grid

Priority of DAC Technology Development

DAC producers have prioritized the development of their technology over collaborating with specific use cases. Their focus currently lies on enhancing their internal technologies before engaging in collaborative efforts with potential users (*Interviewee 1*). While the idea of producing fuel is a potential use case, they have chosen to prioritize storage, thus presenting a significant challenge for the integration of direct air capture into SAF production.

Challenges in Co-Locating DAC-SAF facilities at airports

Co-locating DAC plants at airports has proven to be an impractical option. They do not comply with airport permits for fuel production, as airports are not suited for that purpose. Additionally, the necessary utilities required for such a plant are not available at airports, making it an impractical option (*Interviewee 2*.

Cost Considerations and Importing CO_2

Depending on specific cost factors, importing CO_2 for SAF could potentially be a more economical solution in the short term rather than setting up a DAC plant, although it ultimately depends on the specific circumstances and cost figures (*Interviewee 1*).

Motivations for Investor Involvement

Investors' motivations for involvement in DAC projects vary. Some may be interested in supporting technology suppliers or improving their own technologies at a specific scale. Others may be motivated by the desire to participate in an impactful project. Major corporations, such as oil majors, or large investment funds, are potential candidates for providing substantial equity investment required for such projects.

Policy Support for DAC

DAC as a nascent technology can be compared to other clean technologies such as the solar energy industry from the 1990s. Policy support and technological advancements are necessary to move DAC from the research and development stage to widespread adoption. There is a need for policies similar to the 45Q tax credit in the United States at a member-state level within the EU. These incentives would play a crucial role in encouraging carbon capture and making it a profitable venture for businesses. Next, a stable carbon price is essential for the viability of DAC business models.

Risk of Double Counting in Carbon Capture and SAF Production

If the company that is doing the carbon capture is accounting for a negative emission on their books, but then selling the carbon to a SAF producer there is the risk of double counting which needs to be managed to ensure correct monitoring and verification.

Keeping Revenues Within the Aviation Sector

The revenues that companies generate from carbon reduction efforts are currently leaving the aviation sector via offsetting schemes. However, if these funds were directed towards internal aviation-specific activities like SAF production, they would remain within the sector (*interviewee 4)*. Investing in SAF production facilities would lead to economies of scale, resulting in cost savings and more affordable prices for SAF in the future. By keeping these revenues within the aviation sector, it effectively subsidizes future sustainability initiatives, promoting the industry's long-term growth, rather than diverting resources to unrelated ventures outside of aviation.

Funding Bottlenecks and the Importance of Stakeholder Communication

The main bottleneck lies in funding (*interviewee 3*). It is crucial to facilitate communication and collaboration among various stakeholders, including smaller entities, who currently lack the opportunity to interact. Currently, there is a disconnect, with each stakeholder operating within their own confines, rather than engaging in open cooperation. Bridging this gap and fostering communication is essential for advancing the adoption of DAC in the aviation industry.

Interaction between CORSIA and ETS

The interaction between CORSIA and ETS is still uncertain, and the specifics of how they will work together are not yet clear (*interviewee 5*). The EU wants to ensure that the ETS is still applicable for intra-EU flights. However, the ETS and CORSIA are two different systems with different approaches. ETS is a cap-and-trade system where emissions are limited at the beginning of the year, while CORSIA allows for offsetting and doesn't impose limitations on emissions.

4.3. Action Situation

Using IAD for reference, the physical and material conditions in terms of the technology status and requirements were ascertained. The institutional rules and the key actors were identified. Next, the action situation for analysis is identified.

Action Situation

The use of direct air capture derived CO_2 for the production of sustainable aviation fuel.

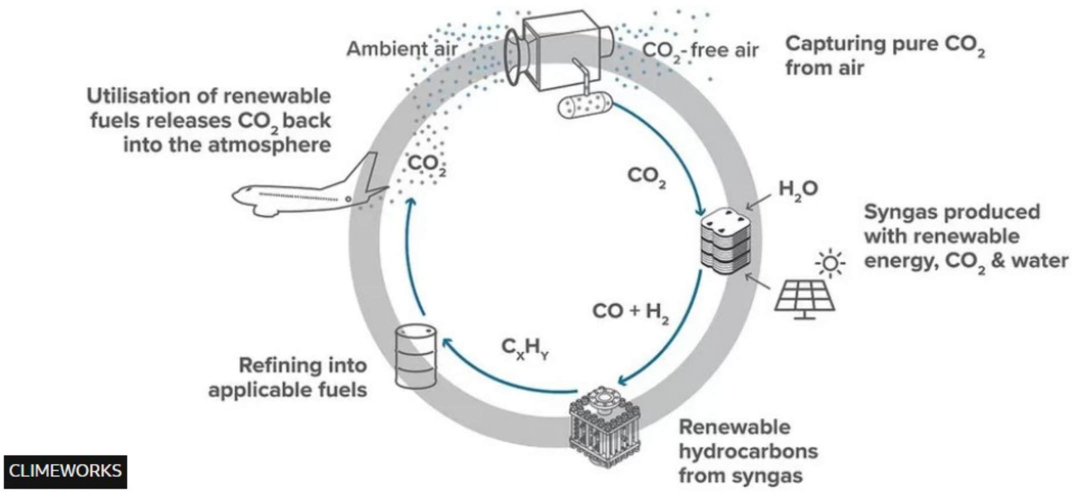

Figure 4.4: Action Situation- Sustainable Aviation Fuel from DAC
(Climeworks, 2022)

Description of the action situation

The aviation industry can collaborate with DAC technology developers and SAF producers to explore the feasibility of using DAC technology for SAF production. The key actors involved are airlines, DAC technology developers, SAF producers, governments, and aviation regulatory bodies. The existing aviation regulations, SAF standards, and research grants play crucial roles as rules and institutions governing the process. Airlines are motivated to reduce their carbon footprint and showcase their commitment to sustainability by adopting SAF produced through DAC technology. At the same time, DAC technology developers see opportunities for commercialization and growth in the aviation market, while SAF producers seek access to a new, sustainable feedstock source to diversify their product offerings. Governments and regulatory bodies aim to support sustainable aviation initiatives and foster technological advancements. However, there are challenges related to the scalability and cost-effectiveness of DAC technology for SAF production, and potential resistance from existing SAF producers and the fossil fuel industry. The success of this collaboration would lead to enhanced aviation sustainability through reduced carbon emissions, diversified SAF feedstock, technological advancements, and overall environmental benefits. Evaluative criteria such as carbon emission reduction, SAF quality and certification, cost-effectiveness, market acceptance, technological feasibility, and policy and regulatory support can be utilized to assess the effectiveness and viability of DAC-SAF production. By considering these outcomes and criteria, stakeholders can make informed decisions and contribute to a more sustainable future for the aviation industry. The next chapter presents an analysis of the action situation.

5

Action Situation- SAF from DAC

Based on the identified action situation, an analysis was carried out. From the previous chapters, the material, physical conditions, rules in use and actors have been identified and analyzed. In this chapter, the patterns of interaction, outcomes and evaluative criteria are discussed.

It is known that the IAD framework can be used to analyze action situations through a systematic approach, which includes input, process, output, and feedback cycles. Inputs consist of external variables, the process involves interactions among these actors. The output represents collective decisions that are implemented, enforced, and evaluated against specific criteria(Ostrom, 2010).

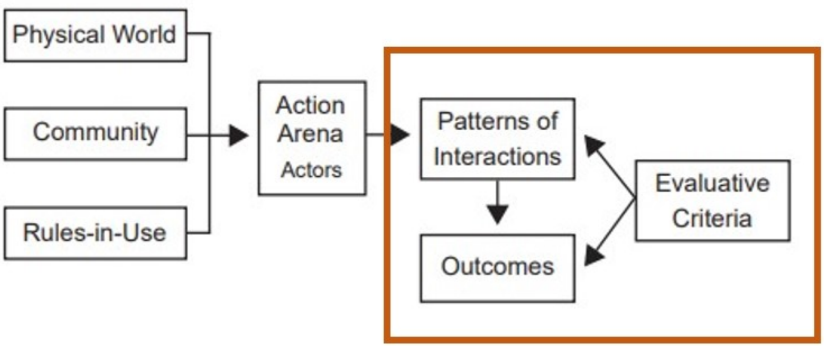

Figure 5.1: Analysis of action situation

The action situation under study related to the usage of DAC derived CO_2 for sustainable aviation fuel.

5.1. Input- External Variables

As seen from the previous analysis, SAF can be produced from DAC derived CO_2 making it the most suitable direct application for aviation. As part of the 'Fit for 55' package, the EU Commission proposed to boost the uptake of sustainable aviation fuels in aviation. SAF has a significant role to play in the decarbonisation of the sector, but currently, its share in EU aviation is negligible. In this case, the

ReFuelEU proposal has the potential to help scale up investment in DAC in order to make this a viable and affordable pathway for e-kerosene production.

Key Actors: *SAF producers, green hydrogen producers, transport and storage infrastructure providers, DAC technology providers, location hosts- airports or other locations with access to renewable energy, policymakers, airlines*

In order to meet the EU's climate objectives, it is expected that by 2050, at least 63% of all aviation fuel used for flights departing from EU airports should be SAF. Synthetic fuels (or e-fuels) will play a major role in the decarbonisation of the air transport market and have great potential. The proposed rules, therefore, set a sub-target to ensure that a certain amount of SAF used are synthetic fuels. The ReFuelEU Aviation proposal would require that 32% and 63% of jet fuel consumed by flights departing from EU airports be SAF in 2040 and 2050, respectively (Tamme & Beck, 2021). DAC-derived SAF falls under this subcategory.

	2025	2030	2035	2040	2045	2050
Percentage of SAF used in air transport:	2%	5%	20%	32%	38%	63%
Of which: sub-mandate Synthetic fuels (or e-fuels):	-	0.7%	5%	8%	11%	28%

Figure 5.2: Sub Targets for SAF uptake

From a production capacity and demand point of view, the SAF industry today is still at an early stage of development with an estimated EU supply of less than 0.1% of total jet fuel demand. According to the supporting study for the ReFuelEU Aviation initiative (Cames, Chaudry, Gockeler, Kasten, & Kurth, 2021), with the introduction of a SAF blending mandate at the EU level, demand for aviation fuel at EU airports would amount to around 46 Mt in 2030. In order to reach 5% of SAF by 2030 for all flights departing from EU airports, approximately 2.3 million tonnes of SAF would be required.

Currently, the maximum potential SAF production capacity in the EU is estimated at around 0.24 Mts, i.e. only 10% of the amount of SAF required to meet the proposed mandate by 2030 (?, ?). Announcements of significant capacity increases from these existing SAF producers, combined with production from new market entrants, mean that the 2030 mandate level is ambitious but realistic. Also, more companies have announced plans to enter the SAF market by 2030. As such, the majority of the needed feedstock is expected to be used for cooking oils, animal fats and waste oils, cover crops and other sustainable biomass. The ReFuelEU Aviation study noted that 7 additional SAF production plants would be needed in the EU by 2030, and 104 additional plants by 2050. To cover the demand for PtL fuels, it is estimated that 0.4% and 5.5% of the EU's renewable electricity generation would be needed by 2030 and 2050, respectively (Mirolo, 2021).

The ReFuelEU initiative does not currently provide any incentive for DAC to be used in e-kerosene production. Instead, the Fit for 55 package still favours CO_2 reuse or carbon monoxide (CO) refining from industrial installations which will ultimately add to the total amount of CO_2 in the atmosphere, lead to a lock-in of fossil sources of CO_2 and is therefore only a transitional solution on the pathway to climate neutrality. Regarding the technology itself, as mentioned in the chapter on technology overview, key challenges faced include scale, cost, energy requirement and suitable business model. This makes it currently commercially unfeasible for SAF makers to adopt DAC-derived CO_2 for their processes.

5.2. Rules of the action situation

From the ReFuelEU proposal, the following points are most relevant to the action situation:

- The ReFuelEU Aviation proposal would require that 32% and 63% of jet fuel consumed by flights departing from EU airports be SAF in 2040 and 2050, respectively
- The penalties for the suppliers who fail to meet the targets set in this Regulation should be complemented by the obligation to supply the market with the shortfall of meeting the quota in the subsequent year
- Member States shall transfer the amount collected through those administrative fines as a contribution to the Sustainable Aviation Fund

The action situation rules of the IAD framework are applied to the context of DAC for SAF:

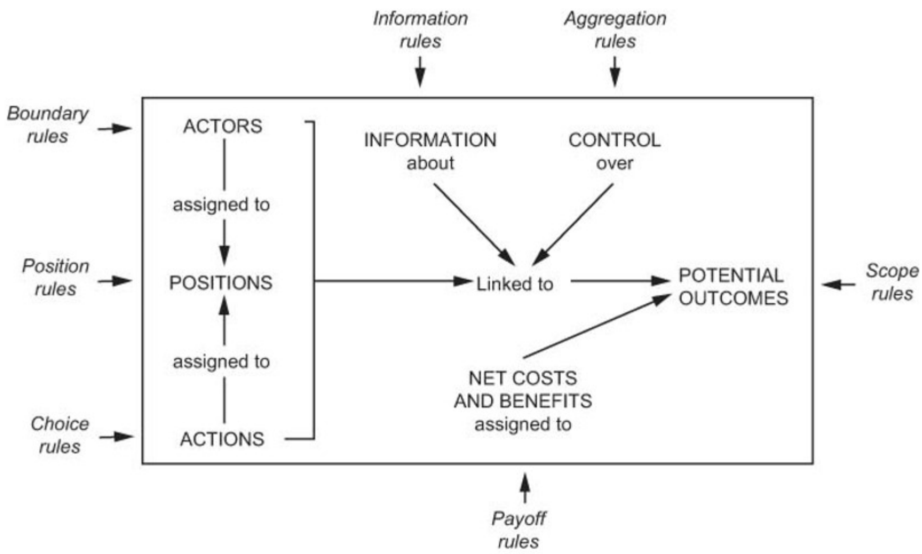

Figure 5.3: Action Situation-IAD

1. **Position Rule** In the context of DAC for SAF, various actors hold different positions with distinct roles and responsibilities. These actors may include DAC technology developers, SAF producers, airlines, government regulators, environmental organizations, and investors. Each actor's position determines their rights and abilities to influence decisions and actions related to DAC integration in SAF production.
2. **Action rule** This outlines the permissible actions that each actor can undertake concerning DAC and SAF. For example, DAC technology developers can work on improving the efficiency of DAC systems, SAF producers can explore DAC utilization for carbon-neutral fuel production, and airlines can consider incorporating DAC-SAF blends into their operations.
3. **Authority Rule** Certain actions in the DAC-SAF context may require authorization from regulatory bodies or governmental agencies. This rule specifies who has the authority to grant permissions or approvals for implementing DAC-related initiatives within the aviation sector and who is driving the adoption through policy or market incentives.
4. **Scope Rule**: The scope rule defines the boundaries of the DAC-SAF action situation. It can refer to the geographical areas where DAC facilities are located or rather restricted based on the

availability on renewable power, the airspace and airports where SAF is produced and utilized, and the timeframe in which actions take place.

5. **Aggregation Rule** The aggregation rule governs how individual actions or decisions by different actors are combined to create collective outcomes. For instance, the aggregated actions of multiple airlines adopting DAC-SAF can lead to a significant reduction in aviation emissions or aggregated investment in carbon removal credits can advance the technology maturation.
6. **Information Rule**: The information rule addresses the flow and accessibility of information in the DAC-SAF context. It determines how data and knowledge about DAC technology, SAF production processes, carbon pricing, and policy incentives are shared among stakeholders to make informed decisions.
7. **The payoff rule** considers the benefits and costs associated with DAC adoption for SAF production. It involves evaluating the economic, and environmental impacts of scaling DAC for the aviation industry.

5.3. Analyzing outcomes

Next, the outcomes of the action situation were evaluated. When analyzing outcomes, an objective standard is required. From the six common criteria listed in Ostrom's literature (Ostrom, 2010), the following three were considered for this case: economic efficiency, fiscal equivalence, and adaptability. These criteria serve as essential benchmarks to assess the effectiveness and impact of policies within the given context.

5.3.1. Economic Efficiency

An outcome is technically efficient if the marginal cost of producing a unit of output is equal to the price. However, many policy issues do not lend themselves to strict economic evaluation because there are no readily observable market prices for some social goods or services, or because inputs to the production process cannot be precisely valued(Ostrom, 2010).

In the case of DAC for SAF, there might not be well-established market prices for the social and environmental benefits of carbon reduction. The positive impact of SAF on reducing aviation's carbon footprint might not be directly translated into market prices. SAF production through DAC also has wider social benefits, including emissions reduction, air quality improvement, and climate change mitigation. These benefits may not have straightforward market prices, making it difficult to quantify and compare them against production costs. Valuing these social goods requires methods beyond traditional market-based pricing. The inputs required for DAC and SAF production, such as renewable energy and technology investments, have uncertain costs today. A precise forecast of the price reduction in the future would be possible only once the technology matures. Additionally, valuing the carbon capture process itself, which is a crucial input, does not have a standardized valuation method.

Given these challenges, strictly relying on traditional economic evaluation models when assessing the efficiency of DAC for SAF or any other use cases might not be the best option. Alternative methods like cost-benefit analysis, life cycle assessments, and non-market valuation techniques become essential for accounting for the broader social, environmental, and economic impacts of DAC for sustainable aviation. These methods aim to capture the true value of the outcome beyond simple market prices and ensure a more comprehensive assessment of DAC's role in promoting aviation sustainability.

5.3.2. Fiscal Equivalence

The concept of fiscal equivalence is one means to evaluate the equity of policy outcomes. Fiscal equivalence or proportionality means that those who benefit from a good or service bear the cost of providing it in equal measure to benefits received from it. Following this principle, those who derive greater benefits pay more than those who derive fewer benefits (Ostrom, 2010)

Implementing DAC for sustainable aviation entails costs, including those related to the capture process, fuel production, and infrastructure development. Meanwhile, the benefits of DAC are diverse and encompass carbon emissions reduction, enhanced environmental sustainability, and potential economic gains for the aviation industry and global economy at large. The concept of fiscal equivalence highlights that entities who derive greater benefits from a good or service should contribute more towards its costs. In the context of DAC for SAF, this would mean that those aviation stakeholders, airlines, or industries that benefit more from reduced carbon emissions and improved sustainability should proportionally contribute more towards the costs of DAC implementation, rather than relying solely on public investments. Without proportional contributions, a free rider problem could arise. Some stakeholders might choose not to invest in DAC-related efforts, relying on others to bear the costs while they still benefit from the collective outcomes. Fiscal equivalence helps prevent this situation by ensuring that beneficiaries contribute their fair share. However, it's important to strike a balance between equity considerations and maintaining incentives for participation. If costs become disproportionately high for certain stakeholders, it might discourage participation in DAC initiatives.

Policymakers and stakeholders involved in implementing DAC projects for SAF can use the principle of fiscal equivalence to guide the allocation of costs. They can design funding mechanisms, incentives, and pricing strategies that align with the principle, promoting equitable participation and maximizing the overall benefits. Therefore, the concept of fiscal equivalence has relevance in the DAC for SAF context by advocating for equitable distribution of costs among stakeholders based on the benefits they derive. Implementing DAC for aviation sustainability requires careful consideration of how the costs and benefits are distributed to ensure fairness, encourage participation, and ultimately drive meaningful reductions in carbon emissions within the aviation sector.

5.3.3. Adaptability

This refers to sustainability through innovation and adaptation in response to change. Sometimes existing policies impose rigidities. The policy context significantly influences the degree to which innovative solutions like DAC can be adopted. Policies that encourage sustainability through innovation and adaptation provide a favourable environment for the development and deployment of technologies like DAC. Policymakers can promote research funding, regulatory frameworks, and incentives that support the integration of DAC into the aviation sector. Existing policies that impose rigidities or barriers can hinder the adoption of innovative technologies such as DAC. If policies favour conventional fuels or lack mechanisms to incentivize sustainable alternatives, it may discourage investments and hinder the growth of DAC technology. Also, since DAC represents an innovative and evolving technology, institutional systems that allow for flexible adaptation are better suited to accommodate its growth and integration into aviation sustainability strategies. In the context of DAC for SAF, regional considerations, local partnerships, and cooperation could play a significant role in its successful implementation. Local control might enable tailored approaches that align with specific aviation industry needs and regional sustainability goals based on the availability of renewable energy, existing infrastructure and local policies.

5.4. Recommendations for action situation

Specific Policy Framework

To fully realize the potential of direct air capture for SAF production by 2050, a comprehensive policy framework encompassing clear guidelines and robust incentives is needed. This framework can pave the way for the seamless integration of DAC technology into the aviation sector and contribute significantly to achieving decarbonization objectives. A proactive and phased approach can be instrumental in driving DAC adoption within the aviation industry. This could involve implementing a sub-obligation within the synthetic aviation target, progressively increasing the utilization of DAC-derived carbon feedstock from 10% in 2030 to 100% by 2050. This gradual transition not only ensures a steady uptake of DAC CO_2 but also serves as an incentive for the aviation sector to embrace this innovative technology over time.

To further the commercialization of DAC technology requires robust policy support. Governments can play a pivotal role in this aspect by introducing funding initiatives for research and development to foster technological advancements in DAC. Investment support for DAC projects can encourage their implementation, while future mandates for DAC use in the aviation industry can provide a strong impetus for adoption. By offering such policy backing, governments can expedite the deployment of DAC for aviation sustainability and facilitate its integration into the broader aviation fuel landscape. The combination of sub-obligations, reporting requirements, measures to prevent double counting, and supportive funding and mandates forms a comprehensive policy framework essential for driving the widespread adoption of DAC for SAF production by 2050. Embracing these policy indications will empower the aviation industry to take significant strides towards its decarbonization goals.

Reporting Standards

Related to transparency and accountability, incorporating reporting obligations could be crucial. These requirements would disclose the origin of carbon feedstock used in synthetic aviation fuel production and the proportion sourced from DAC. Such transparency provides stakeholders with a clear understanding of the role DAC plays in the broader aviation sector's efforts to decarbonize. To address potential issues like double counting and to maintain accurate carbon accounting, a crucial measure is to allow only the carbon capture provider to claim emission reductions resulting from carbon capture. This approach prevents multiple entities from taking credit for the same carbon capture event, ensuring a fair assessment of emission reductions achieved through DAC.

Collaboration

Additionally, fostering collaborative research and development among airlines, DAC technology providers, and research institutions is pivotal. This collaboration serves as a catalyst for addressing technological challenges unique to aviation and tailoring DAC solutions accordingly. By sharing expertise, resources, and ideas, this collaborative approach accelerates technological advancements and enhances the viability of DAC integration in aviation. Moreover, governments hold a pivotal role in supporting DAC integration by offering policy incentives and research grants. These measures incentivize DAC development and its seamless incorporation within the aviation industry. Favourable regulatory environments and financial support from governments play a crucial role in facilitating the growth of DAC initiatives, thereby contributing to the reduction of aviation emissions. By uniting these perspectives, the aviation industry can harness DAC's potential, not only as an innovation but as a key aspect of its sustainable future.

6 Discussion and Conclusion

6.1. Discussion

This chapter presents a discussion of the results by integrating insights from each of the sub-research questions to answer the main research question. The final part of this chapter includes the conclusion with a summary of each research question with answers, followed by broader relevance of the thesis, limitations, and recommendations for future research.

Based on the elements from the technology, actor and policy analysis, the multi-faceted nature of DAC and the factors influencing its role in aviation are outlined below:

- **Technology Complexity**: DAC involves the use of advanced technologies to capture carbon dioxide directly from the atmosphere. The technical feasibility, scalability, efficiency, and costs associated with deploying and operating DAC systems are complex considerations that impact the viability of using DAC as an offsetting method for aviation emissions.
- **Environmental Impact**:The overall environmental impact of DAC extends beyond the mere removal of carbon dioxide. Factors such as the energy source used for DAC, the emissions generated during the construction and operation of DAC facilities, and potential impacts on land use and ecosystems must be carefully evaluated to ensure that the net environmental benefit is achieved.
- **Carbon Accounting:**Accurately quantifying the amount of carbon dioxide removed and ensuring that the removals are permanent are challenging aspects of DAC-based carbon removal. Rigorous carbon accounting mechanisms are necessary to ensure that offset claims are credible and contribute effectively to emissions reduction goals.
- **Policy Requirements:**The adoption of DAC for aviation emissions offsetting requires alignment with existing and potential future policies, regulations, and international agreements related to aviation emissions, carbon markets, and climate goals. This involves complex negotiations, cross-border considerations, and potential interactions with other sectors.

Figure 6.1: Factors influencing role of DAC in Aviation context

- **Scaling up:**Scaling up DAC technology to meet the significant carbon removal needs of the aviation sector requires substantial infrastructure development, including the establishment of DAC facilities, transportation systems for captured carbon, and storage solutions.
- **Economic Viability:**The economic feasibility of using DAC for offsetting aviation emissions depends on factors such as the price of carbon credits, the cost of DAC technology, and market demand. It involves considerations of cost-effectiveness and competitiveness against alternative mitigation strategies.
- **Stakeholder Engagement:** Various stakeholders are involved, such as airlines, regulatory bodies, technology providers and environmental organizations. Balancing the interests and perspectives of these stakeholders is crucial for successful adoption, and engagement strategies need to address diverse concerns.
- **Interplay with other strategies:**DAC as a technology and carbon removal as an approach might face public scepticism or concerns. Ensuring public understanding, acceptance, and support for the use of DAC for aviation emissions offsetting is an important aspect that can influence the success of such initiatives.

To facilitate the adoption of negative emission technologies, it would be more suitable to focus on potential combinations of multiple technologies rather than single technologies as solutions.

Firstly, the exploration of DAC and the fusion of technologies in a hybrid manner can be used as stepping stones. This incremental progression allows for the incorporation of innovative features into the existing decarbonization portfolio.

Secondly, capitalizing on market dynamics becomes crucial. Innovations emerging from niches can gain traction by aligning with the growth of specific market segments. This strategy leverages existing trends to propel novelties into wider acceptance.

Thirdly, the integration of new technologies to experiment with novel functionalities and user behaviours presents opportunities. If these innovations can find application in new market contexts, they can sidestep the challenge of competing directly with established technologies. Apart from the direct application for fuels, other small-scale applications can be encouraged which can help the technology mature.

Lastly, incorporating external stakeholders into the innovation process can be advantageous. Established players within the sector might be hindered by vested interests. In such cases, involving outsiders can inject fresh perspectives and accelerate the adoption of innovative methods and approaches.

Connecting it back to the MLP framework, a general transition policy strategy must have two characteristics. On the one hand, pressure on the existing regime should be increased. This can be done with financial instruments (e.g. carbon tax) and regulations (tradable emission rights, emission norms). On the other hand, radical innovations should be stimulated to emerge in niches. This requires more specific governance policies, e.g. subsidies for experimentation, network management to enrol the right actors in the niche, and the development of guiding visions and future expectations. This does not mean that governments 'pick the winners,' but that variety in innovation needs to be stimulated and guided (Geels, 2002)

6.2. Conclusion

The objective of the thesis was to identify institutional enablers and barriers to the adoption of direct air capture as a measure of aviation sustainability. To fulfil the thesis objective, 4 sub-questions were formulated. The answers to the sub-questions and reflection on the project's relevance are summarized below:

1. *What is the current landscape of decarbonization efforts in the aviation sector?*

   The aviation sector faces a range of challenges that drive innovation and technological advancement. Internal technical challenges, stemming from limitations within current aviation technologies, motivate research and development to enhance fuel efficiency and reduce emissions. Negative externalities, such as environmental impacts and resource consumption, are prompting the industry to innovate in sustainability practices to mitigate these adverse effects. Stricter regulations in response to negative externalities necessitate compliance and drive innovation as stakeholders work to meet and surpass new standards. Evolving user preferences, including the demand for environmentally friendly travel options, create new markets for innovative technologies that cater to changing needs. Furthermore, shifts in the broader landscape, such as geopolitical changes and economic fluctuations, present challenges and opportunities for the aviation industry to adapt its strategies and practices.

2. *What are the key factors defining the current state of Direct Air Capture technology?*

   The current Direct Air Capture capacity is around 0.01 Mt CO_2year. However, DAC technology is still in its early stages and faces challenges due to its high costs. To become economically viable, advancements in its chemical processes are needed to drive down costs. Despite its current limitations, DAC has the potential to partially offset hard-to-abate emissions from various sources. Continuous advancements in DAC technology are necessary to maximize its potential impact on carbon capture and contribute to global climate goals.

3. *Who are the relevant actors involved in the development and potential adoption of Direct Air Capture in the aviation context?*

   The development and usage of DAC involve various relevant actors. DAC technology providers play a key role in innovating and manufacturing the technology, while the aviation industry seeks sustainable practices, including DAC, to reduce carbon emissions. Governments and policymakers shape supportive policies, and research institutions contribute to technological advancements. Green hydrogen producers offer a renewable energy source for CO_2 capture, and SAF producers can utilize captured CO_2 for lower-emission aviation fuel. Transport and storage infrastructure providers facilitate CO_2 transportation and storage. Location hosts, such as airports or ports, provide potential sites for DAC plants with access to renewable energy. Environmental organizations advocate for climate change mitigation and help shape the narrative, and investors support DAC technology development.

4. *What are the current policies and regulations that relate to DAC, specifically to the aviation sector?*

   With regard to technological Carbon Dioxide Removal, the agenda is often aligned with carbon capture and storage technologies. In the EU, there are dedicated proposals and regulations related to carbon capture and storage, of which DAC is a part. The EU ETS can also play a crucial role. Related to aviation, policies incentivizing the uptake of SAF provide a sub-obligation for synthetic fuels which includes DAC-derived SAF. Regarding the use case of carbon offsetting, since 2020, DAC has also got significant attention in the voluntary carbon markets However, it is worth noting that there are currently no methodologies established for DAC projects under the major voluntary market standards. As a result, transactions for these offsetting projects occur outside the scope of the main standards.

5. *How can the institutional arrangements within the aviation sector influence the adoption and implementation of Direct Air Capture, for the relevant use case identified?*

   The assessment of Direct Air Capture for sustainable aviation reveals challenges in applying traditional economic evaluation models due to the absence of readily observable market prices for social goods and services. The positive environmental impact of Sustainable Aviation Fuel produced through DAC lacks direct translation into market prices. The broader social benefits, including emissions reduction and climate mitigation, resist straightforward pricing. Quantifying these requires non-market valuation methods. The uncertain costs of DAC inputs like renewable energy and technology investment hinder cost forecasting. Additionally, valuing the carbon capture process lacks standardized methods. In light of these challenges, traditional economic evaluation might not be optimal. Alternative methods, such as cost-benefit analysis, life cycle assessments, and non-market valuation, prove essential for comprehensive assessment. Fiscal equivalence suggests proportional contributions to costs by those benefiting more, preventing free rider problems. Policymakers can use this principle to guide cost allocation, ensuring fairness and participation. Adaptability is crucial, favouring sustainability through innovation and adaptation. Flexible institutional systems are better suited for DAC's growth and integration into aviation sustainability strategies, allowing tailored approaches based on regional needs and policies.

Answering Main Research Question

Institutional Enablers to DAC Adoption for Sustainable Aviation

To fully realize the transformative potential of direct air capture for sustainable aviation fuel production by 2050, the establishment of a comprehensive institutional framework becomes imperative. A strategic, phased approach to integration is instrumental in overcoming potential hurdles and promoting the adoption of this innovative technology within the aviation sector. This approach could involve setting gradual targets, such as incrementally increasing the utilization of DAC-derived carbon feedstock from 10% in 2030 to a complete reliance on DAC by 2050. By doing so, a clear signal is sent to the aviation industry, encouraging a progressive shift towards embracing the benefits of DAC.

The role of governments cannot be overstated in catalyzing DAC's commercialization and integration. Governments can play a pivotal role by creating an enabling environment through policy mechanisms such as research and development funding, financial incentives, and the establishment of future mandates for DAC integration within the aviation sector. These mechanisms provide a solid foundation for the aviation industry to embark on a trajectory of sustainable transformation, aligning with global decarbonization goals. By nurturing a supportive ecosystem, governments can effectively facilitate DAC's seamless transition from innovation to implementation, shaping the trajectory of sustainable aviation for years to come.

Institutional Barriers to DAC Adoption for Sustainable Aviation

Despite the promising potential of DAC for SAF production, navigating institutional barriers remains a critical challenge. The imperative for clear reporting standards arises to address transparency and accountability issues surrounding DAC adoption. Defining reporting obligations that mandate the disclosure of the origin and proportion of DAC-derived carbon feedstock used in aviation fuel production is essential. These obligations not only enhance carbon accounting accuracy but also ensure that DAC's contributions are duly recognized and accounted for, preventing any potential overestimations or duplications.

Collaboration, while pivotal, might encounter institutional silos between key stakeholders like airlines, DAC technology providers, and research institutions. Bridging these divides necessitates proactive intervention, such as governments incentivizing collaborative research and development. By fostering an environment of collective innovation, institutions can collectively address technological challenges unique to aviation and tailor DAC solutions for industry-specific needs. Overcoming these silos can expedite technology refinement, enhance viability, and ensure a more holistic and coordinated approach to DAC adoption.

In summary, while institutional enablers offer the promise of propelling DAC integration within the aviation sector, careful consideration of institutional barriers is paramount to navigating the complexities that lie ahead. By understanding and effectively addressing these barriers, stakeholders can work collectively towards harnessing the transformative potential of DAC for sustainable aviation. By pursuing these initiatives, the aviation industry can effectively work towards minimizing its residual emissions.

6.2.1. Academic and Societal Relevance

Increasingly climate models emphasize the urgency of large-scale carbon dioxide removal to complement deep emissions reductions in order to meet national and global climate goals. As the pace of emissions reduction remains critical, carbon removal methods like DAC are increasingly seen as essential to address climate challenges. To achieve significant carbon removal at a large scale, a diverse portfolio of approaches, including DAC, will be necessary to mitigate costs and minimize the risk of relying solely on one method. Early investments in DAC technology will help pave the way for successful implementation and contribute to reducing future costs as the demand for carbon dioxide removal becomes more pressing in the aviation sector and beyond.

The academic relevance of using institutional analysis lies in its capacity to provide an understanding of the complex interactions between institutions, actors, and technology in the aviation industry. It helps understand how existing rules have developed into lock-in paths and what actions are needed by policymakers and actors to drive the adoption of carbon removal methods in aviation and beyond. Even though IAD was used, the concept of path lock-in can be related to the meso level of the socio-technical regime of MLP and also to Level 2 (institutional environment) of Williamson's 4-layer model of institutions. The findings of this thesis will hopefully help inform policymakers, industry stakeholders, and researchers in reflecting on the role of institutions and the barriers to the entry of new innovative technologies and help in developing effective strategies and policies to facilitate the widespread adoption of CDR technology and other novel innovations contributing towards sustainable aviation.

6.2.2. Link to CoSEM

This thesis adopted a socio-technical approach to analyze the potential role of DAC in the specific case of aviation. There was a clear technology component related to DAC technology pillars. The focus was on the interplay of institutions, actors and technology in this context. A transition theory framework in the form of a Multi-Level Perspective was used for a descriptive framing of the problem. The institutional analysis based on Ostrom's IAD framework was used to explore policies relevant to aviation and carbon removal. It is aligned with elements from a typical CoSEM master's thesis as it covers the values of different actors involved in the system and there is an analysis of not only the technical and institutional challenges but also management and ethical choices such as whether DAC actually disincentives the industry to prioritize decarbonization or issues related to actor responsibilities and accountability.

6.2.3. Limitations of the study

While the IAD framework is a suitable method for conducting institutional analysis, it does have some limitations when applied to technology-related studies. One significant limitation is the nature of technological interactions. Technology integration involves many interrelated components, actors, and technical dependencies, which may not be fully captured by the IAD framework. In this case, using a technology transitions type of framework or MLP might be more suitable, which focuses on the interaction and co-development of different innovations that need to mutually grow in order to get commercialized. For instance, direct air capture absorption innovation, cost reduction and green hydrogen production efficiency improvements. Secondly, the IAD framework primarily focuses on human behaviour within institutions and may not adequately address the technical aspects of DAC technology. While this is suitable from an institutional viewpoint, it turns out to be a limitation to study newly announced or proposed institutions. Finally, the IAD framework was initially designed to study social institutions, collective action problems, and decision-making processes in relatively stable contexts. As such, its static nature and focus on long-term institutional arrangements may limit its ability to fully consider the rapid pace of technological changes, such as those occurring in the field of DAC. New technological breakthroughs may render certain institutional arrangements or policies obsolete, necessitating adjustments to accommodate emerging technological capabilities.

For the selection of the action situation, the most relevant and direct application of direct air capture for aviation was considered, i.e. for the production of SAF. However, as highlighted in the policy and actor analysis, DAC for carbon storage and carbon offsetting can also be considered and analyzed as multiple action situations. By doing so, the concept of a network of adjacent actor situations could be applied for further insights into the interactions and relationships among various actors involved in the implementation of DAC for both SAF and carbon offsetting purposes. To enhance the actor analysis, conducting additional interviews with key stakeholders, such as DAC startups, green hydrogen producers, transport and storage infrastructure providers, and airlines can provide deeper insights into their perspectives, motivations, and roles in the DAC adoption process.

6.2.4. Scope for Further Research

The following points describe the scope for further research:

- An in-depth case study focusing on SAF can provide a comprehensive understanding of its current status and potential integration with DAC. By combining insights from institutional analysis with existing techno-economic assessments, it could be possible to develop an integrated socio-technical roadmap for DAC adoption in aviation. The roadmap can include policy recommendations derived from the integration of qualitative and quantitative findings. It could also potentially involve the use of integrated assessment modelling to simulate potential scenarios and their outcomes.
- The sample size of the number of stakeholders interviewed was too small (n=6). While it helped in understanding the key challenges and practical difficulties of DAC implementation, engaging in more in-depth interviews with key stakeholders in the aviation industry, such as airlines, DAC technology developers and government policymakers can provide further valuable perspectives on the enablers and barriers related to DAC integration in aviation sustainability.
- Most of the available documentation was in the proposal stage and was yet to be adopted by the EU parliament. Therefore, these policy documents may evolve over time, and once directives and regulations are released, it becomes necessary to revisit and conduct a greater analysis of these documents to ensure their relevance in shaping the roadmap and policy recommendations.
- Finally, a more detailed examination of the historical technology innovation pathway that has led to the lock-in of the current fossil fuel-based system in aviation would be useful. This would uncover the structural underpinnings of the sector and aid in a better analysis of its institutions.

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A

Interview Transcripts

This appendix contains the informed consent form and the anonymized transcripts of the interviews taken as part of the study to understand the technology and policy landscape of decarbonizing aviation.

A.1. Informed Consent Form

The following information was conveyed to the participants before the interviews were conducted.

The information provided in the participant information document accurately describes the risks and possible consequences of participating in the study. Herewith I confirm, the undersigned, that I give permission to participate in the study.

In connection with this, I declare the following:

PLEASE TICK THE APPROPRIATE BOXES as Yes or No

A: GENERAL AGREEMENT – TAKING PART IN THE STUDY

1. I have read and understood the above information about the study. □ □

2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason. □ □

3. I am sufficiently informed about the nature, purpose, and procedure of the interview. □ □

4. I agree to be video recorded while taking part in the interview. □ □

5. I understand that the interviews will be transcribed.

B: DATA PRIVACY & PROTECTION

6. I understand that the information I provide will be used in reports and presentations in an anonymous way (by hiding any personal information) □ □

7. I agree that my information can be quoted as research outputs in an anonymous way □ □

8. I understand that taking part in the study involves collecting specific personal information such as my name, designation, and email address, and will not be shared beyond the graduation committee.

9. I understand that the original transcripts will be anonymised and only the summary of the anonymised transcripts will be made publicly available through TU Delft education repository. □ □

C: DATA STORAGE, ACCESS & REUSE

10. I understand that the video recording of my interview will be deleted 12 months after the thesis defence. □ □

11. I understand that the transcripts generated from the video-recorded interview will be stored till 12 months after the thesis defence and will be accessible only by the graduation committee. □ □

12. I understand that, beyond 12 months of storage of original transcripts, I may be asked for permission to extend the storage. □ □

Participant Signature

I have read the information sheet carefully and understand what I freely agree with

Name of participant Signature Date

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....

The information provided in the participant information document accurately describes the risks and possible consequences of participating in the study. Herewith I confirm, the undersigned, that I give permission to participate in the study.

In connection with this, I declare the following:

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – TAKING PART IN THE STUDY		
1. I have read and understood the above information about the study.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I am sufficiently informed about the nature, purpose, and the procedure of the interview.	☐	☐
4. I agree to be video recorded while taking part in the interview.	☐	☐
5. I understand that the interviews will be transcribed.		
B: DATA PRIVACY & PROTECTION		
6. I understand that the information I provide will be used in reports and presentations in an anonymous way (by hiding any personal information)	☐	☐
7. I agree that my information can be quoted as research outputs in an anonymous way	☐	☐
8. I understand that taking part in the study involves collecting specific personal information such as my name, designation, and email address, and will not be shared beyond the graduation committee.	☐	☐
9. I understand that the original transcripts will be anonymised and only the summary of the anonymised transcripts will be made publicly available through TU Delft education repository.	☐	☐
C: DATA STORAGE, ACCESS & REUSE		
10. I understand that the video recording of my interview will be deleted 12 months after the thesis defence.	☐	☐
11. I understand that the transcripts generated from the video recorded interview will be stored till 12 months after thesis defence and will be accessible only by the graduation committee.	☐	☐
12. I understand that, beyond 12 months of storage of original transcripts, I may be asked for permission to extend the storage.	☐	☐

Figure A.1: Informed Consent Form

A.2. Anonymized Interview Transcripts

Interview 1

The interviewee is a Project Lead in the fuels division at a Sustainable Aviation Fuel production company which is a global market leader for SAF. This interview gave insights into the challenges of DAC and the feasibility of using DAC for synthetic SAF production.

The interviewee is actively involved in project development and research related to future fuels. They work in a dedicated team focused on the initial stages of project development, including business development and assessing opportunities. They were also involved in the demo project, which focuses on direct air capture and SAF production.

About DAC-SAF pilot project at Rotterdam Airport

It was a collaboration which began with Schipol Airport which wanted to explore airport sustainability initiatives. They wanted to investigate the feasibility of a demonstration plant able to produce SAF from air, water and renewable electricity. The European consortium conducting the study was led by the German service provider EDL and further consisted of Climeworks, Sunfire, Ineratec, SkyNRG, Uniper and Urban Crossovers.

What were the practical challenges of DAC derived SAF production with respect to cost and scale?

The planned demonstration plant at Rotterdam Airport was not implemented as there are only a limited number of suppliers of DAC. These suppliers are facing challenges in scaling up their production capacity while keeping costs low. The production of SAF is already challenging, and utilizing DAC for SAF adds another layer of complexity, increasing the risks associated with adopting new technologies. Also, we understood that Climeworks is prioritizing the development of its technology itself rather than collaborating with specific use cases. However, there is a desire among these companies to grow and expand their operations. Their focus currently lies on enhancing their internal technologies before engaging in collaborative efforts with potential users. While the idea of producing fuel is intriguing, they have chosen to prioritize storage, which presents a significant challenge for the integration of direct air capture into SAF production.

What are the cobenefits of DAC? What is a potential market scenario for this service?

These DAC companies recognize the market potential for their service. For instance, Climeworks has their ORCA unit in Iceland, through which they sell negative emissions. They have observed that there is a genuine interest among people to purchase these negative emissions.

What were your key insights from the demo project regarding green energy requirements for DAC?

Initially, we explored the feasibility of co-locating at an airport, taking into account factors such as permitting. Unfortunately, it was determined that co-locating at an airport did not prove to be a viable option. They do not comply with airport permits for fuel production, as airports are not suited for that purpose. Additionally, the necessary utilities required for such a plant are not available at airports, making it an impractical option. As an alternative, the Port of Rotterdam was considered. Although not certain, it was believed that the port had connections to wind power. The objective was to establish a small and straightforward demonstration plant to expedite the process. Airports, in the near term, did not make sense due to potential complaints from nearby residents, as the plant would operate continuously unlike airports that have designated shutdown times. While it is possible to modify permits and consider airports in the future, the project initially aimed to minimize difficulties and pursue the most readily achievable opportunities. The key factors revolve around accessing cheap renewable power, preferably with a base load capacity, and establishing a connection, whether through pipelines or alternative means. Meeting these parameters would be an ideal starting point. In the case of Direct Air Capture, having a location with surplus renewable power is advantageous as it minimizes energy losses during long-distance electricity transportation. Converting excess renewable power to fuel through Direct Air Capture systems would be an ideal approach.

What is your perception of the role of EU policies as a driver for technology advancement of DAC and adoption for SAF?

In principle, there are different considerations to be taken into account. While in the demo project, we explored the option of utilizing CO_2 locally, we also examined the potential of CO_2 transportation. This is because the cost associated with transporting CO_2 is generally lower compared to the hydrogen production process. The production of hydrogen requires a higher power input, which constitutes a significant portion of the overall expenses. In some cases, it may be advantageous to locate the facility in an area where cheap baseload renewable power is available, but CO_2 resources may be limited. In such scenarios, two options can be considered: either employing direct air capture or importing CO_2Depending on the specific cost factors involved, importing CO_2 could potentially be a more economical solution in the short term, although it ultimately depends on the specific circumstances and cost figures.

Regarding other policies, it is precisely what the market requires for growth. When there is clear market demand, it provides confidence to potential investors. Building production facilities for projects of this scale involves significant investments, typically in the range of several million euros. Companies like ours may not have sufficient funds available to finance these projects independently. Therefore, attracting investors becomes crucial. To secure project financing, it is essential to present a robust and compelling story while minimizing risks. Higher risks tend to result in investors seeking higher returns on their equity investments. Having a policy framework in place, such as the one we discussed, ensures that there will be a demand for the project's products. This, in turn, facilitates the financing process by making it more attractive to investors. Regarding the specific aspects of the REFuelEU policy, you may have noticed that there are two sub-mandates: one focused on the bio portion and the other on power-to-liquid technologies. This dual approach allows for the growth of both bio feedstock types and SAF simultaneously. It provides an advantage as it supports the expansion of both feedstock options. However, it is worth noting that direct air capture is even more expensive than other methods.

How can public investment and funding for DAC projects be attracted?

Funding options can vary depending on the scale and category of the project. There are funding opportunities available for smaller investments, typically encompassing projects with budgets up to around 10,000,000 euros. On the other hand, there are funding avenues for large-scale projects. The category in which a project falls determines the suitable funding source. As an example, let's consider a project we worked on, the diesel project that utilizes half our technology, focusing on waste oils and fats. For this particular venture, we pursued innovation funding, specifically aimed at supporting first-of-a-kind commercial projects. We were eligible for this funding opportunity, although it should be noted that it is highly competitive. Numerous organizations and initiatives related to renewable energy and the energy transition apply for such funding. In our category, only a limited number of projects were ultimately granted funding, despite the substantial number of applications received.

What is the role of private investors and funding for DAC projects?

There is definitely a certain appeal to direct air capture from private investors. It captures the interest of people right from the start because it offers a promising solution for achieving sustainable aviation. It is considered an attractive option for both individuals and corporations. Direct air capture represents a goal that many aspire to achieve, as it represents an ideal outcome in terms of sustainability. Corporations, in particular, are inclined to support such initiatives. However, it is crucial to have a solid story that outlines the development plan and long-term profitability, depending on the stage of project development. Currently, we are focusing on the demo plant phase, which requires a relatively lower investment compared to the hundreds of millions needed for a commercial plant. In this stage, it is important to communicate how the scaling process will occur and how the technology combination will contribute to future success. From an investor's perspective, there are various motivations for involvement. Some may be interested in supporting technology suppliers or improving their own technologies at a specific scale. Other stakeholders may be motivated by the desire to participate in an impactful project. When considering investments for a commercial plant, it becomes crucial to engage serious players in the industry who possess the necessary expertise and financial capacity. Major corporations, such as oil majors, or large investment funds, are potential candidates for providing the substantial equity investment required for such projects. Typically, commercial projects rely heavily on equity investments with a smaller portion supplemented by bank loans or a combination of both. Microsoft, for instance, may be interested in investing as part of its emissions reduction efforts. Other stakeholders with experience and a solid understanding of project development may also choose to invest significant amounts, such as investing 100 million euros into a specific project.

What were the key takeaways from the demo project?

Currently, it is important to approach the development process step by step. On the direct air capture side, the focus is on scaling up direct air capture units to achieve commercial viability. Meanwhile, on the SAF production side, the initial goal is to establish functioning commercial power-to-liquid plants. In this phase, the aim is to utilize the most cost-effective source of CO_2 which may not necessarily involve direct air capture. It is likely that the development of direct air capture and SAF will progress separately initially, but eventually, there will be a point where combining them makes sense. Direct air capture technology itself produces high-purity CO_2 which is easily usable. Therefore, integrating it should not pose significant challenges.

The primary concerns at this stage are related to cost and technology validation. The costs associated with direct air capture and SAF production need to be addressed to ensure commercial viability. Additionally, proving the scalability and reliability of the technology is crucial. Often, technologies perform well at small scales but face challenges when scaled up to commercial deployment. Therefore, the initial focus should be on demonstrating the technology's effectiveness and viability at a commercial scale, as this is an important step in reducing technology risks. By successfully validating the technology and achieving commercial deployment, the costs associated with direct air capture and SAF production are expected to decrease. Replication of the technology will further contribute to cost reductions. However, before reaching these milestones, the immediate priority lies in proving the technology's commercial scalability and addressing associated technological risks.

What are your views on airlines and Airbus buying carbon removal offsets?

By signalling to potential investors that a certain percentage of the fuel will be purchased, it provides assurance and encourages investment. This is the approach taken by airlines like KLM and other airlines in various projects I have seen. Their commitment to buying a portion of the fuel ensures a market demand, making it more attractive for investors to participate. Additionally, these airlines may also contribute development funding to the ongoing projects, providing financial support to the current initiatives.

Interview 2

The interviewee works in Business Development, Strategy and New Business at a Dutch airport. This interview gave insights into the airport's perspective on facilitating SAF.

Insights from the demo Project and challenges

The various processes involved in producing SAF can be interconnected, as it is not a single-step procedure but rather a series of interconnected processes. With this understanding, a feasibility study was conducted to determine the potential for collaboration among partners. Key partners such as Climeworks and the RTH airport were approached to gauge their interest work together. The study led to the formation of partnerships between carbon capture and process companies. We had some challenges during the study, including the scale-up and power usage requirements. Given the energy-intensive nature of the power-to-liquid project, scaling up in the Netherlands was found to be difficult due to limited electricity resources and the country's climate conditions. Despite these challenges, a decision was made to proceed with a pilot plant in the Netherlands, with the understanding that scaling up in a different location would likely be more economically viable due to the scarcity of the specific product involved.

Initially, there were plans to establish the demo plant at the airport to showcase carbon capture efforts and the airport's involvement. However, upon further investigation and discussions with relevant authorities such as the municipality and safety district, it became clear that building a chemical facility in close proximity to residential areas near the airport would face numerous challenges, including the need for a chemical plant permit. Additionally, the issue of scale-up was recognized, as even if the DAC pilot plant was successful, scaling up at the airport site would be impractical. Consequently, a decision was made to relocate the pilot plant to a chemical area near the Maas river near the Rotterdam Port, where permit issues would be less restrictive and scaling up would be more feasible.

What is the role of airports in facilitating SAF, especially from novel sources like DAC?

As an airport, our role is to facilitate the availability of SAF for our clients. We have agreements with self-suppliers, ensuring that the certified product is accessible through various means, whether it's delivered by truck or through their supply chains. At smaller airports like ours, we have a concession with Shell and collaborate with them to provide certified SAF. In larger airports like Schiphol with higher demand, the supply chain may involve pipelines or tanks, and the fuel mix in these tanks is also certified. Our focus is on the product itself, and we work to ensure its storage and facilitate its distribution within the airport premises.

Interview 3

The interviewee is a policy associate at an international climate policy think tank specializing in carbon removal certification and carbon capture activities in the EU. This interview gave insights from a policy perspective on the EU carbon capture policies and SAF.

Recognition of carbon capture as a tool to meet climate targets. What is the impact of the policies in the short/long term and which sectors stand to gain from this initially?

So there is a need for concrete policy drivers and incentives for DAC in carbon management strategies. Currently, DAC lacks specific policy measures, and voluntary carbon markets and corporate contributions are not sufficient to drive its deployment. The Certification for Removals is a straightforward process to certify DAC, but it does not provide strong incentives. However, it could lay the groundwork for the potential inclusion of removals into the EU ETS in the future. But industries like aviation, which are considered hard to abate, are not currently driving DAC technology deployment, despite voluntary efforts from other corporates.

Regarding Airbus and airlines partnering to pre-purchase carbon removal credits

The CDR FYI tracker is a resource for tracking purchases of different types of CDR. The recent advice given to the Commission for the 2040 target is also referenced. For example, Rolls Royce's involvement in developing DAC technology is mentioned, but it is noted that they have recently scaled back their efforts in this area, focusing instead on utilization and Power-to-Liquid (P2L) fuel. One of the main challenges is the absence of DAC plants in the EU. Even if such plants were available, the price of CO_2 is not competitive. Additionally, the high energy requirements and associated costs hinder the widespread use of DAC in the near term. However, from a carbon cycle perspective, if energy requirements and costs can be reduced without conflicting with renewable sources, using DAC to remove CO_2 from the atmosphere and incorporate it into the carbon loop could be beneficial. But it is mentioned that if CO_2 capture can be achieved at a specific source point, it is generally more advantageous to store it rather than utilise it elsewhere.

DAC is currently presented under the umbrella of CCUS technologies, in the policy documents and reports. Considering its nascent stage and low TRL level, why is it being promoted so much?

DAC as a nascent technology can be compared to other clean technologies such as the solar energy industry from the 1990s. Policy support and technological advancements are necessary to move DAC from the research and development stage to widespread adoption. The TRL ladder, which focuses on reducing costs while acknowledging the inherent limitations, plays a crucial role in this process. The prominence of DAC is largely due to the IPCC's AR-6 report, which emphasizes the importance of carbon removals. But there are also other CDR options such as enhanced rock weathering and biochar, raising concerns about their permanence. In contrast, DAC has been around for a long time, and cost estimates vary, with some suggesting a reduction to $100 per unit while others remain sceptical about significant cost reductions. Despite the current buzz and hype surrounding DAC, its usefulness lies in its potential as a technological pathway, although the lack of specific policy support remains a challenge in the industry.

Regarding funding for carbon capture and storage Public-Private Partnerships are probably the most effective approaches for addressing climate solutions. The SDE++ mechanism plays a crucial role by subsidizing the price differences in the EU ETS for the capture and storage of CO_2This mechanism promotes funding, coordination, and public perception, and facilitates stakeholder engagement. PPPs have the potential to be significant enablers in driving climate action forward. Regarding the utilization of CO_2 there is scepticism surrounding its efficiency compared to storage. The requirements for site selection, transportation, and storage of DAC technologies pose challenges. Additionally, there is a possibility that DAC companies might evolve into energy companies as they navigate the complexities of CO_2 utilization.

Regarding suitable incentives and business models

There is a need for policies similar to the 45Q tax credit in the United States at a member-state level within the EU. These incentives would play a crucial role in encouraging carbon capture and making it a profitable venture for businesses. Next, a stable carbon price is essential for the viability of DAC business models. It provides predictability and certainty for companies operating in the carbon removal sector, allowing them to plan their operations and investments accordingly.

The concept of a Central Carbon Bank, proposed by Wilfred Rickles, offers price stability to the EU ETS scheme. This economic model could facilitate the integration of carbon removal certificates, providing a streamlined mechanism for trading and incentivizing carbon capture. Finally, reverse tax credits could be a potential approach to incentivize DAC by providing financial support or tax benefits to companies engaged in carbon removal activities. This mechanism would encourage investment and innovation in the DAC sector.

Interview 4

The interviewee is a sustainable aviation consultant. They provide operational aviation advice on sustainability, focusing on supporting airports in developing NetZero Roadmaps. They help airports understand upcoming developments, adapt to new technologies, and create plans and strategies for decarbonization. They also assist governments at regional, national, and European levels in organizing their strategies and understanding the implications of sustainable aviation. This interview gave insights from an industry perspective as a consultant who engages with multiple stakeholders on topics related to aviation sustainability.

Regarding the state of carbon removal technology and use cases

If you're looking at the future, you are looking at captured carbon, either from a point source or from ambient air. but this technology is still in its first steps. There are a few production facilities in Europe and the United States, but they're quite small-scale, lab-size production and the energy efficiency there is relatively very low. So that's still one where there's there needs to be a scale-up before we can speak about any significant views. I think a critical point to make here is that when you're capturing carbon and you are using it you cannot count it twice, right? Because you are emitting it again back into the atmosphere. So, what we like to focus on is the stuff itself and say that if you're making stuff through carbon captured carbon, that's good, that's up to 100%. But where accounting is done is important. When an airline burns this off, that's when they have carbon reduction. So, if the company that is doing the carbon capture uh is accounting for a negative emission on their books, so to speak. But then selling the carbon to a SAF producer you have the risk of double counting, and that's something that we want to highlight. On carbon capture, we see that it's being mentioned more and more within airports that we speak to. They have residual emissions in their own carbon accounting framework. It can be because there are some diesel generators or emergency systems that need to run on carbon. So, the small amount that you need to mitigate the carbon capture currently as it stands can be done through location-based nature solutions.

There are several slightly more advanced carbon capture techniques in terms of storing it with specific materials involving chemical reactions, but that's something that is a bit far away from the aviation sector. And then, of course, you have the synthetic carbon capture, which means you're basically paying an organization such as Climeworks to take carbon out of ambient air. And we've supported airports in understanding how this works. But it's not done location basis, so we need to buy the credits basically from the Climeworks being developed in Iceland as far as I know and that is still that for them is a very high price for looking at 1000 euros/tonne. As per our understanding, we could go down to 400-600 euro per tonne but that's about it. At least for now. So, we are talking about very expensive prices here.

For the aviation sector, we are looking at it from a global scale (CORSIA)- offsetting based not necessarily from a carbon capture perspective. Because they are still betting on carbon offsets to reduce aviation emissions, which I personally totally disagree with on a professional level, we are supporting CORSIA but very, very critical of its pitfalls so to speak, which is no carbon price.

Regarding working with airports

We provide our clients with as much objective information on this as possible and notice that there are usually 2-3 critical points for them. First, it is the availability of the solution. Who else has done it? Can we see what has been done? Do we have a benchmark that allows us to understand how it has happened and that there are companies in place that it's allowed legislatively these kinds of things so that there's a benchmark that's one with carbon capture? That's quite difficult because the benchmarks that are there are very much out of the aviation sector. So, they're being done by Climeworks or by some multinationals that are supporting them. The second thing they ask is the price and if that will change over time. There's a reduction in that and sometimes also the why behind the price. Why is it more expensive now? Does it work? These sorts of questions. For instance, regarding hydrogen aviation, we assess whether they have a feedstock, who is blending it and so on. So, the two main ones were benchmarking and price.

Regarding airlines buying DAC-derived carbon removal credits

What we present airports or governments is the state of play. We don't work with airlines a lot, so I do not have insight into that. In general, it is seen as a last resort due to the high price. (as mentioned by KLM) . Since aviation is a very low-profit margin sector it would be difficult to sell it to a passenger. So they stick to cheaper offset options.

We advise them on a qualitative scale. So, we do not do a comparison of different voluntary offset programs. But we help airports in achieving their carbon accreditation status. In that process, we provide them with examples of good ones and bad ones and advise them to think about the transparency and the validity of the credits that are working on. However, airports generally have contracts with organizations that purchased these credits for them. So, we are not quantitatively involved in that. My two cents on the topic outside of the scope question- I am very skeptical about carbon offsets in the sense that they're providing people with an excuse to continue to emit.

On the role of offsets as an interim solution till decarbonization tech such as H2/ electric become mature

I agree that it shows action. However, this same amount of money can be put into the sustainable aviation field. Where the technology is ready. So, you're actually doing some within the sector and this kind of signalling that you're willing to purchase stuff and signalling that you're willing to engage to, to develop it. And it shows that there is technological solutions within the sector rather than offset. It goes outside of the sectors. All the money is kind of coming from within passengers. Revenues that companies are putting to reduce their carbon are going right out of the sector, whereas instead if you go into SAF, they're staying within the sector because its money is being used to invest in production facilities that will later allow you to buy stuff at a cheaper price because of scale increases. So, you are subsidizing your future in a way, if you keep it within the sector rather than throwing it out of the door to other initiatives that have nothing to do with aviation.

Regarding policies such as ReFuelEU and NZIA which provide targets

So, policy for SAF is critical and there are 2 ways to go about it. There is the United States method, which involves substantial financial support to incentivize production. In Europe, there has been use of mandates, for example from France where a 1% mandate has been implemented. I think mandates as a longer-term solution that creates a stable demand until 2050. Policy decisions involve a trade-off between sector interests and legislative ideals. There is a need of setting ambitious goals to encourage market adoption, even if they initially seem unattainable.

As a consultant, is there a visible difference in stakeholder expectations, such as airports, airlines, and government?

There isn't a fundamental difference, but the bottleneck is that of funding. So, who's paying for this innovation? Because there's not a short-term business model and both want to have a short-term business model and both have to realize that it's not there, but they both do realize that there is a long-term positive perspective on this both from an environmental liveability side that our earth is no longer liveable, if we are emitting too much both locally and globally and from a business perspective, you're leading on the new technology that the rest the world will use. If we're talking about hydrogen infrastructure for aircraft, this is a kind of technology and know-how that the rest of the world, once it goes to the same level of stability as we are in Europe, they will need this and then you realize that this is an asset. But for now, in the short term, it's about who's paying for it, and it's about communicating who is doing what because there are a lot of smaller stakeholders that need to be connected and don't have the chance to talk to each other. Now everyone is very much within their own building rather than getting out there and speaking to each other.

The contrast between the aviation growth trajectory and the sustainability measures.

So we're seeing that there are opportunities to be pushier on that and we're trying to take them, we do see that demand reduction is a part of aviation, whether that's natural because of increasing prices or whether that's unnatural because you have an active policy to push the price up like taxes that are on top of the ETS. But it cannot be a standpoint often with the clients because we have a lot of different customers in this sense and we also see that there's a difference in accessibility in Europe and in other parts of the world, right? We can say now the whole world has to grow, but coming from Europe, where we've grown for the past 100 years and have used all that, it's a bit of an ignorant thing to say.

Interview 5

The interviewee is a researcher in Air and Space Law specializing in European competition law in the aviation industry. This interview gave insights from a legal perspective on the EU carbon capture policies, EU ETS and CORSIA.

Offsetting for airlines

The EU taxonomy lists sustainable activities and the ongoing debate about including the aviation industry in it. The push to include aviation is driven by the desire to qualify it as a sustainable industry.

However, can airlines truly meet all the requirements, especially the "do no significant harm" principle and the avoidance of unsustainable investments? There is a challenge of transitional solutions, where airlines might be asked to purchase planes that are sustainable today but may not be in the future. This conflicts with airlines' desire to use aircraft for extended periods, making it difficult to comply with sustainability goals. Airports have the ability to electrify ground equipment, but airlines face difficulties in achieving sustainability goals due to certification problems and the risk of litigation. Regarding carbon offsetting, it creates the illusion that consumers are investing their money into something worthwhile, but in reality, it may not be effective in creating a sustainable forest or achieving the intended environmental goals. Airlines invest in offsetting because their economic activity involves flying consumers. However, if consumers feel deceived or tricked by false claims of offsetting, it can lead to legal consequences.

Regarding the technicalities of offsetting, it is crucial to prove the worthiness of the offsetting scheme. If an airline can demonstrate that the additional funds paid by consumers are invested in a worthy project that has a positive impact on the environment, it can mitigate the risk of legal challenges. In the case of KLM, they lost the case because they couldn't substantiate the effectiveness of their offsetting scheme. So offsetting should be backed up by evidence that the money is being invested in the correct and worthy projects. This way, consumers and consumer protection agencies can be assured that their money is being used as intended, and the environmental impact is being achieved.

Role of EU ETS and CORSIA

The interaction between CORSIA and ETS is still uncertain, and the specifics of how they will work together are not yet clear. The EU wants to ensure that the ETS is still applicable for intra-EU flights. However, the ETS and CORSIA are two different systems with different approaches. ETS is a cap-and-trade system where emissions are limited at the beginning of the year, while CORSIA allows for offsetting and doesn't impose limitations on emissions. In fact, CORSIA was introduced as a response to the US, Russia, and China opposing the EU's ETS. These countries "stopped the clock" on ETS implementation, leading the EU to seek a compromise. The compromise was CORSIA, which was initially intended to replace ETS eventually. I don't see how these two systems can work together because they have different objectives. However, they could work together if there were specific units for each system to avoid extra costs or exemptions when complying with one or the other. Personally, I feel CORSIA is more of a lip service than a substantial solution. One possible approach could be to apply CORSIA until a certain point and then transition to ETS when entering European airspace. This would require the development of a system to handle this transition effectively. Considering the increasing carbon prices, ETS can make it economically unviable for companies to emit, potentially leading to a reduction in emissions.

Funding for carbon removal activities in aviation

There is the potential for competition issues when certain companies or consortiums acquire carbon removal credits or SAF at a lower cost, giving them a competitive advantage over others. This could create an uneven playing field and impact market share. To address this concern, it is suggested that agreements and collaborations should not discriminate and should take all relevant stakeholders into account. Collaborations and consortia must be careful not to violate competition laws and should be transparent about their goals and terms of cooperation. One example is the Horizon Europe grants, where companies apply for funding together. When applying for such grants, there are specific rules for competition law compliance. These rules include not discussing pricing, avoiding specific company references, and focusing on general terms and goals rather than detailed specifics. If the investment by companies leads to a situation where they pay less to the government, it could potentially be considered illegal state aid. However, I am unsure about the specific regulations related to carbon offsetting and competition within the EU and the US. It could be useful to analyze the agreements and behaviours of companies to determine if they fall under cartel behaviour or illegal state aid.

Challenges of lengthy certification process

Another barrier is the lengthy certification process for new technologies in the aviation industry. Certification takes time, and the industry cannot transition to decarbonized technologies overnight. The process involves ensuring safety, performance, and regulatory compliance, which adds to the time required for implementation. On the other hand, SAF and carbon offsetting were mentioned as potential enablers for faster decarbonization. Ramping up the production and use of SAF can help reduce carbon emissions from aviation. Additionally, carbon offsetting measures can provide a transition towards achieving net-zero emissions by compensating for the emissions produced during flights. However, the industry needs to address the elephant in the room, which is the reduction in flights. While it may not be a popular solution, reducing the number of flights, especially on routes with excessive frequency, could contribute significantly to reducing emissions.

B

Reference List

B.1. References Overview

List of EU Policy Documents referred to is listed below:

Sl.	Name
1	Green Deal Industrial Plan
2	Communication on Sustainable Carbon Cycles
3	EU Taxonomy on sustainable activities
4	EU Renewable Energy Directive
5	Communication to incorporate global market based measure for aviation
6	Proposal for level playing field for sustainable air transport
7	Proposal for Net Zero Act
8	Proposal for Certification of Carbon Removals
9	Trans-European energy infrastructure
10	Directive on geological storage of carbon

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List of key reports referenced:

Sl.	Name
1	AR6 Synthesis Report: Climate Change 2023 — IPCC
2	Climate Change Mitigation Pathways for the Aviation Sector- MDPI
3	Mitigating greenhouse gas emissions in hard-to-abate sectors- PBL
4	State of Carbon Dioxide Removal Report
5	The direct air capture advantage- Kearney
6	Putting CO_2 to Use- IEA
7	A cost curve for greenhouse gas reduction- McKinsey
8	State of Direct Air Capture- IEA

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