Enabling Sustainable Aviation Fuel (SAF) in the EU:

Evaluating technological pathways with a focus on direct air capture (DAC) technology

Taeke Tamsma

Delft University of Technology

TU Delft

Enabling Sustainable Aviation Fuel (SAF) in the EU: Evaluating Technological Pathways with a Focus on Direct Air Capture (DAC) Technology

Master Thesis

By

Taeke Tamsma

Student number: 5655994

submitted to obtain the degree of **MASTER OF SCIENCE** in

Complex Systems Engineering and Management,

Faculty of Technology, Policy, and Management

at the Delft University of Technology,

to be defended on 13-12-2024

Graduation Committee

First Supervisor and Chair:	:	Dr.ir. Rudi Hakvoort	Energy and Industry
Second supervisor:	:	Dr. Jan Anne Annema	Transport and Logistics
External supervisor:	:	Ot Messemaker	Skytree

Cover image retrieved from www.gasworld.com

TU Delft

Abstract

Technologies such as power-to-liquid (PtL) and direct air capture (DAC) offer significant promise in producing carbon-neutral fuels for aviation, also known as sustainable aviation fuels (SAFs) (McQueen et al., 2021; Pio et al., 2023). Despite mandates set by the European Union to accelerate SAF adoption, the airline industry remains hesitant, citing high costs and technological complexities. This hesitancy perpetuates a “chicken-or-egg” problem where high costs limit adoption, and limited adoption prevents cost reductions (Erriu et al., 2024).

Addressing the chicken-and-egg problem and meeting EU mandates to enable sustainable air travel requires identifying the most viable sustainable aviation fuel (SAF) technology incorporating direct air capture (DAC) within the EU. To achieve this, the costs of state-of-the-art electrolysis technologies were analyzed alongside the latest DAC data provided by Skytree, a company specializing in direct air capture. This approach aims to bridge the gap between theoretical literature and practical industry values.

While viewing CO_2 as a valuable feedstock is not a new concept, this analysis is novel in combining this perspective with the varying carbon efficiencies of different SAF production technologies. These efficiencies directly impact the levelized cost of kerosene by requiring different volumes of 'valuable' CO_2 from direct air capture (DAC), offering a fresh approach to evaluating the economic viability of SAF pathways.

This study extends the existing literature, which provides substantial insight into cost and performance metrics, by adopting a socio-technical lens. This perspective explores what is needed beyond lower costs to enable the deployment of sustainable aviation fuel technologies within the current socio-technical system. Therefore, the research question guiding this study is: How can sustainable aviation fuel (SAF) be developed within the EU, specifically considering technologies that incorporate direct air capture (DAC)?

The socio-technical analysis began with a literature review to identify SAF technologies and their components, guiding an actor analysis using the Technological Innovation System (TIS) framework to link stakeholders with technological and regulatory roles. An institutional analysis followed, identified key policies, formal rules, and regulatory hurdles shaping the SAF innovation system, while subsequent network analyses examined system support structures. Together with the problem statement, these analyses guided the development of technical criteria to assess the feasibility of the outlined technologies as well as non-technical criteria addressing broader factors necessary for successful short-term deployment within the EU. Using techno-economic data from the literature review, along with up-to-date direct air capture data provided by the internship provider, Skytree, the best-assessed technologies from the socio-technical analysis were compared based on the levelized cost of fuel. The analysis transitions from an overall cost comparison to a detailed examination of specific cost components, using CAPEX degression curves to average future estimates from literature and comparing cost breakdowns in 2024, 2035, and 2050 to highlight structural shifts as technologies mature. A concluding sensitivity analysis varies key assumptions to identify critical cost drivers influencing the economic viability of SAF technologies.

This study selected fossil, biogenic, and direct air capture (DAC) carbon sources coupled with proton exchange membrane electrolysis (PEM), solid oxide electrolysis (SOE), reverse water-

gas shift (RWGS) reactor, and Fischer-Tropsch (FT) synthesis for further analysis. Socio-technical analyses emphasized collaboration among airlines, knowledge institutes, and supporting organizations, alongside strong connections with energy providers, feedstock suppliers, and infrastructure providers to address supply chain complexities. IATA (International Air Transport Association) was identified as a potential coordinator for collective investments to overcome high costs, low initial demand, and narrow profit margins, particularly in EU states with SAF regulations. Production sites near renewable energy sources and fueling infrastructure were recommended to reduce logistical costs and grid congestion, with regions like Iceland or Norway offering short-term potential despite higher costs. Locating facilities in areas without alternative carbon sources strengthened the case for DAC by reducing reliance on limited carbon infrastructure. Policy analysis highlighted the need to phase out or reevaluate free EU ETS allowances for fossil CO_2 to ensure fair competition and support DAC and biogenic CO_2 adoption.

Techno-economic analysis identified proton exchange membrane electrolysis (PEM) coupled with a reverse water-gas shift (RWGS) reactor, Fischer-Tropsch (FT) synthesis and biogenic (BIO) CO_2 as the most cost-effective current option due to its lower CAPEX compared to solid oxide electrolysis (SOE), though it remains 4 to 5 times more expensive than fossil kerosene. DAC-based pathways, while initially more costly, are projected to become competitive by 2028 with rising EU ETS carbon prices and to surpass fossil-based CO_2 in cost-effectiveness across all scenarios by 2036, highlighting the need to revise transitional fossil CO_2 timelines and phase out free allowances. High-concentration biogenic CO_2 can meet demand but is currently underutilized due to limited economic incentives for capture and insufficient carbon infrastructure. By 2050, all studied sustainable aviation fuel pathways are expected to cost between €1.80 and €2.00/liter, with proton exchange membrane electrolysis (PEM) technology emerging as the most economical and SAF prices ranging from 1 to 2 times the cost of fossil kerosene. Solid oxide electrolysis (SOE) technology demonstrates strong potential with improved efficiency, extended lifetimes, and the ability to co-electrolyze CO_2 and water to produce syngas, making it particularly promising for sustainable aviation fuel (SAF) production. High CAPEX and low operational hours, particularly for direct air capture, drive up costs, necessitating strategies such as electricity storage development and nuclear energy expansion to ensure affordable power and meet the EU's increasing electricity demand for aviation decarbonization. The OPEX-heavy nature of sustainable aviation fuel production underscores the urgency for cost-effective electricity, raising concerns about whether renewable energy could be better utilized in sectors with greater decarbonization potential.

Acknowledgements

This thesis marks the end of a fulfilling academic journey, beginning with my studies in Science, Business, and Innovation at the Vrije Universiteit Amsterdam and concluding with the Energy track within Complex Systems Engineering and Management at Delft University of Technology. It has been a period of deep learning, exploration, and growth, and I am pleased to share the outcome of my work.

I owe a great deal of gratitude to those who made this journey possible. First and foremost, I would like to thank my primary supervisor and chair, Rudi Hakvoort. Your guidance and expertise were essential throughout the research, and our conversations always left me with new insights and directions to pursue. I am also deeply appreciative of my second supervisor, Jan Anne Annema, whose clear and constructive feedback played a crucial role in shaping my work. Although my approach to this project may have been unconventional at times, I am incredibly grateful for the flexibility and openness of my supervisors. They were consistently available, even during summer breaks, on Friday afternoons, and at very short notice. These meetings were not only productive but also genuinely enjoyable, and their collective expertise greatly enriched the quality of my research.

My gratitude extends to Skytree, my internship provider, for giving me the opportunity to collaborate on this project. I would like to specifically acknowledge Ot Messemaker, my external supervisor, for his guidance and support, which were invaluable throughout my time at the company.

I would also like to thank Josephine Vos for her thoughtful feedback on my model, which significantly contributed to the clarity and accuracy of my analysis.

Finally, I want to express my deepest thanks to my family and close friends. Your constant encouragement, patience, and belief in my abilities have been my greatest sources of motivation. A special mention goes to my late grandfather, John Leo, who was a true inspiration during difficult times. I hope that I have made him proud with this achievement. I am profoundly grateful for the love and support from all of you, which helped me stay focused and determined during challenging times.

Thank you to everyone who contributed to this thesis and to my academic journey as a whole.

Taeke Tamsma

Delft, November 2024

List of Abbreviations

Abbreviation	**Definition**
AE	Alkaline Electrolysis
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
BECCS	Bioenergy with Carbon Capture and Storage
BIO	Biogenic CO_2
C	Degrees Celsius
CAPEX	Capital Expenditure
CDR	Carbon Dioxide Removal
CCU	Carbon Capture and Utilization
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	Concentrated Solar Power
DAC	Direct Air Capture
EASA	European Union Aviation Safety Agency
e-fuel	Electrofuel
eSAF	Synthetic Sustainable Aviation Fuel
ETS	Emissions Trading System
EU	European Union
FID	Final Investment Decision
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HEFA	Hydroprocessed Esters and Fatty Acids
H_2	Hydrogen
H_2O	Water
ICAO	International Civil Aviation Organization
IATA	International Air Transport Association
IPCC	Intergovernmental Panel on Climate Change
ISPT	Institute for Sustainable Process Technology
JRC	Joint Research Centre
kJ	Kilojoule
kWh	Kilowatt-Hour
kWhel	Kilowatt-Hour (Electrical Energy)
kWhth	Kilowatt-Hour (Thermal Energy)
LB	Lower Bound
LCA	Life Cycle Analysis

LCA	Levelized Cost Analysis
LCOE	Levelized Cost of Electricity
LCOF	Levelized Cost of Fuel
LHV	Lower Heating Value
m^3	Cubic Meter
MJ	Megajoule
MJSP	Minimum Jet Fuel Selling Price
MOx	Metal Oxide
Mt	Million Tons
MTJ	Methanol-to-Jet
MWh	Megawatt-Hour
NH_3	Ammonia
NPV	Net Present Value
OPEX	Operating Expenditure
PEM/PEMEL	Proton Exchange Membrane Electrolysis
PMT	Payment (Excel Function for Calculating Loan Payments)
Ppm	Parts per Million
PtL	Power-to-Liquid
PV	Photovoltaic
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuel of Non-Biological Origin
RSB	Roundtable on Sustainable Biomaterials
RWGS	Reverse Water-Gas Shift
SAF	Sustainable Aviation Fuels
SA	Sensitivity Analysis
SIP	Synthesized Isoparaffins
SOE	Solid Oxide Electrolysis
TRL	Technology Readiness Level
TSO	Transmission System Operator
UB	Upper Bound
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VC	Venture Capital
WACC	Weighted Average Cost of Capital
WWF	World Wildlife Fund
€	Euro (Currency)
Δh^o	Standard Enthalpy Change
∑	Summation (Mathematical Symbol)
%	Percentage

List of Figures

List of Tables

Table of Contents

1. Research Problem

1.1. Introduction

Given the record-high levels of CO_2 emissions in the atmosphere (Kumar et al., 2015), it is evident that deep emission reductions across all sectors are urgently required. Some sectors present greater challenges than others in this regard, often referred to as hard-to-abate sectors (Paltsev et al., 2021). These sectors, which include industries such as agriculture, heavy-duty transport, shipping, and aviation (Franco & Giovannini, 2023), are characterized by processes that heavily depend on fossil fuels or produce significant CO_2 emissions, making traditional decarbonization approaches difficult to implement (Neuwirth et al., 2022).

Carbon Dioxide Removal (CDR) can be useful in such cases and has therefor been identified as an essential method for reaching net zero goals by the Intergovernmental Panel on Climate Change (IPCC) (2022). CDR refers to a set of methods and technologies aimed at capturing and removing CO_2 from the atmosphere (Mannion et al., 2024). These can be nature or technology based and used to offset fossil emissions. Afforestation and Reforestation are nature-based removals (NBR) and involve planting trees and restoring forests, which absorb CO_2 through photosynthesis. Bioenergy with Carbon Capture and Storage (BECCS) involves growing biomass (plants or algae), using it to generate energy, and then capturing and storing the CO_2 produced during the energy generation process (Fajardy & Mac Dowell, 2017). Direct air capture (DAC) uses chemical processes to directly capture CO_2 from the ambient air, followed by sequestration (storing it underground or using it in various applications) (McQueen et al., 2021). Both are examples of technology-based removal (TBR). In the figure below, other CDR methods are shown.

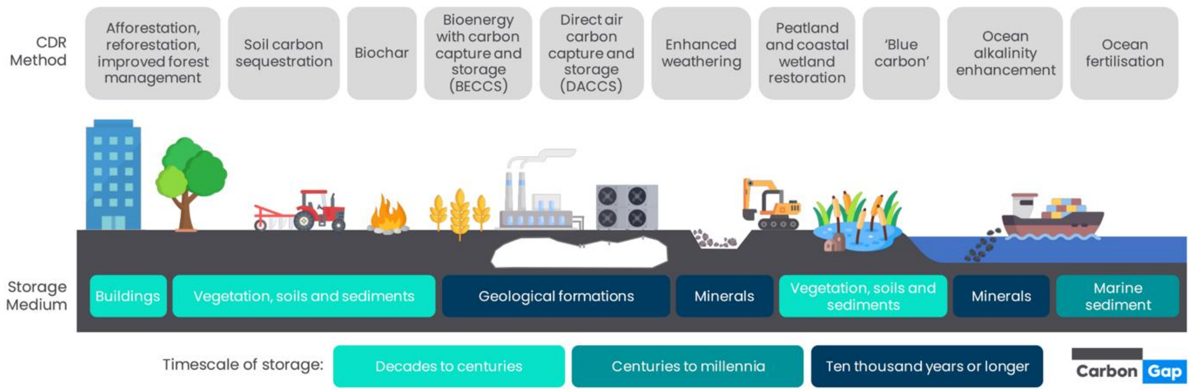


Figure 1.1: Overview of CDR methods (Carbon Gap, n.d.)

1.1.1. Sustainable Aviation Fuels

According to the International Energy Agency (IEA, 2023), aviation contributes 2% of global energy-related CO_2 emissions, showing faster growth than other transportation sectors. This demand is projected to rise further due to economic growth, particularly in low-income countries (Peacock et al., 2024). While enhancing energy efficiency and transitioning to non-emitting electricity sources can reduce emissions (Bergero et al., 2023), decarbonizing air travel poses unique challenges.

The prevalent aviation model favors large aircraft carrying heavy loads, relying on energy-dense liquid hydrocarbons (Peacock et al., 2024). Transitioning to electric or hydrogen-powered planes in the short to medium term faces challenges due to their lower energy density compared to liquid fuels (Hepperle, 2012). Hydrogen-powered planes require nearly four times the fuel volume of kerosene for the same power output. Thus, these technologies are primarily suitable for short-haul flights. However, redesigning aircraft, scaling up manufacturing, and integrating these new models into current markets present significant challenges. While these technologies may be crucial in the long term, the most immediate solution for widespread decarbonization lies in adopting Sustainable Aviation Fuels (SAFs) (Chiaramonti, 2019; Peacock et al., 2024).

Sustainable Aviation Fuels (SAFs) are jet fuels developed to minimize environmental impact and significantly reduce greenhouse gas emissions in the aviation sector. SAFs encompass a range of fuel types, including biofuels derived from organic feedstocks and synthetic fuels produced using renewable electricity. The latter category, often referred to as eSAFs or electrofuels, involves processes such as capturing CO_2 and generating hydrogen through water electrolysis, known as power-to-liquid (PtL) (Dray et al., 2022; Pio et al., 2023). These advancements highlight the potential of SAFs to contribute to aviation's sustainability goals.

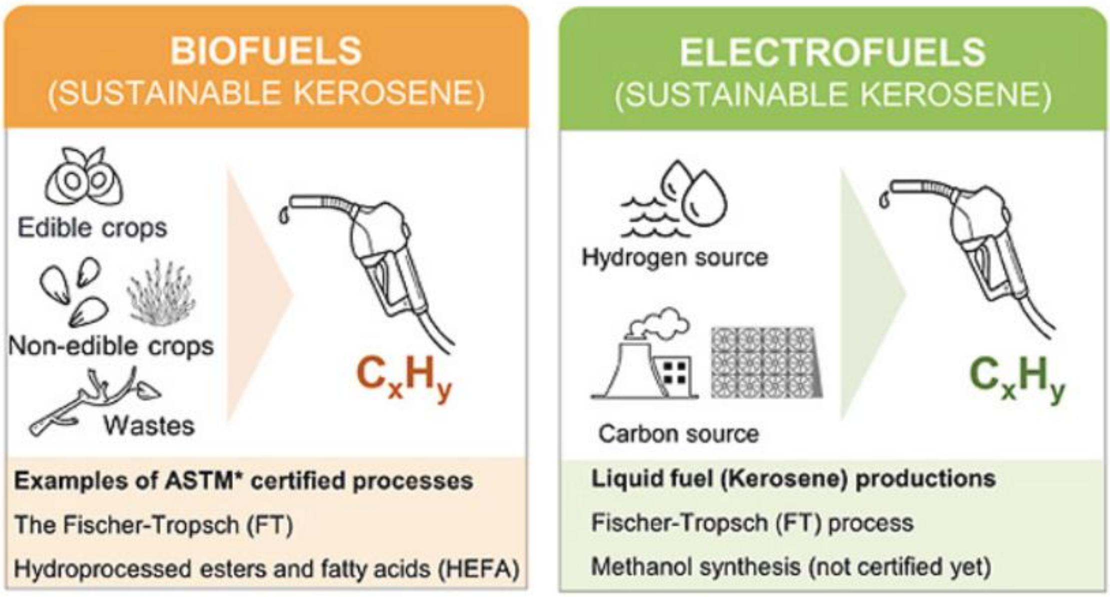


Figure 1.2 Sustainable Aviation Fuel Overview (Su-Ungkavatin et al., 2023)

1.1.2. Direct Air Capture

Direct air capture is a form of Carbon Dioxide Removal and closely related to SAFs. The primary objective of direct air capture technologies is to extract CO_2 from the atmosphere and concentrate it into a denser stream of CO_2. This is challenging mainly because there are very few CO_2 molecules in the air, approximately 417 parts per million (ppm) (National Oceanic and

Atmospheric Administration, 2023). For a meaningful impact on climate change, the captured carbon needs to be stored or recycled back into the atmosphere instead of fossil carbon (McQueen et al., 2021). Given the expansive nature of DAC's definition, there exists a diverse range of promising and evolving DAC techniques (National Academies of Sciences, Engineering, and Medicine, 2019). Despite this diversity, these technologies fundamentally adhere to the same principle illustrated in figure 1.3. Ambient air flows into the system (left side of the figure), where it is brought into contact with the sorbent. The sorbent is a chemical medium that can selectively adsorb CO_2. An interaction between the sorbent and CO_2 takes place. The CO_2 - depleted air is removed from the system, as can be seen at the top of figure 1.3. In a second stage, the CO_2 - sorbent mixture is separated again (regeneration). The sorbent is fed back so it can take up new CO_2. On the right side of the figure, the concentrated CO_2 is removed from the system, after which it can be processed depending on its application. This CO_2 serves as carbon feedstock for e-fuel production. Currently, the two most advanced methods in the field are solid sorbent and liquid solvent DAC (McQueen et al., 2021; Zeeshan et al., 2023).

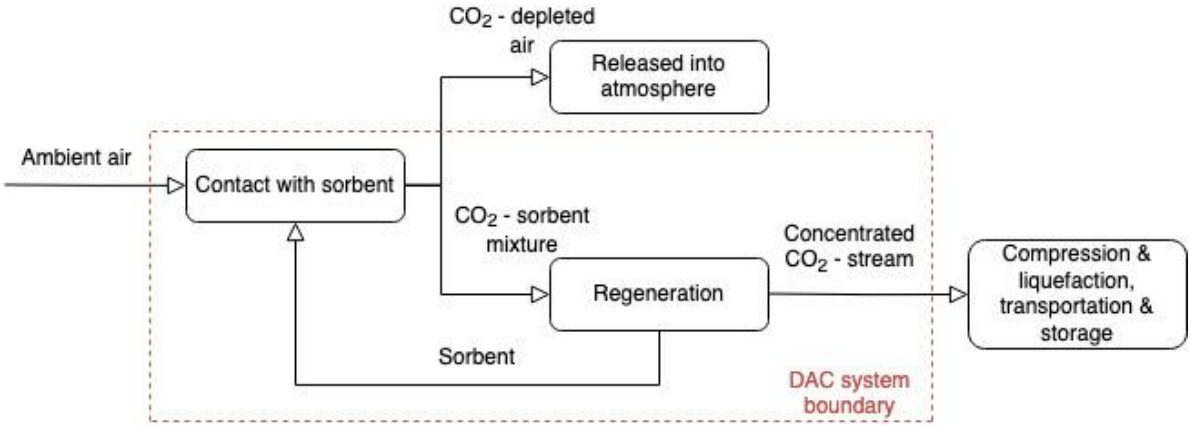


Figure 1.3 Basic DAC-principle flow diagram

1.2. Problem statement

The aviation sector is one of the most challenging to decarbonize due to its reliance on energy-dense fossil fuels and the high costs associated with alternative technologies. As global warming intensifies (Kumar et al., 2015), the urgency to decarbonize aviation has become critical. However, current low-carbon alternatives, such as hydrogen and batteries, face significant barriers, including non-existent fueling infrastructure and lower energy density compared to hydrocarbons (Hepperle, 2012). These challenges make hydrocarbons the preferred choice for long-haul flights, posing a significant obstacle to the sector's decarbonization (Peacock et al., 2024), but also presenting an opportunity for sustainable aviation fuels.

Technologies such as power-to-liquid and direct air capture have received significant attention for their potential to produce carbon-neutral fuels (McQueen et al., 2021; Pio et al., 2023). Recognizing the importance of SAF, the European Union has introduced regulations to help decarbonize the aviation sector through SAF adoption (Council of the EU, 2023). However, despite their promise, the adoption of these technologies has been slow due to high costs and technological complexities (Becattini et al., 2021; Martin et al., 2023). This situation creates a vicious cycle: the technology remains too expensive to adopt widely, and without widespread adoption, costs cannot decrease through economies of scale and practical experience. This complexity is often referred to as a “chicken-or-egg” problem (Erriu et al., 2024). This cycle further delays progress toward decarbonizing the aviation sector.

Immediate investment in projects is essential for achieving future cost reductions and facilitating the broader adoption of these technologies. Beyond the economic considerations, successfully implementing these projects necessitates a comprehensive understanding of the current socio-technical system, including regulatory, social, and market dynamics (Neuwirth et al., 2022). By thoroughly analyzing these broader factors, it is possible to identify the technology that aligns with the existing socio-technical landscape and can be effectively implemented in the near term.

While much of the current research provides detailed techno-economic analyses of sustainable aviation fuels, there is potential to further enhance these studies by also studying socio-technical considerations and emerging technologies like solid oxide electrolysis. Expanding the focus to include these factors will enrich our understanding of the interactions between various stakeholders, regulations, and technological choices, offering a more comprehensive perspective on near-term deployment.

This research will build on existing insights by not only comparing DAC within a socio-technical context but also exploring its role alongside competing technologies. By doing so, it seeks to identify the most promising SAF technology for near-term implementation in the EU as well as criteria to do so. The selected pathways will be assessed through a detailed techno-economic analysis, providing decision-makers with informed recommendations aligned with the EU’s decarbonization goals.

1.3. State of the Art

Scopus served as the literature database. The search strategy involved an iterative process of progressively combining more synonyms for DAC and SAF as search terms until no additional hits were generated. This resulted in 48 hits. The synonyms used are detailed in Appendix A table 6.1, with the final search query provided underneath the table. The results were further refined by limiting the document type to articles with open access. Finally, the relevance of the individual abstracts from these 23 articles was assessed. The reasons for exclusion can be found in Appendix B. The selected 10 articles are are presented in overview Appendix C. The search strategy is additionally depicted in figure 1.4 below.

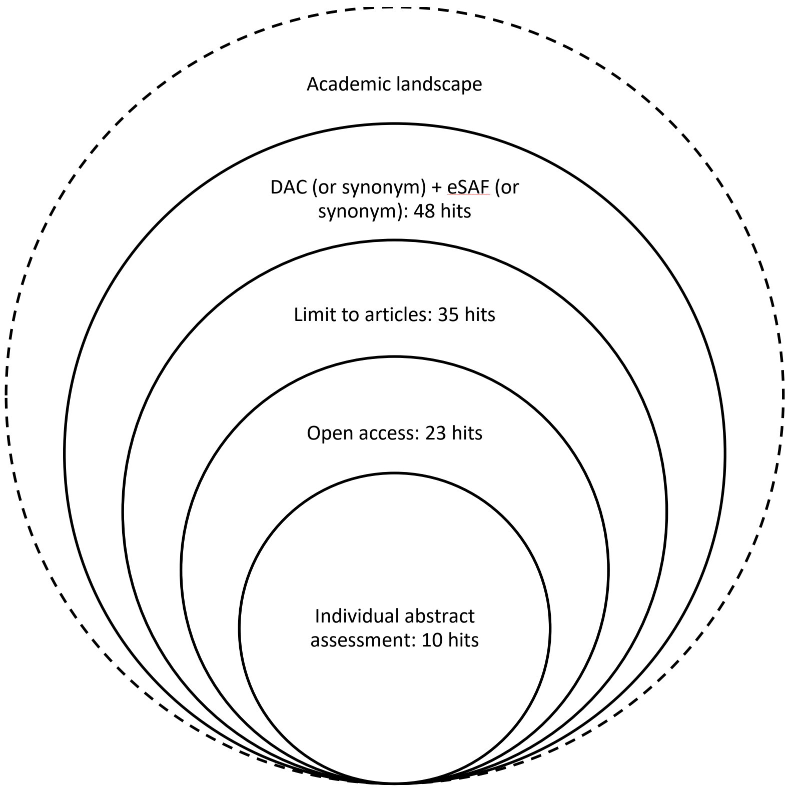


Figure 1.4: Nested circle graph of Scopus search strategy hits

The literature selected through this process was reviewed and organized based on common elements and themes.

Each article examined employed a model supported by scenario analysis. While one article discussed a pilot study, most focused on developing a model that necessitated specifying location, energy supply, fuel type, and fuel production method. Two distinct types of literature emerged: techno-economic analyses (TEA) and life cycle analyses. Seven articles fell into the techno-economic analysis category, with two articles specifically detailing a novel production pathway, one article combining two pathways and one article doing a techno-economic, as well as life cycle analysis. The remaining three sources pertained to life cycle analyses.

Techno-Economic Assessment

Becattini et al. (2021) explore strategies for achieving net-zero CO_2 emissions in aviation until 2050. They demonstrate that mitigating fossil fuel use by combining point source capture with carbon capture and storage (CCS) is the most cost-effective option and could become cost competitive with continued fossil fuel use plus carbon taxation in the future. This expectation aligns with the fact that carbon tax revenues are earmarked for carbon mitigation efforts. Similarly, Höglund et al. (2020) show that carbon capture and utilization (CCU) is more costly due to the hydrogen requirements involved. However, certain factors were overlooked in these analyses: the inadequate reflection of true environmental costs by current carbon prices (Bachmann, 2020), the finite nature of fossil fuels, and the growing competition for bio-based feedstock in point source capture (PSC) CCS as other sectors decarbonize (Peacock et al., 2024).

Martin et al. (2023) compared scenarios for global trucking, shipping, and aviation up to 2050, focusing on Norway due to its carbon-neutral freight transport and abundant renewable electricity. Like Becattini (2021), they emphasize the need for stable, renewable, and inexpensive electricity, a recurring theme in the literature. The challenge of comparing fuels mirrors that of comparing models due to varying assumptions. Martin (2023) addresses intermittency with hydrogen storage, though this doesn't resolve the continuous electricity needs of DAC.

Intermittency remains a key issue for SAF production, as final synthesis requires continuous operation. Typically, intermediates are stored instead of electricity, as batteries increase costs and reduce energy efficiency (Rojas-Michiga, 2023). Only Sherwin (2021) includes battery storage in his model, and this, combined with outdated DAC performance and diverse assumptions, contributes to higher fuel prices, as noted by Martin (2023).

D'Adamo et al. (2024) provide a more optimistic analysis of e-fuel prices, using Fischer-Tropsch (FT) and reverse water-gas shift (RWGS). However, their model overlooks costs for intermediate storage, component sizing, and DAC inefficiencies when not run continuously. Their model's simplicity and optimistic assumptions for PV, electrolyzer, DAC, and fuel synthesis costs and efficiencies lead to lower e-fuel costs compared to similar studies, reflecting rapid technological progress.

Alternative Production Methods

Becattini (2021) explores an alternative to the RWGS reaction by converting CO_2 to CO, but the process remains heavily reliant on electricity. In contrast, Prats-Salvado et al. (2022) and Moretti (2023) investigate a solar thermochemical approach, where concentrated solar energy drives reactions, eliminating the need for an electrolyzer. Components requiring electricity, such as DAC, are either powered by a power block driven by steam turbines that recover heat, or by the grid. Moretti, citing Prats-Salvado (2022), explores various configurations and concludes that low-temperature DAC, integrated with waste heat recovery, is the most cost-efficient approach for these systems. This finding aligns with Sherwin (2021) and Rojas-Michiga (2023), who also modeled low-temperature DAC as a cost-effective addition due to its compatibility with heat integration in various configurations.

Furthermore, the challenge of cross-comparing articles is exacerbated by the variation in input parameters and assumptions across different models. These differences in approach underscore the complexity of comparing findings across studies and emphasize the importance of understanding the specific assumptions and methodologies employed in each model.

Life Cycle Analysis

While it's logical to assume DAC should use renewable electricity to minimize emissions, life cycle assessments (LCA) of e-fuels produced with DAC reveal deeper insights. The electricity grid's emission factor emerges as the primary source of uncertainty, particularly in electricity-intensive methods like DAC-based approaches, which exhibit the widest uncertainty range (Ballal et al., 2023). LCAs offer a comprehensive view of DAC's environmental impact, facilitating comparisons with other carbon capture methods.

Liu et al. (2020) were the first to conduct an LCA on a DAC system paired with Fischer-Tropsch synthesis, using direct data from a pilot plant. Their baseline scenario, powered by a low-carbon grid and including either an electric or gas-powered calcinator, showed that the electric variant significantly increased electricity consumption. The study achieved an 84% reduction in CO_2 emissions—from 75 to 12 grams per MJ fuel—highlighting the influence of electricity carbon intensity and electrolysis energy.

Rojas-Michaga's (2023) LCA, reliant on offshore wind electricity, showed a 76% reduction in emissions (21.43 gCO_2/MJ SAF) compared to the baseline of 89 gCO_2/MJ SAF. Similar reductions of 75% and 89% were reported by Micheli et al. (2022) and Ballal (2023), emphasizing the importance of low-carbon inputs. Notably, low-temperature DAC stands out as both the most cost-effective and cleanest option (Micheli, 2022).

In contrast, Ballal (2023), who also explored different electrolysis methods including solid oxide electrolysis (SOE), found that DAC energy usage had a greater effect on overall emissions. SOE, due to its higher efficiency from operating at elevated temperatures, was particularly interesting with respect to heat integration.

1.4. Knowledge Gap

The existing literature offers extensive techno-economic analyses and life cycle assessments on sustainable aviation fuels, including technologies such as direct air capture and power-to-liquid technologies. Studies like those by Becattini et al. (2021), Sherwin (2021), and Martin et al. (2023) provide strong insights into the economic and environmental implications of these technologies. While this work is robust in its focus on cost and performance metrics, there is room for expansion by incorporating a socio-technical lens to better understand how these technologies could be deployed in the near future.

Further exploration of DAC's role could benefit from re-evaluating its potential not only as a carbon removal method but also as a valuable feedstock source, particularly when combined with emerging technologies like solid oxide electrolysis. Some models, such as those by D'Adamo et al. (2024) and Rojas-Michaga (2023), tend to view CO_2 primarily as a waste product, which may underestimate its full potential when utilized in fuel synthesis. Shifting this perspective to see DAC as a source of negative emissions could open new possibilities for more competitive and viable synthesis pathways when compared to traditional carbon capture or bio-based options.

In summary, while current research provides substantial contributions to the field, broadening the focus to include socio-technical factors and a redefined view of CO_2 as a feedstock could enhance the analysis. Doing so could reveal new, viable pathways for SAF production, contributing to a more comprehensive approach to decarbonization.

1.5. Research Questions

The body of literature on techno-economic analyses consistently emphasizes that high costs are the predominant issue, creating a "chicken and egg" problem: the technologies are too expensive to adopt widely, and without broader adoption, costs cannot decrease. Addressing this issue requires a better understanding of the broader socio-technical system that will influence the successful deployment of SAF technologies. Therefore, the research question (RQ) guiding this study is:

How can sustainable aviation fuel (SAF) be developed within the EU, specifically considering technologies that incorporate direct air capture (DAC)?

This requires exploring the range of possible technologies within the socio-technical system, determining which is the most viable for short term implementation in the EU, along with the requirements for their deployment, leading to SQ 1:

Which sustainable aviation fuel (SAF) technologies are promising for short-term viability in the EU, considering the current socio-technical system?

Once these technologies are identified, comparing them based on their costs is essential for determining which options are most promising. This comparison drives SQ 2:

How do the identified technologies perform in their overall costs?

Sub-question 3 identifies the key cost drivers influencing SAF production. The sensitivity analysis highlights how varying these components impacts overall feasibility.

What are the key cost drivers within the identified SAF technologies, and how do these components evolve over time?

Together, these sub-questions aim to offer a comprehensive understanding of the most promising SAF pathways by assessing both their interaction with the current socio-technical system and their overall cost-effectiveness. This analysis, by considering both technical and economic factors, will help identify viable options for scaling SAF production in alignment with the EU's decarbonization goals.

1.6. Link to CoSEM

This thesis strongly aligns with the core principles of the CoSEM program, emphasizing the management of complex socio-technical systems. The research integrates techno-economic analysis with a socio-technical lens, addressing the challenge of developing and adopting synthetic sustainable aviation fuels (SAF) within the EU's regulatory and market framework. Through a systems-thinking approach, it examines the interdependencies between SAF technologies, policy, and stakeholders—core aspects of the CoSEM curriculum. Additionally, the development of a model to evaluate these pathways reflects CoSEM's interdisciplinary focus and commitment to informed decision-making in multi-actor environments. Ultimately, this research aims to contribute to actionable strategies for decarbonizing the aviation sector, supporting the broader goals of the CoSEM program.

1.7. Structure of this Thesis

Chapter 1 establishes the foundation for this thesis by providing an overview of the core concepts, identifying the knowledge gaps, outlining the research questions, and defining the scope of the study. In Chapter 2, the methodology adopted to address the research questions is presented. Chapter 3 presents the outcomes of the socio-technical analysis, offering insights into the interactions between regulatory, market, and technological factors within the context of sustainable aviation fuels. Chapter 4 follows with a techno-economic analysis, providing a comprehensive evaluation of the economic viability of different SAF technologies. Chapter 5 discusses and reflects on the findings, offering a critical assessment of the methodologies used and proposing directions for future research. Finally, Chapter 6 concludes the thesis by revisiting the research questions, summarizing the key findings, and highlighting the study's contributions to both academic knowledge and practical applications.

2. Research Methodology

Chapter 2 provides a detailed overview of the research methodology. Section 2.1 presents the research approach. Section 2.2 delves into the data collection process. Section 2.3 explains the application of the Technological Innovation System (TIS) framework for socio-technical analysis, focusing on its specific relevance to the study. Section 2.4 discusses the techno-economic analysis, assessing the economic dimensions of e-fuel production. A flow diagram is included to visually represent the research process, showing how the methodologies align with the study's objectives. This structure ensures that the methodology is both comprehensive and aligned with the research goals.

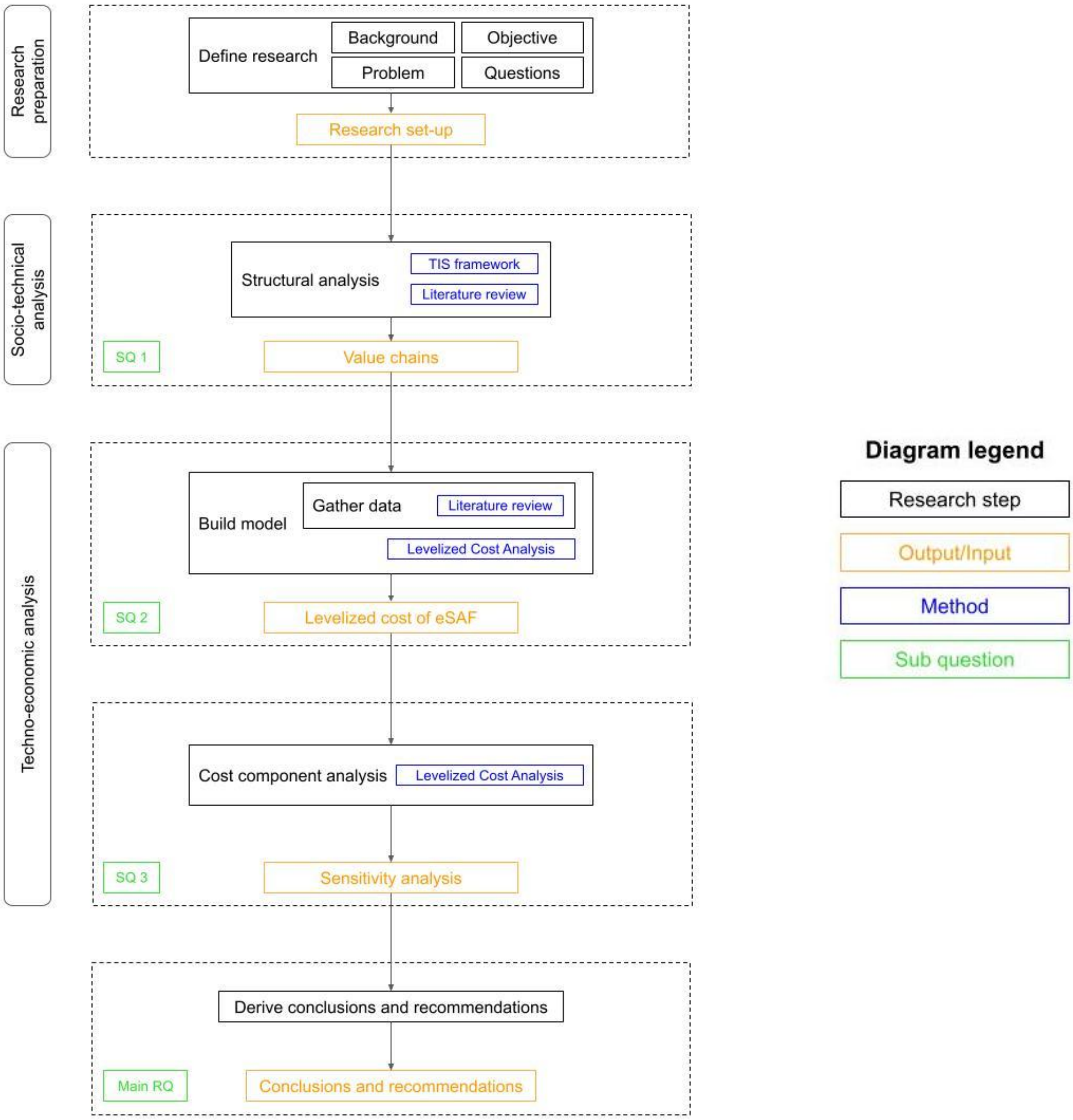


Figure 2.1: Research Flow Diagram

2.1. Research Approach

The research problem, centered on the high costs, resulting in the limited adoption of both SAF and DAC, requires a thorough approach. Addressing this complexity necessitates a deep understanding of both the economic viability of DAC, e-fuels and the broader socio-technical dynamics that influence its adoption. The research objective—identifying the most viable sustainable aviation fuel technology for DAC within the EU—led to the adoption of a mixed-methods approach.

This mixed-method approach integrates both qualitative and quantitative analyses. The qualitative component involves conducting a socio-technical analysis through a literature review, exploring the interactions between stakeholders, regulatory frameworks, and technological factors. This approach is essential for capturing the complexity of the current system (Creswell, 1994).

Meanwhile, the quantitative component focuses on assessing the economic feasibility of various SAF pathways through a techno-economic assessment using a modeling approach. Quantitative research allows for the testing of objective theories by examining relationships among variables. By subjecting proposed value chains to quantitative tests, this mixed-method approach captures the strengths of both analyses, generating actionable insights that are economically viable and socio-technically feasible, aligning with the EU's decarbonization goals (Creswell, 1994). Both elements are illustrated on the left-hand side of figure 2.1.

2.2. Data Collection

During the initial literature review, the primary focus was on identifying the existing literature gap. Simultaneously, this review facilitated the identification of key roles and processes within the SAF value chain, including but not limited to energy generation, hydrogen production, carbon supply, and fuel production. Building on this foundational work, a more detailed search was conducted to systematically explore the alternative technological pathways. The adjusted search query can be retrieved in Appendix D. Additionally, two webinars, organized by airlines, airports, CO2 suppliers, fuel producers, NGOs, and IATA, were attended to gather additional insights into the socio-technical system. Detailed notes were taken during the sessions, followed by discussions to identify key takeaways. The most important insights were summarized, providing valuable perspectives that complemented the literature review. These webinars offered deeper insights into the challenges the industry faces, potential technologies, and the roles of various stakeholders. The insights gathered laid the groundwork for a more comprehensive socio-technical analysis.

Literature studies enable the extraction and synthesis of information from diverse sources, fostering new insights and enhancing the credibility of research (Leech & Onwuegbuzie, 2010). This process also helps identify potential contradictions or inconsistencies within the field. A structured literature review offers significant advantages, including representation and legitimization. Peer-reviewed literature is particularly valuable for its credibility and academic rigor. Its standardized format also facilitates efficient searching, selection, and content analysis (Paez, 2017). While grey literature lacks peer review, it broadens the scope of the review by incorporating a wider range of sources. This inclusion is vital in rapidly evolving fields like SAF, where grey literature provides the most current context. However, challenges such as varying quality, time-consuming analysis, and the absence of standardized presentation formats are associated with grey literature (Paez, 2017).

The literature for this study was sourced primarily from Scopus, with articles selected based on relevance, recency, and peer-reviewed evaluations, ensuring a solid foundation for the research. The structured literature review adhered to the PRISM framework, as detailed in Appendix D (Page et al., 2021). Both grey literature and scientific sources were incorporated to achieve a comprehensive and current understanding. International agencies, including the International Energy Agency (IEA) and the International Air Transport Association (IATA), were regarded as credible as academic articles, significantly contributing to the techno-economic data foundation. Search queries were tailored to target key concepts and relevant information, with a focus on identifying different technologies. The literature review predominantly includes articles published after 2021 to ensure alignment with current developments. Older sources were selectively included through snowballing, with rigorous vetting to ensure their relevance to the research objectives.

The quantitative data gathered from the literature review formed the basis for the techno-economic analysis in this research. Key metrics such as cost estimates, efficiency rates, and production capacities were extracted from the reviewed articles. These figures were then used to develop models assessing the economic feasibility of various SAF technological pathways. Data related to direct air capture were provided by the internship provider, Skytree, ensuring up-to-date information from the industry. Price and capacity data were sourced from both previous and current product iterations, while future projections were co-developed with Purolite, Skytree's sorbent provider (Purolite, 2024). Purolite, an Ecolab company and global leader in sorbent development, helped set future sorbent generation upgrade performance levels until 2028. All data can be accessed in the supplementary model, with additional details available upon request. Data on co-electrolysis were sourced from Sunfire, one of the only commercially available co-electrolysis technologies, making it a critical reference for understanding the efficiency and cost dynamics of hydrogen production combined with CO_2 utilization (Choe et al., 2022; Sunfire GmbH, 2023). This data-driven approach ensured that the TEA was grounded in credible and up-to-date quantitative insights, providing a solid foundation for evaluating the cost-effectiveness of different SAF technologies.

2.3. Socio-Technical Analysis

A socio-technical analysis was conducted, guided by the Technological Innovation System framework developed by Hekkert et al. (2007), focusing on the first step of the structural analysis, as shown in the figure below (Hekkert et al., 2011).

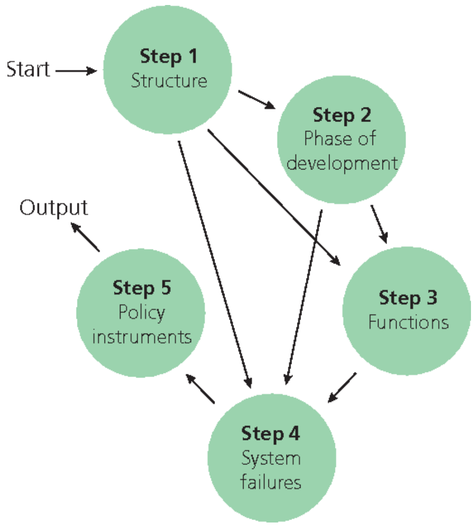


Figure 2.2: Schematic representation of the 5 steps in analyzing a technological innovation system for policy analysis (Hekkert et al., 2011)

This framework provided the conceptual structure for addressing the first sub-question: **Which sustainable aviation fuel (SAF) technologies are promising for short-term viability in the EU, considering the current socio-technical system?** As a framework, TIS is particularly well-suited for analyzing complex innovation systems, such as the emerging SAF sector within the EU, by highlighting the interactions between key components that drive innovation (Hekkert et al., 2007; Bergek et al., 2008). The primary components of the TIS framework—technologies, actors, institutions, and networks—guide the socio-technical analysis, ensuring that both technical and non-technical factors are thoroughly explored.

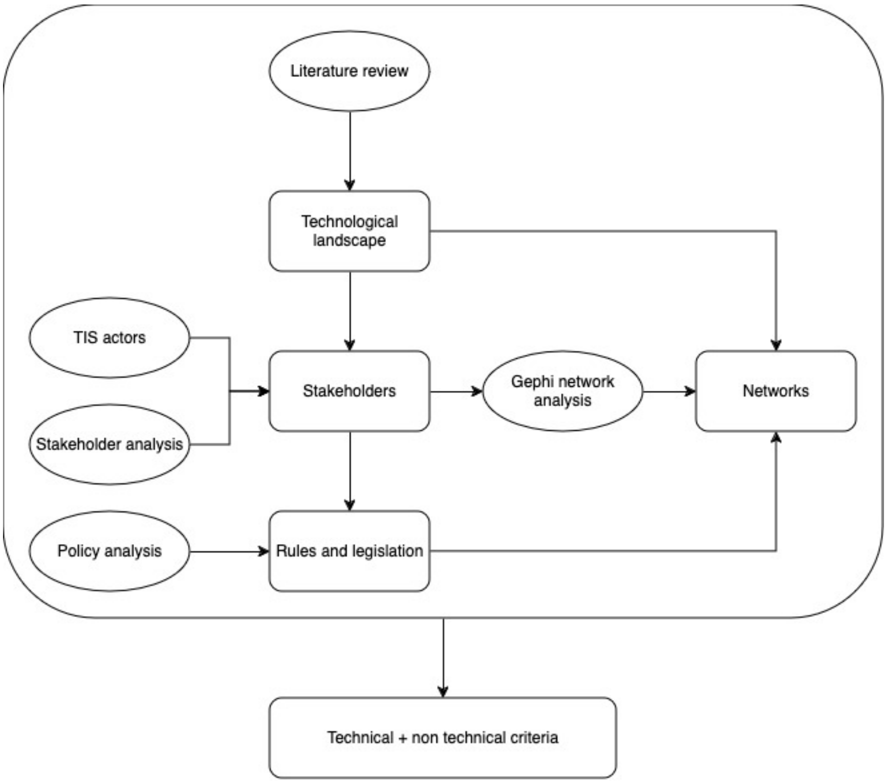


Figure 2.3: Socio-technical Analysis

Answering sub question 1 follows a multi-step approach, beginning with a literature review to identify the various technologies for SAF, as can be seen at the top of figure 2.3. This review allowed the breakdown of technologies into individual components (e.g., hydrogen production methods, fuel synthesis pathways), which are crucial for later analysis. These components were not immediately evaluated but were mapped to provide the basis for actor identification and criteria formulation.

The actor analysis was guided by the technological components identified in the literature review and the TIS actor framework shown in figure 2.4. Each technological component corresponds to specific actor roles (e.g., energy and energy supplier), ensuring that all relevant stakeholders are included. Defining these actors also allowed for the identification of regulatory bodies, which informed the subsequent institutional analysis. The actor analysis further contributed to understanding the system's structure and the needs of each actor, which are essential for setting technical and non-technical criteria.

The institutional analysis focused on identifying the formal rules, policies, and regulations that govern the SAF innovation system. Although it did not evaluate the technologies directly, it highlighted key policy frameworks and regulatory hurdles, contributing to the formulation of criteria related to policy alignment and regulatory feasibility.

Once the technical, social, and political aspects were mapped, the networks supporting the system were examined. Together with the problem statement, technology-, actor- and policy analysis, insights from this structural analysis informed the creation of a set of technical criteria to determine which technologies would be further investigated in the subsequent sub-question, as well as the non-technical criteria necessary for successful implementation.

Technical criteria were applied to the specific technological components identified during the literature review. While some of these criteria, such as policy alignment, may appear non-technical, they are included in the technical evaluation because they reflect how well a specific technological component adheres to the criteria. Each technology is then scored relative to its alternatives based on the technical criteria (with equal weighting for each criterion), and the most promising technologies for short-term implementation are identified. Meanwhile, non-technical criteria address broader socio-political factors needed for successful implementation.

The purpose of this approach is to gain an understanding of the different technological pathways available for sustainable aviation fuel production, as well as how these technologies interact with the broader socio-technical system within the EU. The approach allows us to define technical criteria to determine which technologies are suitable for further investigation in the subsequent techno-economic analysis. Additionally, non-technical criteria—applicable to all technologies—are established to capture broader requirements that are essential for the successful near-term implementation of SAF technologies within the EU. These criteria ensure that the analysis not only considers technical feasibility but also addresses the critical regulatory and market factors required for successful deployment.

2.3.1. Description of Components

In the structural analysis of the SAF Technological Innovation System, four key components are distinguished (Hekkert et al., 2011):

Actors

Organizations that drive the development, adoption, regulation, and financing of SAF technologies. These include knowledge institutes, industry players, market actors, and government bodies.

Institutions

The formal rules and informal norms that guide actor behavior within the SAF ecosystem. Formal institutions include EU policies, while informal ones encompass cultural norms. This analysis focuses on formal institutions due to their direct impact.

Networks

Networks consist of the relationships and interactions among actors, facilitating the exchange of knowledge, resources, and technologies. Understanding the geographical scope of these networks is essential; they may be localized within Europe or have a global reach, influencing the spread and adoption of SAF technologies.

Technologies

Technological structures encompass the physical artifacts, such as machinery and infrastructure, necessary for SAF production, as well as the technological systems in which they operate. The technological analysis emphasized the various approaches to synthetic sustainable aviation fuel production within the European context. It highlighted the most relevant production methods and underlying technologies.

Figure 2.4 gives an overview of the actors and institutions involved in the development and adoption of technology, though their interactions within networks were not represented in this figure.

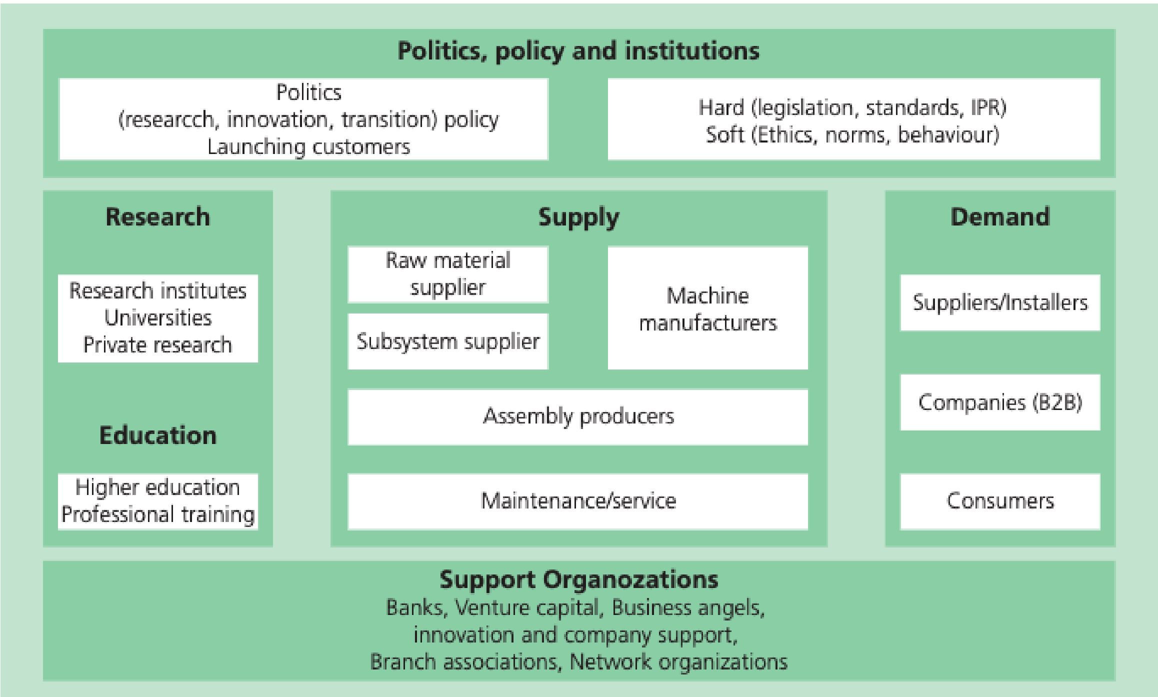


Figure 2.4: Actors within the Technology Innovation System (Hekkert et al., 2011)

2.4. Techno-Economic Analysis

To assess the competitiveness of the SAF technologies identified in the preceding socio-technical analysis against fossil jet fuel, a techno-economic analysis was conducted. This structured approach included developing a detailed spreadsheet model in Excel to calculate and compare the levelized costs of jet fuel using real-time industry and market data.

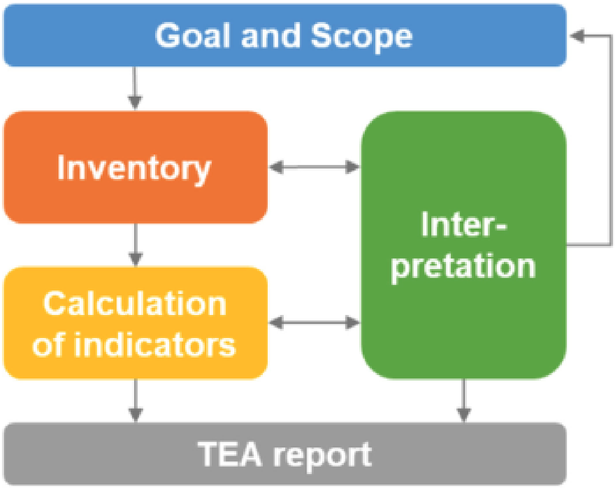


Figure 2.5: Phases of Techno-economic Assessment (Zimmerman et al., 2020)

The "Phases of Techno-Economic Assessment" outlined by Zimmerman et al. (2020) and illustrated in figure 2.5 provide a structured approach for evaluating the technical and economic performance of carbon capture and utilization technologies. These phases were directly applicable to this thesis on sustainable aviation fuels.

For sub-question 2, **How do the identified technologies perform in their overall costs?**, the levelized cost analysis assessed the overall techno-economic feasibility of each SAF technology. The levelized cost of fuel (LCOF) was determined by summing the levelized costs of each component required for SAF production, multiplied by the quantity needed per liter of SAF, facilitating a direct cost comparison across technologies.

For sub-question 3, **What are the key cost drivers within the identified SAF technology, and how do these components evolve over time?**, the analysis transitions from an overall cost comparison to an in-depth examination of specific cost components impacting techno-economic performance. Cost breakdowns of the researched technologies are compared at three time points—2024, 2035, and 2050—requiring estimates of cost evolution over time. Additionally, costs are normalized per technology to visualize shifts in cost structure, highlighting which components are expected to decrease as technologies mature and efficiencies improve.

A concluding sensitivity analysis varies key assumptions and economic parameters to gauge their influence on total costs, identifying the cost drivers most critical to the economic viability of SAF technologies.

2.4.1. Goal and Scope Definition

This phase involved establishing the objectives, system boundaries, and key questions for the TEA study. The problem statement highlighted the urgency of making short-term investment decisions in SAF adoption, which defined the overall goal of the study. This urgency required a clear, quantifiable method for assessing the economic viability of these technologies, leading to the selection of a levelized cost analysis (LCA). The socio-technical analysis conducted for Sub-question 1 helped define the scope, providing the necessary context and boundaries for the TEA. The LCA was chosen for its systematic approach to comparing the costs of various SAF production methods over their lifecycles, supporting the goal of making informed, data-driven investment decisions.

2.4.2. Inventory

This phase focused on gathering technical and economic data, including inputs, energy requirements, and costs. As decribed in section 2.2, Data Collection, the data was sourced from the two literature reviews conducted earlier in this study, supplemented with market data, DAC data provided by the internship partner Skytree, and additional targeted (grey) literature searches when necessary to fill any gaps.

2.4.3. Calculation of Indicators

The calculation of key indicators represents a crucial step in the techno-economic analysis, with the primary goal of determining the levelized cost of fuel for various SAF production methods. This process utilized Excel, supplemented by the Excel Solver add-on, to systematically process the collected data and perform detailed cost assessments.

Levelized cost analysis (LCA) originated from the concept of the levelized cost of electricity (LCOE) (Short et al., 1995) and has since become a widely accepted method for evaluating cost efficiency in energy production processes (Choe et al., 2022; D'Adamo, 2024; Eyberg et al., 2024). Initially used for comparing electricity generation technologies, LCA has been adapted to assess the levelized cost of various energy carriers including hydrogen (Nguyen et al., 2019), methane (Salomone et al., 2019), methanol (Andika et al., 2018), and jet fuel. In SAF production, the levelized cost of fuel, also known as the minimum jet fuel selling price (MJSP), is used to determine the price at which the net present value (NPV) of the project is zero (Rojas-Michaga et al., 2023; Sherwin, 2021; Zang et al., 2021).

LCA calculates the net discounted cost of production relative to the net discounted quantity of fuel produced over the plant's lifetime. This metric provides a clear measure of cost efficiency by incorporating all expenditures throughout the project's lifespan. Given the range of production methods for e-fuels, LCOF is a critical financial metric for assessing economic viability. It enables a comparative analysis of different technological pathways, giving policymakers and investors a reliable foundation for making informed decisions (Branker et al., 2011).

CAPEX Calculation

The first step of the levelized cost analysis involves projecting future capital expenditures because it provides the foundation for estimating long-term costs of production. Accurate CAPEX projections are crucial for modeling how costs evolve over time, directly influencing the overall cost-effectiveness of emerging technologies like SAF (Jamasb & Kohler, 2007; McDonald & Schrattenholzer, 2001).

Rather than relying on a single learning or improvement rate, this thesis employs the shape parameter k, as introduced by Seymour et al. (2024). For each component, the shape parameter k in the empirically defined CAPEX degression curve C(t) is calculated using Excel Solver, ensuring that the projected cost for 2050 aligns with the average of all literature values for that year. While most literature tends to model future CAPEX using a specific learning or improvement rate, the advantage of using the shape parameter k is that it captures and averages the learning and improvement rates from various studies, offering a more comprehensive and balanced projection of cost reductions over time (Dimartino, 2023). This ensures that future costs reflect a wide range of projections from existing research. The formula is constructed as follows:

$$C(t) = \frac{1}{2}(C_0 * (1+t)^{-10k} + C_0 * e^{-kt})$$

Where:

- $C(t)$:
  - This represents the cost of the component at a specific time t.
- C_0:
  - This is the initial cost of the component. It serves as the baseline cost against which future costs are compared. In this study, this was the average CAPEX of the values found in literature.
- $\frac{1}{2}$:
  - The factor of 1/2 in front of the entire expression is used to average the two different cost projections contained within the parentheses. It suggests that both terms contribute equally to the overall cost projection, balancing polynomial decay and exponential decay contributions.
- $(1+t)^{-10k}$:
  - This term represents a polynomial decay function. This reflects the early-stage learning curve, where substantial cost reductions occur quickly.
  - The expression (1+t) indicates that as time t increases, this value grows.
  - Raising (1+t) to the power of −10k causes the overall term to decrease as time passes because the negative exponent leads to an inverse relationship with time.
  - The factor −10k is critical here. The constant 10 is a scaling factor, and k is the shape parameter, comparable with a learning or improvement rate. This parameter determines how quickly costs decrease with time, effectively controlling the rate of decay in the polynomial term.
- e^{-kt}:
  - This is an exponential decay function. This reflects the later stage of technology maturation where cost reductions slow down but continue over a longer period.
  - It represents the exponential decline in costs over time. The parameter k controls the rate of this decay.
  - As time t increases, e^{-kt} decreases, causing this term to shrink and thus reduce the overall cost of $C(t)$.

Calculation of Annualized CAPEX

For each component involved in the production of SAF, the annualized capital expenditure (CAPEX) was calculated using the PMT function in Excel. The formula used is as follows:

$$Annualized\ CAPEX = -PMT(r, N, CAPEX)$$

Where:

- r = discount rate, which was taken as the WACC (Weighted Average Cost of Capital)
- N = depreciation period in years, which was set to the asset's lifetime
- CAPEX = initial capital cost.

The PMT function calculates the annual payment needed to cover both the principal and the interest over the component's lifetime. The formula behind the PMT function is:

$$PMT = \frac{P * r * (1 + r)^n}{(1 + r)^n - 1}$$

Where:

- P = present value or initial investment (CAPEX).
- R = interest (discount rate).
- n = number of periods (system lifetime).

Calculation of Annualized OPEX

The operating expenditure (OPEX) was annualized separately. The fixed OPEX was calculated based on a percentage of the CAPEX, while the variable OPEX is mostly energy dependent.

$$Annualized\ OPEX = Fixed\ OPEX + Variable\ OPEX$$

Where:

- Fixed OPEX is expressed as a percentage of CAPEX.
- Variable OPEX depends on the energy consumption per unit and energy cost.

Calculation of variable OPEX: Electrolyzer

The variable OPEX determines how much electricity is used and depends on the technology (efficiency), fuel type (LHV) and the electricity price:

$$Variable\ OPEX = \frac{1}{Efficiency} * LHV * Electricity\ Price$$

Where:

- Efficiency = electrolyzer efficiency (%)
- LHV (Lower Heating Value) = representing the energy content of a fuel per unit mass or volume, either in kWh/kg or kWh/m^3.
- Electricity price = a given constant representing the levelized cost of renewable electricity in €/kWh

Calculation of variable OPEX: DAC

DAC systems use both electricity and thermal energy to capture CO_2 from the atmosphere. The Variable OPEX for DAC is the sum of the costs associated with the electrical energy and the thermal energy required for the process.

$$Variable\ OPEX = Electrical\ Energy\ Requirement * Electricity\ Price + Thermal\ Energy\ Requirment * Thermal\ Energy\ Price$$

The electrical and thermal requirements are driven by three key energy-consuming processes. CO_2 separation, sorbent regeneration, and air suction represent the fundamental steps in capturing and isolating CO_2 from the atmosphere. Each process was calculated using thermodynamic and fluid dynamics principles.

CO2 Separation

This step involves isolating CO_2 from a dilute air stream and calculating the minimum work required to separate CO2 from air. This can be described by the Gibbs free energy equation:

$$W = R * T * \ln\left(\frac{1}{X_{CO_2}}\right)$$

Where:

- R = gas constant
- T = temperature
- X_{CO2} = molar fraction of CO2 in air

Sorbent Regeneration

After capturing CO_2, sorbents must be regenerated to allow further capture cycles. This process calculated the energy needed to regenerate the sorbent using the enthalpy of desorption:

$$Q = mol\ CO_2 * desorption\ enthalpy$$

Where:

- Mol CO2 = number of moles per kg CO_2
- Desorption enthalpy = energy needed to release CO_2 from sorbent material

The desorption enthalpy is a material specific property because it reflects the energy required to break the bonds between the sorbent and the CO_2molecules. The sorbent used by Skytree has a desorption enthalpy of 85 kJ/mol, which is in line with the average of 80 kJ/mol for amine-modified materials (Shi et al., 2022).

Air Suction

To capture CO_2, a large volume of air needs to be processed due to the low concentration of CO_2. This formula quantifies the energy needed to operate the fans or compressors that move the required air volume, making air handling a critical energy-intensive step in DAC. The energy cost is dominated by the pressure drop across the system and the flow rate needed to push air through the system, calculated using fluid dynamics principles:

$$P = \frac{pressure\ drop * flow\ rate}{fan\ efficiency}$$

Where:

- Pressure drop = pressure difference required to force air through the system
- Flow rate = volume of air required to capture 1 kg of CO_2
- Fan efficiency = efficiency of fan moving the air

Each of these processes was modeled using thermodynamic and fluid dynamics principles, ensuring accurate calculations of energy consumption, which is expected to decrease over time.

Calculation of Annual Throughput

The annual throughput, or the total output of a given component, was calculated based on operational hours or days per year and, in some cases, efficiency. The formula for annual throughput is:

$$Annual\ Throughput = Operation\ Capacity * Operational\ hours\ per\ day * Operational\ days\ per\ year * Efficiency$$

where:

- Operational Capacity = maximum output capacity of the production facility (e.g., kg of hydrogen per hour).

This step is crucial as it determines the denominator in the calculation of the levelized cost per unit.

Calculation of Levelized Cost of Each Component

The Levelized Cost of each component was then calculated by summing the annualized CAPEX and OPEX and dividing by the annual output or throughput of that component:

$$Levelized\ Cost\ of\ Component = \frac{Annualized\ CAPEX + Annualized\ OPEX}{Annual\ Output\ (e.g., kg\ H_2)}$$

Calculation of Levelized Cost of SAF

To obtain the Levelized Cost of SAF, the levelized costs of all components were combined. Specifically, for each liter of SAF produced, the levelized cost of each required component was multiplied by the amount of that component needed to produce one liter of SAF.

$$LCOF\ (SAF) = \sum_{i=1}^{n} (Levelized\ Cost\ of\ Component_i * Quantity\ of\ Component_i\ /liter\ SAF)$$

Where:

- n = number of different components required for SAF production.

3. Results: Socio-Technical Analysis

The results section of the socio-technical analysis addresses the first sub-question: **Which sustainable aviation fuel (SAF) technologies are promising for short-term viability in the EU, considering the current socio-technical system?** This analysis is grounded in the Technological Innovation System framework, which was used to systematically explore technological pathways, key actors, institutions, and networks influencing SAF development within the European Union. Through a literature review, technologies were mapped to assess approaches to energy, hydrogen, and fuel production, as well as to identify the main stakeholders in each value chain step. Different analyses were executed to develop technical criteria to subject the technologies to, as well as non-technical criteria essential for technologies to succeed in a broader socio technical context.

The chapter is structured as follows. Section 3.1 introduces the technological trajectories, outlining the key processes in the different SAF pathways. Section 3.2 examines the roles of key actors, including technology providers, feedstock suppliers, and infrastructure developers within the value chain. Section 3.3 focuses on the institutions involved. Section 3.4 concludes the structural analysis, evaluating the network relationships among renewable energy availability, carbon capture, fuel infrastructure, and policy environments. Section 3.5 explains the development of evaluation criteria and applies them to assess various SAF technologies, identifying the most suitable options for further analysis. Section 3.6 consolidates these findings with non-technical considerations, providing a comprehensive basis for the techno-economic analysis in Chapter 4.

3.1. Technological trajectories

Figure 3.1 provides a high-level representation of any fuel production process. It illustrates the fundamental stages common to all SAF pathways, including the conversion of renewable energy into hydrogen, the potential use of hydrogen carriers, and the final synthesis of fuel. While this model captures the essential components, specific production methods may involve additional steps or variations depending on the technologies and processes employed.

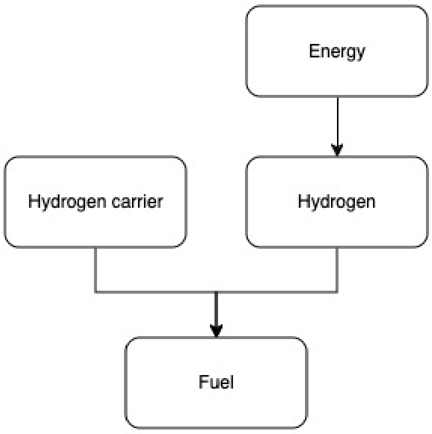


Figure 3.1: high level flow chart for SAF production

Diagram 3.2 is derived from the literature review and illustrates the complex interplay between energy sources, hydrogen carriers, hydrogen production technologies, and fuel conversion processes involved in the production of e-fuels. Biofuels are also considered in this analysis due to their close connection with e-fuels, particularly when biogenic CO_2 is used as an alternative to DAC CO_2. This analysis will focus on differentiating these elements and clarifying their roles in the overall system. Heat integration and electricity requirements other than electrolysis are not shown.

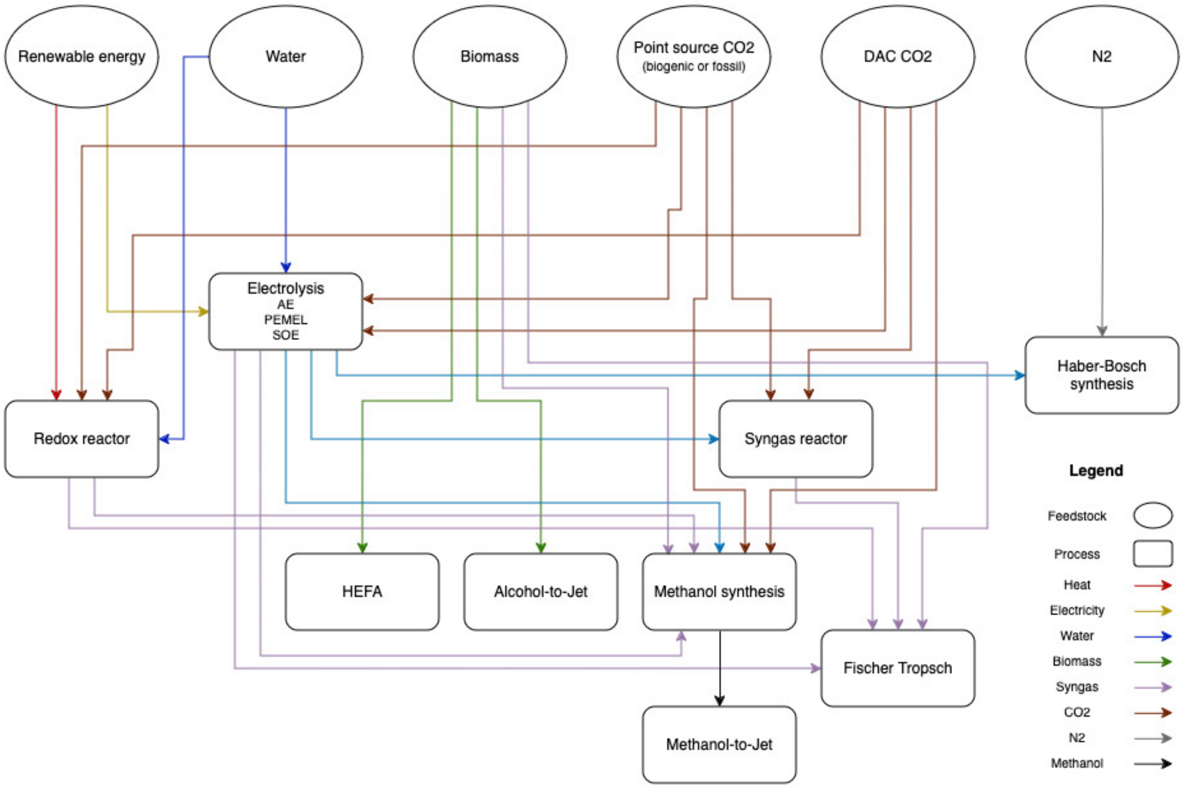


Figure 3.2: integrated pathways for e-fuels and biofuels production

3.1.1. Energy

Renewable energy is depicted in the upper left of the diagram as a vital component for all production pathways, primarily for generating electricity and, in some cases, producing heat through concentrated solar power. This heat drives redox reactions, reducing H_2O and CO_2 without the need for an electrolyzer (Moretti et al., 2023; Prats-Salvado et al., 2022). Electricity is commonly sourced from photovoltaic (PV) systems, wind, or a combination, with the latter providing the most stable supply (Ordóñez et al., 2022; Seymour et al., 2023; Sherwin, 2021). Nuclear energy, as applied by Peacock et al. (2024), ensures a stable electricity supply, eliminating the need for balancing measures. Additionally, electricity can be sourced from the grid, with GHG emissions reductions contingent on the renewable share in the grid mix (Liu et al., 2021; Rojas-Michaga, 2023). For this approach to be sustainable, the electricity grid must predominantly consist of renewables, which is why case studies often focus on countries like Sweden, Finland, and Norway, where renewables dominate the energy mix (Ballal et al., 2023; Martin et al., 2023).

3.1.2. Electrolysis

The hydrogen necessary for various synthesis processes is produced through three main electrolysis technologies, each offering distinct advantages and challenges in terms of technology, costs and performance.

Alkaline Electrolysis

Alkaline Electrolysis (AE) is the most mature technology with technology readiness level (TRL) 8-9 and has relatively low upfront investment costs, making it widely adopted in industrial applications (Rojas-Michaga et al., 2023). However, its lower efficiency, particularly at partial loads, combined with its slower start-ups, extended cool-downs and slower ramping rates, limits its suitability for integration with intermittent renewable energy sources (ballal et al., 2023; Habermeyer et al., 2023).

Proton Exchange Membrane Electrolysis

Proton Exchange Membrane Electrolysis (PEMEL), with a TRL of 6-8, is particularly valued for its flexibility and responsiveness to intermittent renewable energy, making it well-suited for integration with sources like wind and solar (Ballal et al., 2023; Habermeyer et al., 2023; Seymour et al., 2023). Having recently become commercially available (Ordóñez et al., 2022), PEMEL systems are frequently modeled due to their ability to match the full load hours of the electricity source. Although PEMEL offers higher efficiency than Alkaline Electrolysis, it comes with higher CAPEX and relies on expensive materials, which are significant drawbacks (Grahn et al., 2022; Martin et al., 2023; Seymour et al., 2023; Sherwin, 2021).

Solid Oxide Electrolysis

Established electrolysis technologies like AE and PEMEL are only capable of converting H_2O into H_2. The direct conversion of H_2 and CO_2 into hydrocarbons is limited to simpler reactions such as methanation and methanol synthesis. For producing more complex and valuable products, syngas is required, necessitating an additional reverse water-gas shift reaction step. Syngas, short for synthesis gas, is a mixture of carbon monoxide and hydrogen. The composition of syngas is governed by equilibrium reactions such as the water-gas shift reaction:

$$CO + H_2 \rightleftarrows CO_2 + H_2$$

A more efficient alternative is the use of solid oxide electrolysis (SOE), which enable the direct production of syngas from CO_2 and H_2O through co-electrolysis (Choe et al., 2022; Herz et al., 2018). This process is particularly effective because the enthalpy changes for both reactions are similar, as illustrated by the associated reactions below:

$$H_2O \rightleftarrows H_2 + \frac{1}{2}O_2, \Delta h^0 = +285,8\ kJ/mol$$

$$CO_2 \rightleftarrows CO + \frac{1}{2}O_2, \Delta h^0 = +283,2\ kJ/mol$$

Operating at elevated temperatures (700°C to 1000°C), SOE reduces the required electrical energy as more of the energy demand is met by thermal energy, which is cheaper and more readily available. The simultaneous operation of both reactions within the same high-temperature environment optimizes energy usage, enhancing the overall efficiency of syngas production (Ballal et al., 2023; Choe et al., 2022).

SOEs also present several significant challenges that limit their practical application. The high operating temperatures required for SOEs complicate start-up and shutdown procedures, making it difficult to integrate these systems with variable renewable energy sources. Continuous external heat is necessary to maintain efficient operation, as the system loses viability without it. Additionally, SOE is less proven (TRL 5-7), with higher initial costs and fast stack degradation. The limited data on long-term performance, future costs, and efficiencies further complicates their scalability and economic feasibility (Choe et al., 2022; van ‘t Noordende et al., 2023).

3.1.3. Hydrogen Carriers

Carbon and nitrogen can be used as hydrogen carriers due to their ability to form stable bonds with hydrogen, creating energy-dense compounds like hydrocarbons (e.g., methane, propane) and ammonia (NH_3). These compounds store energy in their chemical bonds, which can be released during combustion or other chemical reactions, making them valuable fuels.

Carbon for fuel production can be sourced from several origins. Biomass, with its carbon-hydrogen (C-H) bonds formed through photosynthesis, is an efficient source for biofuel production. The efficiency of biomass lies in the fact that it already contains energy in the form of these C-H bonds, eliminating the need for additional hydrogen (Habermeyer et al., 2023; Habermeyer et al., 2024).

Alternatively, carbon can be sourced from CO_2, which may originate from fossil-based or biogenic point sources, or directly from the atmosphere through direct air capture. In these cases, CO_2 is combined with hydrogen, produced using renewable electricity, to create synthetic fuels or e-fuels. DAC has received significant attention due to its potential to produce carbon-neutral fuels, though its adoption remains slow due to high costs and technological complexity (McQueen et al., 2021; Pio et al., 2023; Becattini et al., 2021). This creates a "chicken-or-egg" problem: DAC technology is too expensive for widespread use, yet without wider adoption, costs cannot decrease through economies of scale (Erriu et al., 2024). This delay further complicates efforts to decarbonize sectors like aviation, where synthetic fuels are urgently needed.

Lastly, hydrogen can be reacted with nitrogen (N_2) in the Haber-Bosch process to produce ammonia (NH_3), which serves as a hydrogen carrier and can be utilized as a fuel or as a chemical feedstock. The nitrogen required for this process is directly sourced from the atmosphere, as indicated in the diagram (Grahn et al., 2022; Martin et al., 2023).

Biomass vs Biogenic CO2

Biogenic CO_2 refers to carbon dioxide released from biological sources, such as the combustion or decomposition of biomass. Once captured, this CO_2 can be utilized in e-fuel production by combining it with renewable hydrogen. In contrast, biofuels are produced directly from biomass, sourcing both carbon and hydrogen from the biomass itself. The quality of the biomass dictates its processing method; lower-quality biomass may only be suitable for gasification, yielding CO and H_2, which are processed similarly to captured CO_2 and hydrogen (Grahn et al., 2022). Although gasification breaks C-H bonds, the C-H bonds and molecules in the final product still originate from the biomass, classifying the end product as a biofuel (Habermeyer et al., 2024). However, the challenges of biofuel production, including its environmental impact and the need for sustainable alternatives, remain critical concerns for long-term fuel production strategies (Fiorini et al., 2023; European Parliament, 2022).

3.1.4. Fuel Conversion Technologies

Redox Reactor with Concentrated Solar Power

The redox reactor on the far left of diagram 3.2 is a promising technology, as it does not require an electrolyzer and electricity for hydrogen production. The production of solar fuels uses heat generated through concentrated solar power to run a redox reactor. This involves a two-step thermochemical cycle using a metal oxide. In the first step, the metal oxide (MO_x) is heated at high temperatures, causing it to reduce by releasing oxygen, forming a reduced oxide ($MO_{x-\delta}$). The general reaction is:

$$MO_x \rightarrow MO_{x-\delta} + \frac{\delta}{2} O_2$$

In the second step, the reduced metal oxide is re-oxidized by reacting with CO_2 and/or H_2O at a lower temperature, producing CO and/or H_2:

$$MO_{x-\delta} + \delta CO_2 \rightarrow MO_x + \delta CO$$

$$MO_{x-\delta} + \delta H_2O \rightarrow MO_x + \delta H_2$$

This cycle allows for the direct conversion of CO_2 and H_2O into syngas, which can be further processed into liquid fuels. The metal oxide is not consumed, allowing the process to be repeated continuously. (Moretti et al., 2023; Prats-Salvado et al., 2022).

Solar thermochemical energy conversion shows promise for producing fuels at lower costs, especially when integrated with technologies like DAC to utilize waste heat effectively, leading to reduced fuel production costs. This is evident in these technologies having lower fuel prices than standard ones. However, the approach faces challenges, including complexity, limited scalability, efficiency concerns, and higher upfront costs compared to established technologies like photovoltaics.

HEFA

HEFA (Hydroprocessed Esters and Fatty Acids) is a process that converts renewable lipids, such as used cooking oils and fats, into jet fuel. While a number of alternative methods fall within the broader HEFA framework, the process mainly involves hydrotreating, where hydrogen is added to remove oxygen, followed by cracking and isomerization to produce hydrocarbons similar to those found in conventional jet fuel (Grahn et al. 2022; Grimme, Peacock et al., 2024). This method is highly efficient and the least expensive SAF option, which is demonstrated by it being the dominant pathway in current global announcements, representing 85% of announced capacity until 2030 (Dietrich et al., 2023; SkyNRG, 2024). The largest issue is related to feedstock, as the supply of waste oils is very limited (Grahn et al., 2022, Peacock et al., 2024; et al. Williams, 2015).

Alcohol-to-Jet

The alcohol-to-jet (ATJ) process converts alcohols, such as ethanol or butanol, into jet fuel, with these alcohols typically derived from starch/sugar-producing feedstocks (Dietrich et al., 2023). The production of these alcohols begins with the fermentation of biomass, such as corn, sugarcane, or cellulosic materials, where sugars are converted into ethanol or butanol. Once the alcohol is produced, it undergoes dehydration to form olefins, which are then oligomerized and hydrogenated to produce hydrocarbons (Peacock et al., 2024). This pathway is highly flexible, utilizing various biomass sources and contributing to sustainable aviation fuel production by converting renewable alcohols into drop-in jet fuels.

Methanol Synthesis followed by Methanol-to-Jet

Methanol synthesis can be performed using either syngas or a combination of CO_2 and green hydrogen (eyberg et al., 2024). Syngas can be produced from the redox reactor, co-electrolysis or from biomass, as indicated by the purple arrows in figure 3.2. When using biomass as a feedstock, the gasification process produces syngas which is then converted to methanol via the reaction:

$$CO + 2H_2 \rightarrow CH_3OH$$

Syngas will not be sourced from the RWGS reactor, as methanol can be synthesized directly from CO_2 and green hydrogen. This process co-produces water via the following reaction:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Both reactions are exothermic and operate at high temperatures and pressures (Grahn et al., 2022). This methanol can then be processed into jet fuel through the methanol-to-jet (MTJ) process. In MTJ, methanol undergoes dehydration, oligomerization, and hydrogenation to produce jet fuel. These techniques were originally developed for fossil raw materials, where methanol synthesis is a well-established and industrially proven technology. They have since been adapted for renewable fuel production, providing a sustainable pathway for jet fuel synthesis (Ruokonen et al., 2021).

Syngas/RWGS Reactor

The syngas reactor is a critical component in processes requiring a specific mixture of carbon monoxide and hydrogen, such as Fischer-Tropsch synthesis. This technology is relatively new and has a low TRL of 5-6 according to Rojas-Michaga (2023), with only limited data available (Sherwin, 2021; Zang et al., 2021). The reactor employs the reverse water-gas shift reaction to convert carbon dioxide and hydrogen into CO and water. Achieving the optimal CO ratio is essential for downstream synthesis and is managed by controlling temperature, pressure, and feedstock composition. Additionally, selectively removing products like water or CO from the reaction mixture can shift the equilibrium, driving the reaction toward the desired ratio (Grahn et al., 2022; Peacock et al., 2024). This method allows for precise control over syngas composition, enhancing the efficiency of subsequent chemical synthesis processes. This process is endothermic where heat supply is integrated with the highly exothermic FT synthesis (Ballal et al., 2023; Rojas-Michaga et al., 2023; Sherwin, 2021).

Fischer-Tropsch Synthesis

Fischer-Tropsch synthesis is a chemical process that converts syngas into liquid hydrocarbons through a polymerisation reaction (Ordóñez et al., 2022). The general reaction is:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$$

Developed in the 1920s by German chemists Franz Fischer and Hans Tropsch, this well-established technology was initially used to produce synthetic fuels from coal (Sherwin, 2021; Tremel, 2018). Today, FT synthesis is being adapted to renewable sources, using syngas derived from concentrated solar power, biomass, or CO_2 and green hydrogen to create carbon-neutral fuels. The process described by the reaction produces long-chain hydrocarbons, including solid waxes, which are then cracked and isomerized to produce liquid drop-in fuels (Dietrich et al., 2024). The kerosene produced has properties similar to petroleum-based jet fuel. The process is highly exothermic, which is repurposed for other energy needs like high temperature electrolysis, DAC or RWGS, enhancing overall efficiency (Herz et al., 2018; Seymour et al., 2023).

Haber-Bosch Synthesis

The Haber-Bosch process synthesizes ammonia (NH_3) by reacting nitrogen (N_2) captured from the atmosphere with hydrogen (H_2) under high pressure and temperature, using a catalyst. Like other syntheses, this process is exothermic and requires requires stable, high full load hours of renewable electricity. While the technology is mature, future innovations could enable dynamic operation, potentially reducing costs by using hydrogen from intermittent renewable sources without the need for expensive storage (Martin et al., 2023; Grahn et al., 2022).

3.2. Actors

Figure 3.3 provides a high-level overview of the key actors involved in the SAF value chain, subdivided in the four actor groups as introduced by Hekkert et al. (2011). These four types of actors will be discussed in detail below.

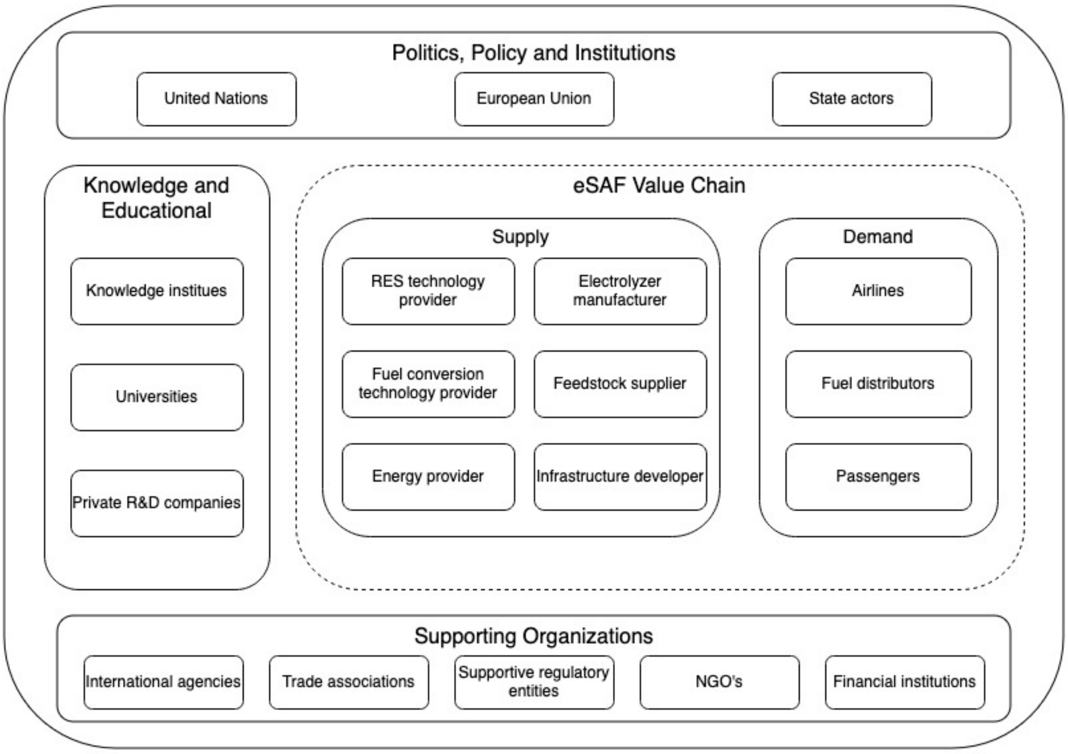


Figure 3.3: overview of the SAF TIS actors

3.2.1. Knowledge Institutes and Educational Organizations

Knowledge institutes and educational organizations, including universities, research centers, and private entities, play a crucial role in advancing sustainable aviation fuel technologies. They focus on deepening technical understanding, demonstrating sustainability, and showcasing the feasibility of various SAF technologies to attract policymakers and investors. These institutions also provide governments with insights that help shape policies and regulatory frameworks. Additionally, experts from these organizations often influence policymaking by taking on roles within legislative bodies or supportive organizations. By bridging the gap between research and commercial application, they drive the transition toward commercially viable SAF solutions, supporting the broader adoption of sustainable aviation practices.

3.2.2. Industry & Market Actors

In the context of the Technological Innovation System framework, the industry actors involved in the sustainable aviation fuel sector are categorized into supply-side and demand-side actors, each playing a pivotal role in the development and adoption of these technologies.

Supply

Supply-side actors are integral to the development and operationalization of the SAF value chain, as they are responsible for producing and providing the necessary technologies, materials, and infrastructure required for SAF production. This group encompasses a variety of stakeholders, each playing a crucial role in enabling the production and distribution of sustainable aviation fuel.

Technology providers are central to the supply side, as they develop and supply the systems necessary to produce SAF, including RES energy technologies, hydrogen production systems, and fuel synthesis processes. These providers are at the forefront of innovation, driving advancements in the efficiency and scalability of SAF technologies.

Feedstock suppliers are another critical component of the supply side. They supply the raw materials required to synthesize SAF, such as water, carbon sources, and other necessary inputs. The availability of these feedstocks directly impacts the feasibility and cost-effectiveness of SAF production.

Energy providers play a pivotal role by supplying the renewable energy needed to power SAF production processes. Electricity can be sourced either directly from actors generating renewable energy, such as solar or wind farms, or from the broader electricity network, provided it is renewable. In this case, a Transmission System Operator (TSO) is a key market actor and seen as an energy provider also, ensuring the delivery of renewable energy to SAF production facilities. The reliance on renewable energy ensures that SAF production aligns with sustainability goals and contributes to reducing carbon emissions in the aviation sector.

Infrastructure developers are also key actors on the supply side. They are responsible for constructing and maintaining the physical infrastructure necessary for large scale SAF production, including production facilities, storage units, and transportation networks. This infrastructure supports the entire supply chain by enabling the efficient production, storage, and distribution of feedstocks intermediaries and the final SAF product. The availability and quality of this infrastructure are critical to the scalability and economic viability of SAF production, as well as the ability to meet market demand.

Demand

Demand-side actors within the SAF Technological Innovation System primarily consist of those who purchase and use the final product, with airlines being the main consumers. Rather than buying fuel directly from producers, airlines typically acquire it from fuel distributors and retailers, who act as intermediaries in the supply chain. These distributors—including large oil and gas companies, airports, airport operators, commodity traders, and specialized fuel distribution firms—serve as critical market actors. They manage logistics, storage, and delivery, ensuring timely and reliable fuel availability while balancing the market to meet industry demand.

In addition to airlines and distributors, passengers also influence demand within the SAF ecosystem. Their travel behavior and opinions on sustainable aviation significantly impact airlines' decisions to adopt more sustainable practices, including the use of SAF. As public awareness and concern about environmental issues grow, passenger preferences for greener travel options can drive airlines to increase their demand for SAF, potentially influencing the overall market dynamics in favor of sustainable aviation fuels.

3.2.3. Government Bodies and Supportive Organizations

Government bodies and supportive organizations play a crucial role in the development and regulation of synthetic sustainable aviation fuel technologies. These actors create the necessary frameworks, provide funding, and set industry standards to drive innovation and ensure the adoption of sustainable aviation fuels. Their influence spans international, European, and national levels, ensuring that the SAF industry operates within a structured and coherent regulatory environment.

At the international level, the International Civil Aviation Organization (ICAO) is responsible for setting global aviation standards. While ICAO has a regulatory function, it is classified as a supportive organization rather than a governing body because it lacks direct enforcement authority being a UN agency. Since the UN facilitates international cooperation rather than governance, ICAO relies on member states to adopt and enforce its standards. In this way, member states act as their own governing bodies in implementing ICAO's regulations.

In contrast, the International Air Transport Association (IATA) serves as a global trade association representing airlines. IATA's primary role is to advocate for the commercial interests of the aviation industry, promoting operational efficiency, safety, and sustainability among its members. Unlike ICAO, IATA does not create regulatory frameworks but influences industry practices by developing guidelines and recommendations for best practices within the aviation industry. IATA's focus is on ensuring that airlines can meet sustainability targets within a commercially viable framework, including through the widespread adoption of market-based measures for reducing carbon emissions.

ASTM International (formerly known as the American Society for Testing and Materials) plays a central role in setting technical standards for SAF which outline the criteria that must be met to be approved for aviation use. These standards are developed through collaboration with global experts and are internationally recognized. ASTM standards are used by regulatory bodies such as ICAO and EASA (European Union Aviation Safety Agency) to ensure that SAF meets the required technical and safety benchmarks. EASA, while a European regulatory body, recognizes ASTM standards for the certification of fuels used within Europe. EASA enforces these standards within the EU by certifying aviation fuels that meet ASTM's technical criteria, ensuring that they are safe for use in European airspace.

The European Council, one of the key decision-making bodies in the European Union, plays a significant role in shaping the overall direction and priorities of the EU, including its environmental and energy policies. Comprising the heads of state or government of EU member states, the European Council sets long-term policy objectives, which guide the development of specific legislation by other EU institutions, such as the European Commission. This includes directives and regulations aimed at reducing carbon emissions and promoting sustainable fuel production within the aviation industry. The European Council's policy direction influences the work of agencies like EASA, which are responsible for implementing and enforcing the technical and safety regulations for SAF across EU member states.

While ASTM sets the global technical standards for fuel properties and safety, the Roundtable on Sustainable Biomaterials (RSB) focuses on certifying the sustainability of SAF production processes. RSB ensures that production aligns with environmental, social, and economic sustainability criteria. RSB certification is often required by stakeholders to verify that the fuel not only meets ASTM's technical specifications but also adheres to stringent sustainability guidelines. RSB's role complements that of ASTM, as it adds a layer of sustainability assurance that goes beyond the technical properties defined by ASTM.

Non-governmental organizations (NGOs) like the RSB and the DAC Coalition play an important role as supportive organizations. While they do not set legal regulations like government bodies, NGOs influence policy and industry standards through advocacy, research, and the promotion of sustainable practices. NGOs act as watchdogs to ensure that industries, including the aviation sector, adhere to sustainable practices. Examples include organizations supporting carbon capture and utilization initiatives, which contribute to the advancement of sustainable aviation fuel technologies by promoting environmental responsibility and technological innovation.

More broadly, NGOs such as Greenpeace, the World Wildlife Fund (WWF), and Friends of the Earth also advocate for sustainability and environmental preservation on a global scale. These organizations focus on a range of issues, including climate change, biodiversity conservation, and the promotion of renewable energy, ensuring that industries like aviation move towards greener, more sustainable practices. Their efforts help shape public opinion, influence corporate behavior, and drive the adoption of more sustainable technologies, including SAF.

Financial institutions play a crucial supportive role in the development and adoption of sustainable aviation fuel technologies, particularly in financing large-scale production projects. These projects require significant capital investment and are often funded through loans from banks or other financial institutions. However, banks are cautious when providing such loans and typically require that production is pre-sold through off-take agreements to airlines or other buyers (Mutrelle, 2023).

Airline/Airline Group	**Business Year**	**Total Costs in Millions**	**Fuel Costs in Millions**	**Fuel Cost Share (% of Total Costs)**	**Operating Profit Margin**
Air France KLM	2019	EUR 26047	EUR 5511	21.2%	3.2%
easyJet	2018/2019	GBP 5984	GBP 1416	23.7%	6.7%
IAG	2019	GBP 22221	GBP 6021	27.1%	13.9%
Lufthansa (Network Airlines)	2019	EUR 22132	EUR 5326	24.1%	7.8%
Lufthansa (Eurowings)	2019	EUR 4655	EUR 1054	22.6%	-4.0%
Ryanair	2019/2020	EUR 2762	EUR 2762	34.2%	13.3%

Table 3.1: Overview of the fuel cost share and operating profit margin of Europe's largest airlines (Grimme, 2023)

As the table shows, fuel costs already account for approximately 25% of total operational expenses for airlines, with some, like Ryanair, having fuel costs as high as 34% of their total costs. If SAF production costs remain several times higher than fossil jet fuel, it would be nearly impossible for airlines to remain profitable without significant price hikes. Given the narrow operating profit margins across the industry, such as Air France KLM's 3.2% or Lufthansa's 7.8%, absorbing the higher cost of SAF would severely impact airlines' financial viability.

This challenge highlights the urgent need for technological advancements that lower the cost of SAF production. Without cheaper production methods, airlines would struggle to adopt SAF on a large scale. Additionally, venture capital (VC) firms play a vital role in financing SAF technology companies. By providing early-stage funding, VC firms help new entrants scale innovative technologies, contributing to the development of more cost-effective SAF solutions. These efforts are critical to making SAF a viable option for the aviation industry.

3.3. Institutions

In the TIS framework, institutions are essential for shaping the technological landscape by establishing the formal and informal rules that guide development and adoption. These rules include regulations, policies, and standards that govern how technologies are certified, financed, and adopted in markets. For the purposes of this study, we will focus on the formal rules, such as legislation and policy frameworks, as they directly influence the viability and scalability of SAF technologies within the regulatory environment. These formal institutions help shape innovation by providing the necessary legal and economic incentives or constraints for technological progress.

3.3.1. Policy Foundations and Global Initiatives

The Paris Agreement, functioning under the framework of the United Nations Framework Convention on Climate Change (UNFCCC), is a multilateral environmental agreement related to climate change and considered as one of the most important institutions (United Nations n.d.). It legally binds member states to global objectives aimed at limiting the rise in global temperatures to below 2°C, with ambitions to keep it closer to 1.5°C. While the agreement does not impose specific emission reduction targets on individual countries, it requires states to establish their own goals and work towards progressively higher ambitions. Although these country-specific targets are not legally binding, the agreement mandates the reporting, review, and scaling up of Nationally Determined Contributions (NDCs), creating a degree of accountability (United Nations, n.d.). The Intergovernmental Panel on Climate Change (IPCC) plays a vital role as a knowledge institute and supportive organization by providing the scientific basis for the Paris Agreement's goals through its research efforts, although it does not create policy. The research it conducts highlights the necessity of global sustainability measures.

CORSIA

The ICAO developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in alignment with the Paris Agreement. CORSIA aims to cap international aviation emissions at 2020 levels. Airlines expanding beyond these limits must either adopt carbon-reducing technologies or purchase carbon credits from ICAO-approved sources (Erriu et al., 2024). E-fuels can qualify under CORSIA as a carbon-reducing technology, provided they meet sustainability criteria, including at least a 10% GHG reduction over fossil fuels (Erriu et al., 2024; European Union Aviation Safety Agency, 2022). CORSIA also emphasizes monitoring, reporting, and verification to ensure transparency and compliance in emission reductions.

ASTM D7566

As discussed in Section 4.2, ASTM International is responsible for certifying fuel production pathways to meet industry standards for blending with fossil kerosene. Seven technologies are currently certified under ASTM D7566, allowing their use in the EU (European Union Aviation Safety Agency, 2022; Federal Aviation Administration, 2020). Although these processes may differ slightly, they typically fall under HEFA, ATJ, and FT pathways, as shown in Figure 4.2. For example, Synthesized Isoparaffins (SIP) ferment sugars into hydrocarbons, then processed similarly to HEFA. The main difference is that SIP synthesizes hydrocarbon chains, whereas HEFA uses feedstock already containing longer hydrocarbons. Methanol-based pathways remain uncertified (Eyberg et al., 2024; Grimme, 2024). Once a SAF pathway is certified, it can be blended with conventional jet fuel for commercial use. PtL fuels produced via FT are already approved, with electricity production and CO_2 sourcing as key factors (European Union Aviation Safety Agency, 2022).

3.3.2. European Climate Law

The EU's climate policy also stems from its commitment to the Paris Agreement. At the constitutional level, the European Climate Law, which came into force in 2021, serves as a legal foundation for the EU's climate targets. It mandates that the EU achieve a balance between greenhouse gas emissions and removals by 2050. This law also establishes an ambitious goal of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (Cifuentes-Faura, 2022). The Climate Law functions as a foundational policy guiding all subsequent EU climate initiatives.

EGD and Fit for 55 Package

One of the key initiatives built upon this law is the European Green Deal (EGD). The EGD is a broad policy framework rather than a law, setting the agenda for revising existing regulations and creating new laws to drive climate action (European Commission, 2019; European Commission, 2021). Under the Green Deal, specific rules targeting carbon removal have emerged. The collective of these laws is known as Fit for 55. This legislative package provides the specific laws and regulations needed to meet the 2030 reduction target of 55% set by the European climate Law, and thus forms the Green Deal strategy. These rules emphasize directing investments toward sustainable projects to meet the net-zero targets. The EU has created a classification system, known as the "EU taxonomy," to clearly define which economic activities are environmentally sustainable. This taxonomy helps guide investments by companies, investors, and policymakers. One of the six objectives of the EU taxonomy is transitioning to a circular economy, where carbon capture and DAC technologies play a crucial role in achieving sustainability goals (European Commission, 2023).

EU ETS

The EU Emissions Trading System (ETS) is a key element of the European Green Deal and Fit for 55 initiatives, aimed at reducing greenhouse gas emissions. It imposes a cap on total emissions from industries like aviation and power generation, which decreases over time to drive emission reductions. Companies trade emission allowances, creating a market-driven incentive to lower emissions. Revenue from allowance auctions supports the EU Innovation Fund, currently valued at €22 billion (European Commission, 2023). Airlines initially received free allowances, but full auctioning will begin in 2027, with an annual linear reduction of 4.2% (European Commission, 2022; Grimme, 2023).

RED II/III

The Renewable Energy Directive (RED III) serves as the EU's primary framework for advancing renewable energy adoption across sectors, aiming for a 42.5% renewable energy share by

2030. Within the transport sector, Member States are required to reduce greenhouse gas (GHG) intensity by 14.5% or achieve a 29% renewable share by 2030 (Erriu et al., 2024). To meet these targets, sustainable aviation fuels and Renewable Fuels of Non-Biological Origin (RFNBOs) play a key role in decarbonizing transportation (Erriu et al., 2024).

The Delegated Acts on RFNBOs

SAFs under RED III must come from either advanced biofuels or RFNBOs (Renewable Fuels of Non-Biological Origin), ensuring they avoid competition with food production and do not harm biodiversity (Erriu et al., 2024). The Delegated Acts on RFNBOs specify that RFNBOs, including sustainable aviation fuels (eSAFs) derived from CO_2 and low-carbon energy, must either achieve a minimum of 70% CO_2 reduction compared to fossil fuels or source their energy from a renewable grid with at least 90% renewable content (European Commission, 2023). Nuclear energy, while not classified as renewable, is permissible for RFNBO production, as it meets the 70% CO_2 reduction requirement. Additional criteria mandate power-purchase agreements (PPAs) with renewable energy providers unless the 90% renewable grid threshold is met. From 2030, hydrogen production must also be temporally and geographically aligned with renewable electricity generation. Additionally, fossil-derived CO_2 is counted as zero-emissions until 2036 for power stations and until 2041 for other industrial sources under the EU ETS, after which only CO_2 from direct air capture or biomass is eligible (Martin et al., 2024; Mutrelle, 2024). A clear overview of the qualification directly presented by the RSB is given below:

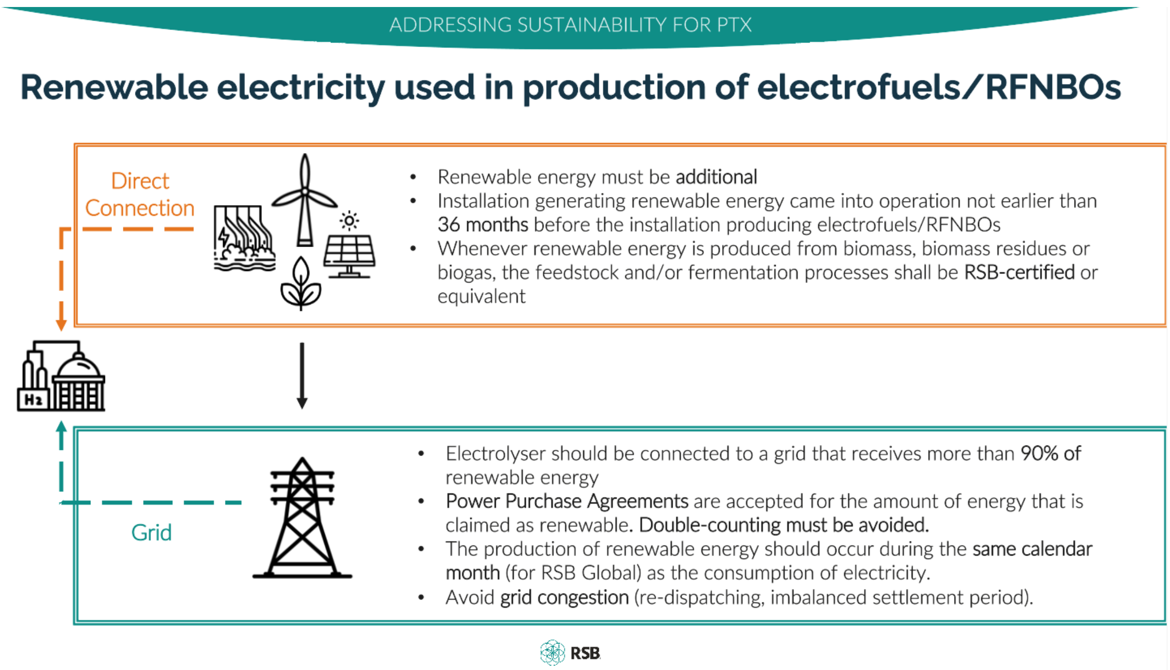


Figure 3.4: Diagram representing renewable electricity and the criteria for RFNBOs (Appendix F; Roundtable on Sustainable Biomaterials, 2024)

RefuelEU Aviation

The European Commission's "ReFuelEU Aviation" initiative aims to boost the supply and demand for SAFs in Europe by introducing mandates (Council of the EU, 2023). It includes measures to ensure that a certain percentage of fuel used by airlines is sustainable, with this percentage increasing over time. Failing to comply with obligations results in an administrative fine being twice as high as the difference between the yearly average price of conventional aviation fuel and sustainable aviation fuel per ton of the quantity of aviation fuels not complying with the minimum share. Total current European Union SAF targets are shown in the upper row of table 3.2 and set to increase up to 70% in 2050.

	2025	2030	2032	2035	2040	2045	2050
SAF (total)	2%	6%	6%	20%	34%	42%	70%
eSAF	-	1.2%	2%	5%	15%	20%	35%

Table 3.2: EU mandates regarding sustainable aviation fuel consumption (Council of the EU, 2023)

These mandates reflect the growing importance of eSAFs, which are required to make up 35% of aviation fuel by 2050 (Council of the EU, 2023). Currently, bio-based SAF solutions dominate the market due to their cost-effectiveness and availability (Fiorini et al., 2023). However, biofuels face challenges like limited feedstock availability and competition from other decarbonizing sectors (SkyNRG, 2024; European Parliament, 2022). Expanding biofuel cultivation also risks competing with food supplies and reducing carbon sinks, further complicating its scalability (Fiorini et al., 2023;). To address these limitations, the EU mandates a minimum share of synthetic fuels (eSAFs), recognizing direct air capture as a key technology for carbon sourcing (European Parliament, 2022).

Industries receiving free allowances under the EU ETS can offer fossil CO_2 to eSAF producers at a reduced cost, effectively subsidizing fossil carbon. This creates a cost advantage for fossil CO_2 over DAC-sourced carbon, potentially delaying the transition to DAC as a primary carbon source for eSAF production until free ETS credits are completely phased out (Martin et al., 2024). This imbalance could hinder DAC's development and competitiveness as a sustainable solution in aviation fuel production.

Additional Financial Measures

The EU has introduced financial mechanisms to support the adoption of sustainable aviation fuels. One such measure is the allocation of €20 million worth of SAF allowances under the EU Emissions Trading System, designed to reduce the price gap between SAF and fossil kerosene and make SAF more competitive (European Commission, n.d.). A preferential tax treatment for SAF through the Energy Taxation Directive has also been proposed, incentivizing the transition to cleaner fuels by offering economic benefits to operators using SAF (European Commission, n.d.).

Additional financial support is provided at various stages of SAF development through programs like Horizon Europe, which funds early-stage research, and the Innovation Fund, which supports projects ready for commercial scaling (European Commission, 2024; European Commission n.d.). For more mature SAF technologies, InvestEU helps attract private investments by offering loans, guarantees, and equity, reducing financial risks for investors (European Union, 2024). Together, these initiatives provide comprehensive support for SAF from research through to market deployment (European Commission, n.d.).

3.4. Networks

As of 2024, there are 45 e-kerosene (e-fuel or eSAF) projects identified in Europe, comprising 25 large-scale industrial projects and 20 smaller pilot projects (Mutrelle, 2024). Collectively, the large-scale industrial projects are projected to have a production capacity of 1.7 Mt by 2030, which surpasses the 0.6 Mt target (1.2%) set by ReFuelEU for the same year, and 2% (1.0 Mt) by 2032 (Council of the EU, 2023). However, none of these major projects have reached a final investment decision (FID) yet, and many are still in the feasibility study phase. Until these FIDs are finalized, the projected capacities should be considered tentative.

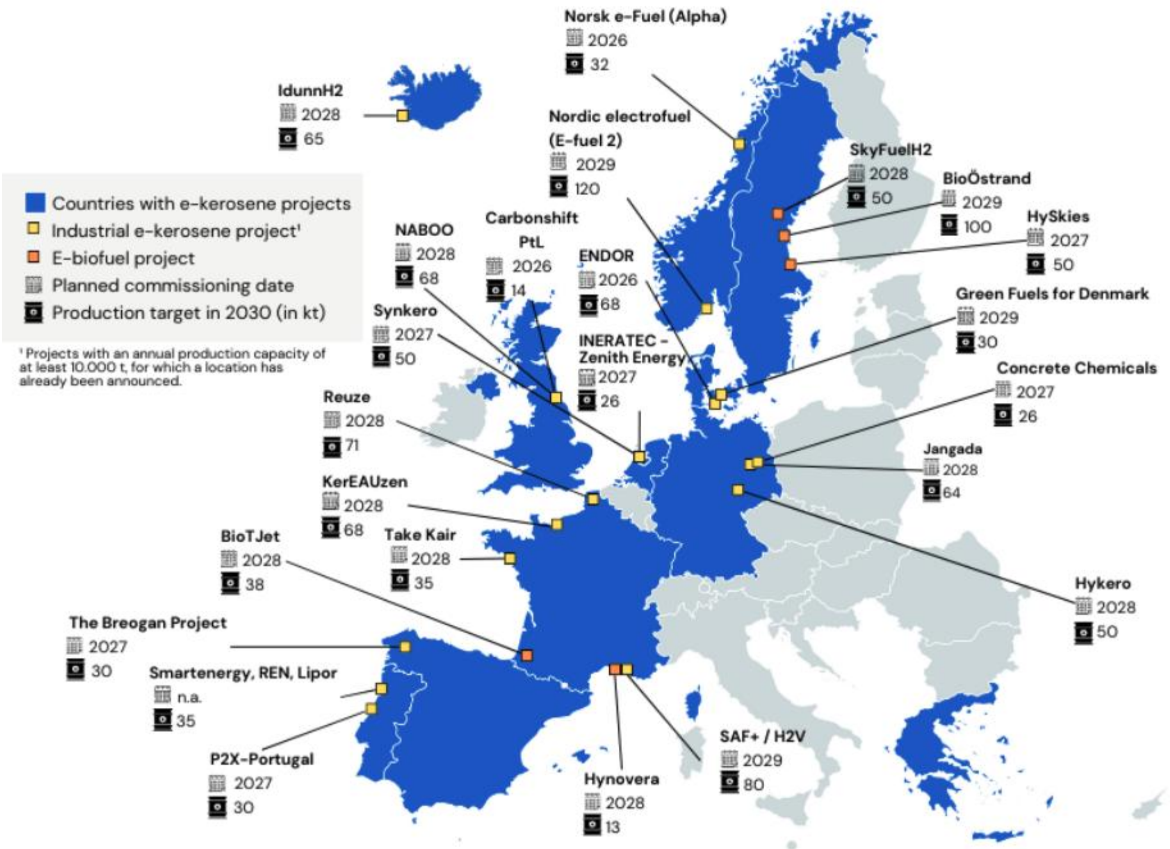


Figure 3.5: Map of announced large scale e-kerosene projects in the EU (Mutrelle, 2024)

This map shows the geographical distribution of major e-kerosene projects across Europe, which can be analyzed in relation to the availability of renewable energy sources and existing electricity networks, carbon capture and utilization infrastructure, aviation fueling infrastructure, local legislation and the project actors.

Renewable Energy Sources and Electricity

The regions highlighted in the map, such as southern European coastal areas, northern Germany, and Scandinavia, are well-suited for e-kerosene production due to their significant renewable energy resources, including solar, wind, and hydropower. Northern Germany stands out for its offshore wind capacity, while Norway leverages hydropower, both of which provide the renewable electricity needed for green hydrogen and e-kerosene production. France, with six announced projects—the highest in Europe—includes two biofuel projects, while three of the remaining four have indicated to build additional nuclear or renewable capacity.

Locating eSAF plants near renewable energy sources minimizes electricity transport challenges caused by grid congestion. Hydrogen transport and storage issues further support the localized production of eSAF, ensuring efficient energy use. Additionally, proximity to a robust renewable energy grid is vital for balancing supply and stabilizing production, allowing for the exchange of surplus energy when necessary. EU regulations mandate that at least 90% of grid electricity must come from renewable sources for eSAF production to meet sustainability standards if sourced directly from the grid. This makes countries like Norway and Iceland with their renewable-heavy grids ideal locations for these projects. Conversely, regions like Spain and Greece, despite their strong solar potential, may require significant grid infrastructure upgrades to fully support large-scale e-fuel production. The success of e-kerosene projects, therefore, depends on both the availability of renewable energy and the capacity of the infrastructure to manage and utilize it effectively.

Carbon Capture and Utilization Infrastructure

Figures 3.6 and 3.7 depict potential configurations of the European CO_2 transport network, as envisioned by the European Commission's Joint Research Centre (JRC) (European Commission et al., 2024). The report underscores the critical gaps in the current CO_2 infrastructure, particularly the absence of commercially proven storage and transport solutions. Developing a robust network is essential for supporting decarbonization goals.

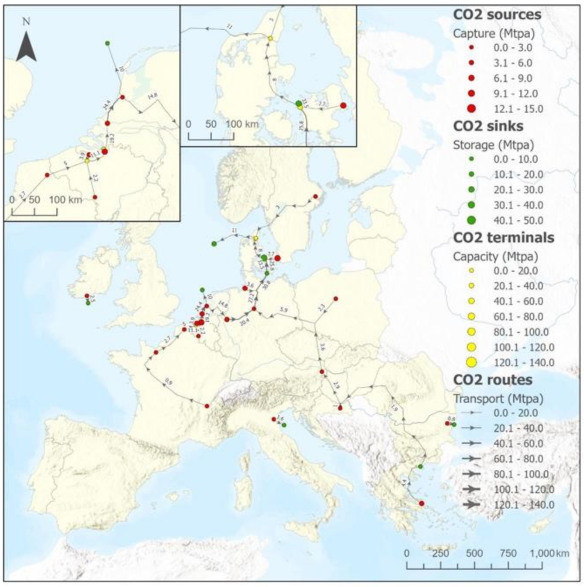


Figure 3.6: European CO_2 infrastructure for 2030 (European Commission et al., 2024)

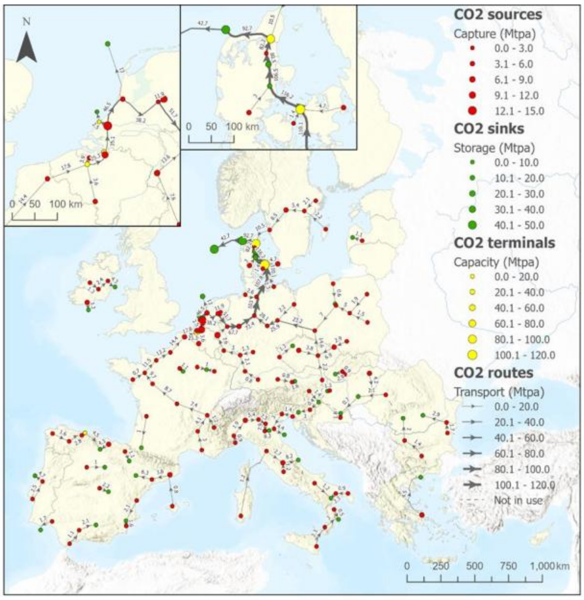


Figure 3.7: European CO_2 infrastructure for 2050 (European Commission et al., 2024)

By comparing figure 3.5 with 3.7, similarities in the network structure between current eSAF developments and the envisioned 2050 carbon infrastructure can be seen. However, the current infrastructure remains underdeveloped, as highlighted by the map for 2030. This lack of established carbon pipelines and storage facilities results in CO_2 being transported using expensive methods such as trucking, which significantly increases operational costs. Direct air capture is most effective in regions with limited biogenic sources, where CO_2 is not readily available from point sources or pipelines. By minimizing reliance on expensive transportation, DAC can streamline the integration of captured CO_2 into sustainable fuel production, making it a more viable solution in areas where carbon infrastructure is still developing.

Fueling Infrastructure

Airports with significant traffic, such as those in Germany, France, and the Netherlands, are already equipped with the necessary fueling infrastructure to accommodate the blending and storage of e-kerosene. Major airports like Schiphol (Amsterdam) and Frankfurt present strategic locations for eSAF projects, reducing the distance between production and distribution, which minimizes transportation costs. Additionally, many eSAF projects are in coastal regions, where fuels can be easily shipped to other parts of Europe, further simplifying logistics. This coastal positioning also supports flexibility in distributing e-kerosene to regions that may lack direct pipeline connections, ensuring a more efficient supply chain.

Local and National Policy

The success of e-kerosene projects is closely tied to the strength of local and national policies that support renewable energy and sustainable aviation fuel. Countries like Germany and Portugal have already implemented SAF regulations or incentive programs, providing critical financial and regulatory backing to accelerate project development. In contrast, regions like Italy may face delays due to less mature policy frameworks. The presence of effective local and national policy networks significantly influences the speed and scale at which these projects can advance.

Actor Network

For this analysis, data from the Transport and Environment report on announced eSAF projects in the EU were used (Mutrelle, 2024). Each participant in these projects was categorized according to specific roles defined in the actor analysis, such as airline, fuel distributor, energy provider, and knowledge institute. The interactions between these roles within each project were then mapped to analyze the connections between different types of actors across multiple projects. A pivot table (located in Appendix G) was used to quantify the frequency of these role-based collaborations, identifying the most common interactions. The full dataset used in this analysis is available in the supplementary materials.

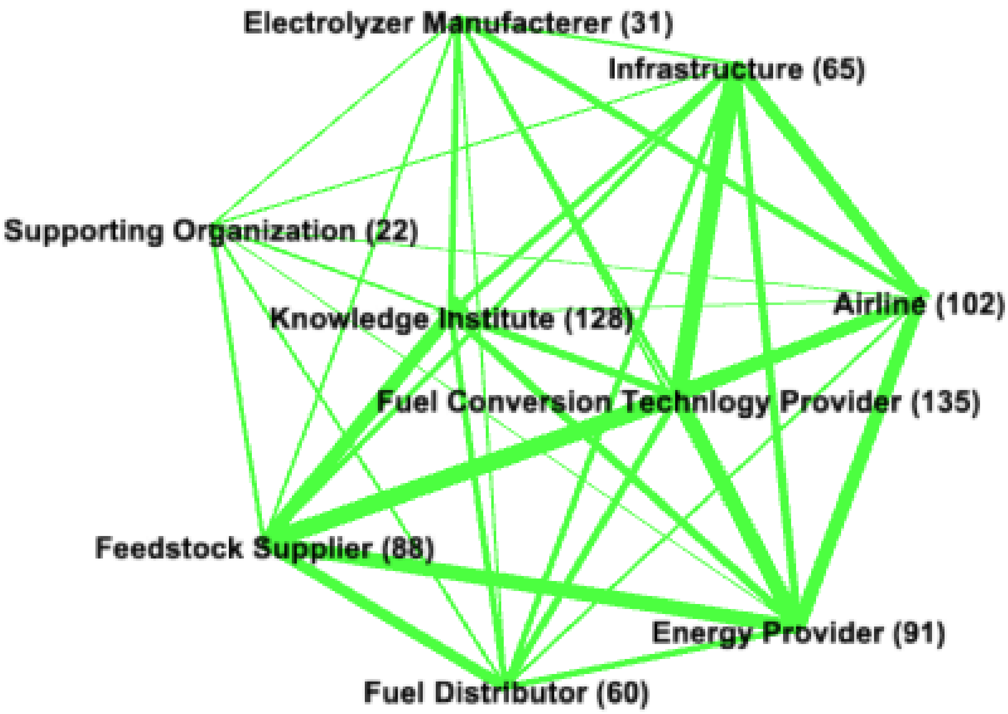


Figure 3.8: Fruchterman Reingold layout representing the network of the European eSAF projects

The role-based network data were subsequently imported into Gephi, where the Fruchterman-Reingold layout was applied to visualize the network structure. In this visualization, nodes represent the roles identified during the actor analysis, and the thickness of the edges between them reflects the frequency of collaboration within the eSAF projects. Thicker edges indicate stronger, more frequent connections between roles, providing a clear representation of the most prominent interactions within the EU eSAF network. This approach allowed for an effective visualization of the relationships between key actors, highlighting the central roles and the intensity of their collaborations within the ecosystem.

The network graph shows Fuel Conversion Technology Providers (135), Knowledge Institutes (128) and Airlines (102) as the most prominent roles, with the highest number of connections, indicating their central importance in eSAF projects. Strong connections between Airlines, Energy Providers, Feedstock Suppliers, and Infrastructure highlight the close collaboration needed across the supply chain for successful eSAF production and use. Knowledge Institutes also play a key role in fostering innovation and development, connecting with various actors to support the projects. These collaborations are further supported by the webinar speakers, representing fuel conversion companies (Twelve), airlines (Alaska Airlines and Swiss Airlines), knowledge institutes (ETH Zurich), supporting organizations (IATA and RSB), and feedstock suppliers (Climeworks) (Appendix E; Appendix F).

3.5. Criteria

To identify the most suitable technology, criteria were developed based on the problem statement and insights from the technology, actor, policy, and network analyses. These criteria were categorized into technical and non-technical types. Technical criteria assessed specific technological components, such as energy sources, electrolysis methods, and fuel synthesis processes. While some criteria, such as policy alignment, were not purely technical, they were included to evaluate the feasibility of technological components within the socio-technical context. Non-technical criteria addressed broader socio-technical factors necessary for successful implementation.

Each technological component was scored on a scale—excellent, moderate, concern, or critical—based on how well it met the technical criteria. These criteria held equal weight, and components were evaluated relative to each other. A "critical" score led to exclusion from further analysis. Aggregated scores identified the most favorable options for further consideration in the techno-economic assessment, with lower scores indicating higher suitability.

Color code	Excellent (0)	Moderate (1)	Concern (2)	Critical (3)

Table 3.3: Color-coded scoring system scale

3.5.1. Setting Technical Criteria

The problem statement identified that existing fuels are pollutive, and alternative options remain underdeveloped due to high costs. Consequently, key criteria for any alternative technology were defined as sustainability, cost-effectiveness, short-term viability, and scalability to meet current and future demand and policy mandates. Since it was difficult to evaluate technologies directly against these criteria, they were adapted to align with specific technological components identified in the technology analysis. These criteria were further reinforced by experts during the webinar, who emphasized the necessity of initiating investments and scaling projects immediately—not only to meet mandates but also to drive down costs and accelerate learning rates, which are otherwise unpredictable without real-world implementation (Appendix E).

- Sustainability: An alternative technology needed to demonstrate reduced environmental impact. While only the sustainability of the electricity source and hydrogen carrier could be assessed directly, a more efficient electrolyzer indirectly enhanced sustainability by requiring less energy, and thus sustainability was captured through efficiency.

- Cost-effectiveness: Given high costs as a primary barrier, subsequent sub-questions address cost analysis in detail. Efficiency, however, affects cost-effectiveness directly by minimizing energy loss, making it an essential criterion for electrolysis.
- Short-term viability: Represented by TRL for electrolysis and fuel synthesis technologies, with higher TRLs indicating readiness for near-term deployment. For hydrogen carriers, this criterion was reflected in fuel infrastructure alignment, as switching to a new carrier was considered unfeasible over the next two decades, as supported by studies on electrical and hydrogen-powered aviation. For electricity generation, short-term viability also assessed how quickly new capacity could be developed and integrated, an important factor in meeting immediate fuel demand and policy mandates.
- Scalability: To ensure technologies could meet sectoral fuel demands, feedstock availability captured this requirement for hydrogen carriers. For technologies like electrolysis and fuel synthesis methods, scalability was partially represented by TRL, as higher TRLs indicated closer proximity to commercialization and easier scalability.
- Policy alignment: The policy analysis revealed that various policies beyond mandates influenced technology feasibility, leading to this criterion's inclusion. Policy alignment assessed the support for each type of electricity generation, energy carrier classification within policy frameworks, and certification status of fuel synthesis methods.

Additional criteria were developed based on system challenges and technological requirements identified in the analyses:

- Independence: To address grid congestion challenges associated with electrification, an energy independence criterion was added to remove reliance on external grids with additional grid costs.
- Non-intermittency: As SAF production is a continuous process requiring many operational hours, energy sources that are non-intermittent scored higher.
- System integration: To capture the differences among electrolysis technologies, the system integration criterion evaluated how well each technology fit within the broader system to ensure operational efficiency.
- Direct air capture compatibility: Given that the research focuses on DAC, compatibility with DAC was included as a criterion, ensuring technologies are assessed for their alignment with DAC integration.

3.5.2. Technical Criteria

Energy

	Dedicated RES	RES grid	Nuclear
Independence		2	
Sustainability			1
Non-intermittency	2		
Policy alignment			1

Short-term viability	1		3
Total:	3	2	5

Table 3.4: Energy source scoring table

Building dedicated renewable or nuclear capacity allows e-fuel projects to achieve energy independence, insulating them from market uncertainties and price fluctuations tied to grid-sourced electricity. By bypassing grid congestion and associated costs like taxes and transmission fees, projects can ensure a stable and predictable energy supply over time. A connection to the grid does not offer these benefits, which is why it scores lower on energy independence compared to dedicated energy generation options.

Hydropower provides a stable and continuous energy output, but it is already extensively utilized where available, leaving more intermittent sources like wind and solar as the primary renewable options for near-term expansion (International Energy Agency, 2021). These alternatives, however, require time to be built. Although nuclear energy provides a reliable and consistent power source, it faces sustainability challenges, including the use of non-renewable materials and waste management issues. Moreover, nuclear energy's short-term viability is hindered by high investment costs, long construction timelines, and complex regulatory barriers, making it less favorable for supporting the electricity needs of synthetic aviation fuel production. While existing nuclear plants could potentially supply energy for this purpose, their current capacity is mostly dedicated to meeting existing base load (World Nuclear Association, 2024). Expanding nuclear energy is constrained by significant societal and regulatory hurdles within the EU, limiting its role in eSAF production.

Electrolysis

	AE	PEM	SOE
TRL		1	2
Efficiency	2	1	
System integration	1		
Total:	3	2	2

Table 3.5: Electrolysis technology scoring table

Alkaline Electrolysis achieves the highest Technology Readiness Level (8-9) due to its long-standing industrial use, but it falls short in efficiency compared to other methods and presents no significant technological benefits for eSAF production, reflected in its lower score for system integration. Proton exchange membrane electrolysis, with a TRL of 6-8, offers better efficiency than AE, though it still lags behind solid oxide electrolysis. PEM's ability to integrate effectively with intermittent renewable energy sources is a notable advantage. SOE, being a newer technology, has the lowest TRL, particularly in the context of co-electrolysis, but its capability to directly co-electrolyze CO_2 and water significantly improves system integration by eliminating a synthesis step. Additionally, its high operating temperatures result in the highest efficiency among the three electrolysis methods.

Energy Carrier

	Biomass	Biogenic	Fossil	DAC	Nitrogen
Sustainability	1		2	1	
Feedstock availability	2	2			
Policy alignment	*		2		
Fuel infrastructure alignment					3
Total:	3	2	4	1	3

Table 3.6: Energy carrier scoring table

The EU has prioritized the use of residual or waste biomass for biofuel production to minimize environmental impact and avoid competition with food production (European Commission & Directorate-General for Energy, 2023). However, the availability of residual biomass is limited, making it challenging to meet the large-scale demands of sectors like aviation. This constraint is reflected in the moderate scores for sustainability and feedstock availability. Since bio-based SAF is cheaper than e-fuels due to not needing additional energy for production, it is expected that the available biomass will be depleted soon. To ensure that eSAFs are also developed, bio-based SAF and eSAF have been given separate mandates. While bio-based fuels fit within EU policies, they are regulated under different frameworks compared to DAC-derived eSAFs, as indicated by the distinction marked with * in the table.

Biogenic CO_2, produced through processes such as biomass combustion, digestion, and decomposition, can be captured from industries like biogas upgrading, fermentation, wastewater treatment, and the pulp and paper sector (European Biogas Association, n.d.). While it offers a sustainable feedstock for e-fuel production, limited availability and competition with other decarbonization sectors restrict its long-term potential for aviation, resulting in this being a concern as seen in the table above (McKenna, 2024). Additionally, competition with carbon capture and storage presents a significant barrier, as CCS is seen as simpler and more financially viable due to more favorable regulatory incentives. High capture costs, underdeveloped CO_2 markets, and insufficient CO_2 infrastructure, such as pipelines and storage, further complicate the widespread use and availability of biogenic CO_2. Without substantial market and infrastructure advancements, scaling its use for e-fuels remains challenging. These findings coincide with the remarks made by carbon conversion experts, who identified challenges for scaling power-to-liquid, including limited availability and competition for biogenic CO_2, high capture costs, and the declining long-term feasibility of non-biogenic CO_2 sources (Appendix F).

Fossil CO_2 is permitted for eSAF production from certain sectors until 2036 and 2041, leading to its "concern" score, on sustainability and policy alignment. DAC's primary sustainability issue is its dependence on renewable electricity, which is required for eSAF production to meet EU environmental standards.

Although ammonia is being explored as a maritime fuel, it is currently unsuitable for aviation due to its lower energy density compared to jet fuel, the need for significant modifications to engines and infrastructure, and the safety concerns posed by its toxicity and handling risks in confined environments like aircraft (Amhamed et al., 2024).

Fuel Synthesis

	REDOX + FT	RWGS + FT	FT	HEFA	Alcohol-to-Jet	Methanol-to-Jet
TRL	2	2			1	1
Certified pathway						3
Integrable with DAC	2			3	3	
Total:	4	2	0	3	4	4

Table 3.7: Fuel synthesis scoring table

Fuel synthesis using a redox reactor powered by concentrated solar energy has been demonstrated at a pilot scale, such as the reverse water-gas shift reactor (Moretti et al., 2023). While RWGS represents the most advanced power-to-liquid technology, its application to SAF production requires adaptation, as it has predominantly been used in other industries (Appendix F). Both redox and RWGS reactors have lower Technology Readiness Levels compared to established methods like Fischer-Tropsch and Hydroprocessed Esters and Fatty Acids, which have reached TRL 9. The variability in reported TRLs for these newer technologies across the literature underscores concerns regarding their readiness for large-scale deployment. Biofuel types like AtJ and MtJ are now being optimized for commercial deployment, placing them at TRL 8, indicating they are near full maturity (Su-Ungkavatin et al., 2023). Methanol to jet has not been certified, which is why it will not be considered in the TEA. DAC cannot be combined with HEFA or AtJ due to their need for organic feedstocks rather than CO_2, so they are also excluded from the following analysis.

Integrating Concentrated Solar Power (CSP) with direct air capture is theoretically feasible but presents challenges. DAC requires additional electricity, which undermines CSP's advantage of avoiding the need for both electricity and an electrolyzer. If DAC is powered by a renewable grid, it would need to be located in regions like Denmark or other Scandinavian countries, which are not optimal for solar energy. Alternatively, building new RES capacity for DAC would negate CSP's benefit of avoiding additional infrastructure. Furthermore, using heat and steam from CSP for electricity generation requires thermal storage, but this differs from the storage used in FT or RWGS + FT processes, complicating comparisons. While excluding storage for FT and RWGS + FT is fair due to their similar storage needs, excluding it in a CSP + REDOX + FT setup could create an unequal comparison (Moretti et al., 2023; Prats-Salvado et al., 2022).

3.6. Concluding remarks

3.6.1. Technical Criteria

The EU's strategy to phase out nuclear energy prioritizes flexibility over generation capacity. However, a doubling of the EU's current generation capacity will be required solely to meet the 2050 decarbonization goals of the aviation sector, suggesting the EU may need to reconsider its stance, as coupling nuclear energy with eSAF plants offers advantages given the constant energy demand of eSAF production (Su-ungkavatin et al., 2023). Yet, since new nuclear capacity will not be added in time to meet near-term mandates, eSAF projects should focus on countries with grids over 90% renewable electricity. This approach also simplifies the following model by removing the need to optimize renewable generation profiles, electricity storage and plant sizing.

This study will further focus on proton exchange membrane electrolysis and solid oxide electrolysis. PEM electrolysis is favored for its efficiency and compatibility with intermittent renewables, making it ideal for integration with wind and solar power. SOE, especially in co-electrolysis, is underexplored but could offer advantages by directly converting water and CO_2 into syngas, which is processed via Fischer-Tropsch synthesis. Exploring these technologies further aligns with expert views expressed during the webinar (Appendix F). Methanol synthesis is excluded as it is not yet certified for sustainable aviation fuel. The TEA will compare DAC, fossil point source capture, and biogenic CO_2 for carbon sourcing, incorporating EU ETS carbon pricing. Biofuels, which follow a separate regulatory framework and have much lower costs, will not be included in the TEA for e-fuels because of this.

3.6.2. Non-technological Criteria

Supported by the webinars, the actor and network analysis showed that bringing together Fuel Conversion Technology Providers, Knowledge Institutes, and Airlines is essential, as they are the most frequently involved stakeholders in current eSAF projects. Strong collaboration between Airlines, Energy Providers, Feedstock Suppliers, and Infrastructure Providers is key to ensuring the success of eSAF production, given the complexity of the supply chain.

The significant costs and economies of scale associated with establishing eSAF production facilities, combined with the small initial quantities of eSAF needed by airlines and narrow profit margins, emphasize the importance of collective investments. This is where the International Air Transport Association could play a crucial role. By representing airlines and promoting operational efficiency, safety, and sustainability, IATA could facilitate these joint investments in new eSAF production sites, particularly in EU member states that have specific eSAF regulations in place.

Strategically, eSAF production sites should prioritize proximity to fueling infrastructure and regions with abundant renewable energy resources, as long-distance electricity transport is inefficient, and grid congestion poses significant challenges. Ideally, these sites would be situated in sparsely populated areas with limited alternative uses for renewable energy, ensuring both optimal availability and minimal competition. For short-term implementation, regions like Iceland or Norway, with their renewable-heavy grids, address intermittency challenges by offering stable energy supplies, albeit at higher costs. In the long term, coupling eSAF production with new nuclear capacity should be explored to provide a dependable and low-carbon energy source. Furthermore, selecting locations without alternative carbon sources bolsters the case for DAC by eliminating reliance on inadequate carbon infrastructure and enabling streamlined on-site CO_2 capture for eSAF production.

Finally, one crucial criterion for DAC adoption is ensuring a level playing field with fossil-based carbon sources. The transitional use of fossil CO_2, regulated under the EU Emissions Trading System, imposes additional costs, which can be offset by free allowances. However, this creates a potential disadvantage for DAC if fossil alternatives continue receiving preferential treatment through free ETS credits. Phasing out these credits in a timely manner is essential to ensure fair competition between DAC and fossil alternatives in the eSAF production landscape.

4. Results Techno-Economic Analysis

Chapter 4 introduces the core results of this thesis, addressing the second and third sub-questions that aim to evaluate the techno-economic performance of competing eSAF value chains. Sub-question 2 focuses on comparing the key technologies identified in the socio-technical analysis: " **How do the identified technologies perform in their overall costs?**". Sub-question 3 delves deeper into identifying what impacts this performance: " **What are the key cost drivers within the identified SAF technology, and how do these components evolve over time?**". The goal is to evaluate which technology offer the most economical potential and identify key factors driving cost and feasibility.

This chapter is structured as follows: Section 4.1 outlines the model framework and key assumptions, explaining the input choices and validation process for the analysis. Section 4.2 presents the results of the technology comparison, addressing sub-question 2. Section 4.3 examines the impact of specific components on techno-economic performance, directly addressing sub-question 3. Finally, Section 4.4 finalizes the TEA with a sensitivity analysis, assessing the robustness of the results under varying model conditions, followed by Section 4.5, which provided a wrap-up of the chapter.

4.1. Model Framework and Assumptions

4.1.1. CAPEX Degression Curve, Efficiencies and Energy Requirements

Direct Air Capture

For DAC, internal company performance and cost data (EUR/ton) from previous years, current operations, and planned upgrades over the next four years were used instead of literature values to shape the CAPEX degression curve. These company-specific data were integrated as hard constraints into the Solver model. The 2050 price endpoint, however, was averaged from literature, as Skytree does not project costs or performance for its technology beyond 2028. The CAPEX curve is depicted by the orange line in figure 4.1.

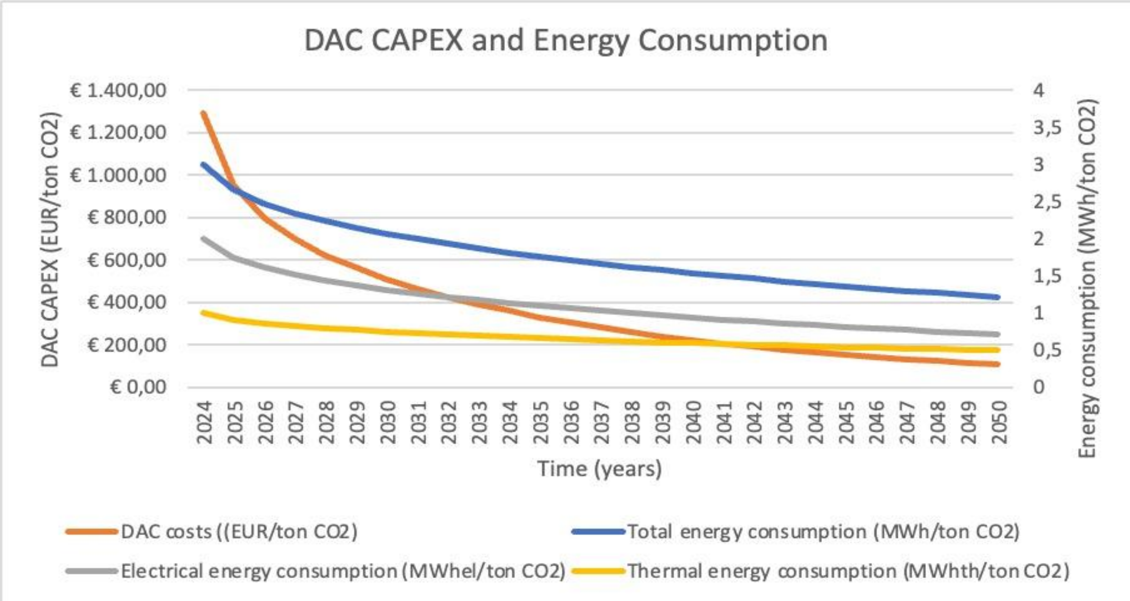


Figure 4.1: CAPEX and energy requirement curve for DAC from 2024 to 2050

Like the approach taken for CAPEX calculations, the energy consumption of direct air capture was modeled using a degression curve. This curve captures the non-linear decrease in energy consumption, as observed in Skytree's data, and provided a better fit for representing expected energy reductions over time. Additional constraints were applied using Excel Solver to align the model with Skytree's projected technology upgrades.

The total energy consumption for DAC was split into thermal and electrical components, reflecting the different energy sources involved. While data for thermal and electrical energy requirements up to 2028 were provided by Skytree, future energy consumption up to 2050 was conservatively assumed to approach a total of 1 kWh/kg CO_2, with 0.5 kWh/kg CO_2 to be supplied by thermal energy. This estimate is based on the minimal energy requirements for DAC outlined in the methodology.

Process	**Minimum Value**	**Assumption**	**Unit**
CO2 separation	0.122		kWh/kg CO2 (electrical)
Sorbent regeneration	0.536	0.5	kWh/kg CO2 (thermal)
Air suction	0.136		kWh/kg CO2 (electrical)
Total	0.794	1	kWh/kg CO2

Table 4.1: Overview of the minimal energy requirements for DAC supporting the assumptions for 2050

Proton Exchange Membrane Electrolysis

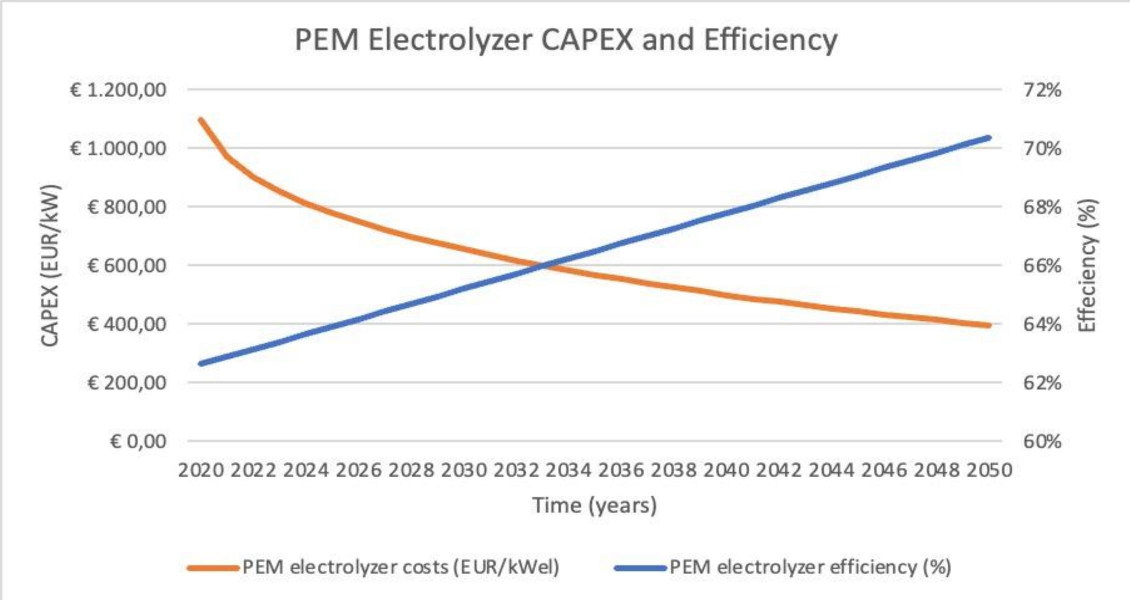


Figure 4.2 CAPEX and efficiency curve for PEM from 2020 to 2050

The efficiencies of the PEM electrolyzer was modeled linearly, as this provided the best fit with data points other than 2050 (IEA, 2019, Martin et al., 2023; Seymour et al., 2023; Sherwin, 2023).

Solid Oxide Electrolysis

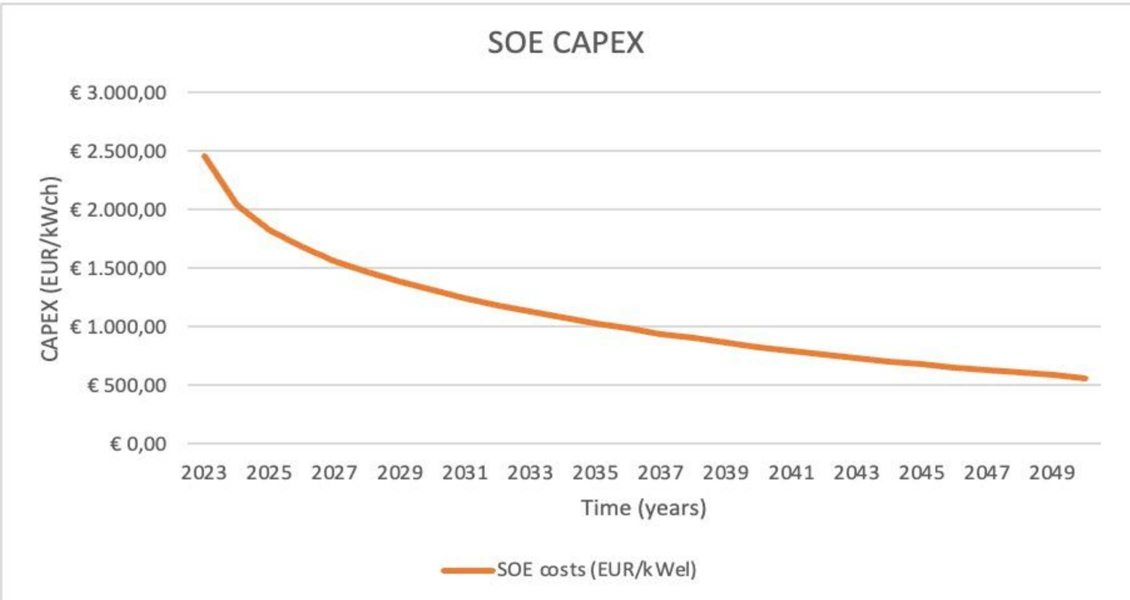


Figure 4.3: CAPEX curve for solid oxide co-electrolysis from 2023 to 2050

Co-electrolysis requires minimal adjustments to the SOE electrolyzer and can leverage existing data on future price reductions as SOE has frequently been modelled for hydrogen production (Zheng et al., 2017). However, co-electrolysis efficiencies differ from regular SOE efficiencies, and limited data is available, so no efficiency gains were modeled or depicted in figure 4.3.

Fuel Synthesis

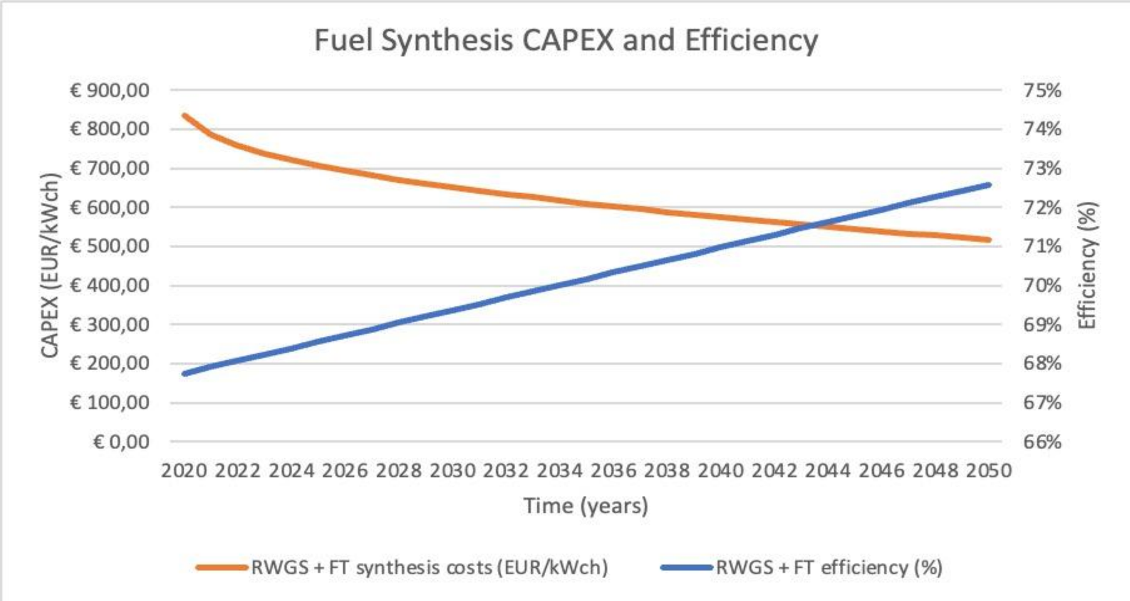


Figure 4.4: CAPEX and efficiency curve for fuel synthesis from 2020 to 2050

Fuel synthesis, typically modeled as a single step, consists of the reverse water-gas shift reactor and Fischer-Tropsch synthesis. As FT synthesis is a mature technology from the oil industry, efficiency improvements were attributed to advancements in the RWGS reactor. By assuming FT efficiency at its maximum of 83%, the RWGS reactor's efficiency was deduced (Sherwin, 2021; Tremel, 2018). This distinction was essential, as not all pathways include the RWGS reactor. CAPEX costs across these components were assumed to be split evenly, with an average distribution of 55% to FT synthesis and 45% to RWGS found in literature (Rojas-Michaga et al., 2023; Sherwin, 2021; Zang et al., 2021). The efficiencies for 2024 are summarized in the table below.

Technology	**Energy efficiency (%)**
PEM	65
SOE	82
RWGS reactor	83
FT synthesis	82

Table 4.2: Energy efficiencies for 2024

4.1.2. Cost of Carbon

While most literature typically only considers the cost of carbon capture, this study expanded the analysis to include the costs of capture, purification and liquefaction, and transport. Additionally, the source of the CO_2, whether fossil or biogenic, determined the inclusion of the EU ETS price, further influencing the total carbon cost.

Capture Costs

Capture costs were categorized according to the concentration levels of CO_2 and the nature of the source, whether biogenic or industrial. Higher CO_2 concentrations in off-streams were associated with lower capture costs, while lower concentrations resulted in higher costs. For the purposes of this study, processes eligible to supply CO_2 during the transitional period, as defined by their inclusion in the EU ETS, along with biogenic sources, were averaged and adjusted to align with average data reported in the literature for high and low concentration (Brynolf et al., 2018; CBO, 2023; E4tech, 2021; Grahn et al., 2022; IEA, 2019; Rodin et al., 2021; Singh et al., 2023; Tanzer et al., 2021; Yang et al., 2022; Zang et al., 2021). In this model, CO_2 capture costs were assumed to be €20/ton for high-concentration streams and €75/ton for low-concentration streams.

Purification and Liquefaction

Purification and liquefaction were treated as a single cost component, critical for preparing CO_2 for transport and storage. Purification is necessary to remove contaminants that are not permitted in pipelines, while non-condensable gases must be eliminated before liquefaction to ensure safe and efficient handling. Liquefaction is particularly required for maritime and road transport, as CO_2 must be in liquid form to facilitate these methods. The associated costs consist of the initial investment and the energy required for compression and cooling. To determine the levelized cost of liquid CO_2, three quotations from suppliers were obtained and conservatively adjusted to align with lower values from the literature, which typically reflect large industrial processes benefiting from economies of scale (Chen & Morosuk, 2021; Debergh et al., 2023; Deng et al., 2019;). For this analysis, we assumed annualized fixed costs of €10.00 EUR/ton and an energy consumption of 130 kWh/ton.

Transport

Transport costs were averaged from literature, which included both pipeline and maritime transport (Becattini et al., 2021; Fasihi et al., 2019; Mandova et al., 2019; Smith et al., 2021; Tanzer et al., 2020; Yang et al., 2021). However, given that eSAF production is likely to occur in locations with high renewable energy availability—areas not necessarily connected to CO2 pipelines or harbors—and considering the small quantities involved in initial demonstration projects, more expensive truck transport is likely to be required. Despite this, average data from the literature were used to maintain consistency and provide a conservative analysis, resulting in a transport cost of €15/ton.

Cost component	**Unit**	**Average found for this study**	**Assumed for this model**
Capture costs high concentration CO2 stream	(EUR/ton)	€ 20,86	€ 20,00
Capture costs low concentration CO2 stream	(EUR/ton)	€ 62,18	€ 75,00
Transport costs	(EUR/ton)	€ 15,59	€ 15,00
Purification/liquefaction	(kWh/ton)	164,67	130,00

Annualized fixed CAPEX + OPEX	(EUR/ton)	€ 13,44	€ 10,00

Table 4.3: Key assumptions regarding the cost of carbon

Alternative
High concentration biogenic
Low concentration biogenic
High concentration fossil
Low concentration fossil

Table 4.4: Classification of alternative CO_2 sources

4.1.3. EU ETS Price

For fossil CO_2 sources, the cost of carbon also included the EU ETS price. A report from a workshop organized by the Federal Ministry of Education and Research provided the basis for forecasting the EU ETS price (Kopernikus-Projekt Ariadne, 2023). The workshop included experts and academics from multiple organizations specializing in carbon market modeling. The forecasted ETS prices were used to estimate the carbon tax component, with the standard deviation from the forecast providing upper and lower bounds for sensitivity analysis.

To project the EU ETS carbon price for 2041, trendline analysis was conducted in Excel using data from 2025 to 2040. A 4th-degree polynomial was selected, as it provided the best fit for the data, accurately capturing the nonlinear behavior of carbon prices influenced by regulatory and market factors. The trendline formula generated from this analysis was then used to extrapolate price data for 2041. The results are depicted in the graph below. This projected cost was added to fossil CO_2 sources to facilitate fair comparisons with biogenic CO_2, and DAC carbon, and to conventional jet fuel prices (adjusted for carbon emissions) to enable comparison with eSAF prices.

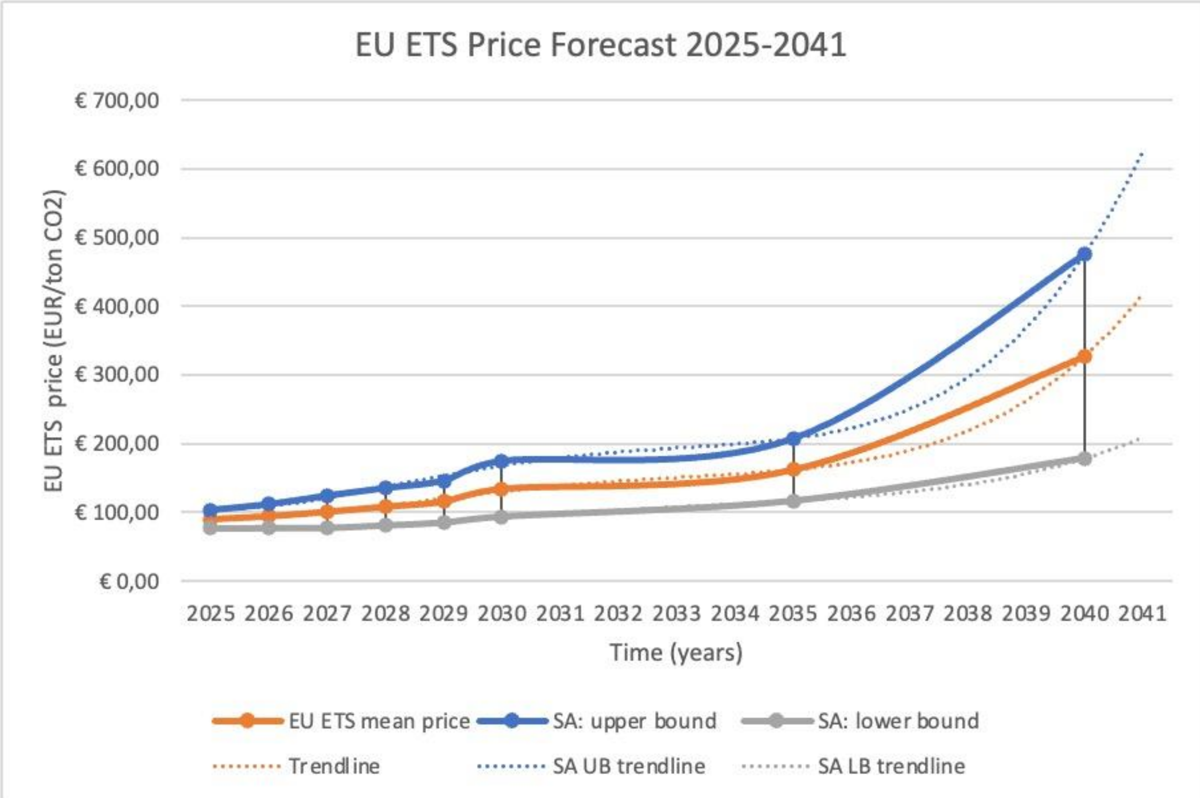


Figure 4.5: EU ETS price forecast for 2025 to 2041. Data obtained from 6 organizations specialized in carbon market models (Kopernikus-Projekt Ariadne, 2023). The forecast was extended to 2041 using trendline analysis in Excel. 2041 marks the final year in which fossil CO_2 can be used for eSAF synthesis.

4.1.4. CO_2 Efficiencies

In the model, the CO_2 efficiency of various components was determined, considering the high value of captured CO_2 when DAC is employed due to the use of renewable energy. An overview of the carbon efficiencies is given in table 4.4 below.

RWGS Reactor and FT synthesis

The CO_2 efficiency of the RWGS and FT reactors was initially unknown. To calculate this, the minimum amount of CO_2 required to synthesize 1 liter of eSAF was estimated based on its chemical composition. For simplicity, kerosene was assumed to consist primarily of $C_{12}H_{26}$, with an average density of 0.8 kg/liter. This theoretical value was compared with the average CO_2 required in processes modeled in the literature using similar technology, allowing for an approximation of overall CO_2 efficiency.

CO_2 loss occurs during both the RWGS reactor and FT synthesis stages. In the RWGS reactor, incomplete CO_2 conversion leads to losses, while in FT synthesis, side reactions and incomplete reactions result in further CO_2 emissions. The overall carbon efficiency was calculated at 83%, closely matching the literature-reported efficiency of 85% (Markowitsch et al., 2023). CO_2 losses were assumed to be evenly distributed between the RWGS and FT processes, each accounting for 50%, leading to an estimated CO_2 efficiency of 91% for both processes.

Co-electrolysis

To calculate the carbon efficiency of the solid oxide electrolyzer, key data such as the CO_2 input, syngas output, and molar masses of the gases involved (CO_2, CO, and H_2) were used. The ratio of H_2 to CO was known to be 2:1, a crucial factor for fuel synthesis, aligning with the requirements of Fischer-Tropsch synthesis and comparable RWGS reactors. The total number of moles of gas in 1 normal cubic meter was set at 44.6 mol, based on the molar volume of an ideal gas at standard temperature and pressure. The carbon efficiency was then calculated by comparing the moles of CO_2 input to the moles of syngas output, yielding a carbon efficiency of 67%. Sunfire's SOE was chosen for modeling as it represents one of the only commercially available co-electrolysis technologies (Choe et al., 2022; Sunfire GmbH, 2023). This efficiency is critical for enabling cost comparisons between different technologies, as a lower efficiency would require more CO_2, driving up costs. The balance between higher electrical efficiency and increased CO_2 usage, compared to PEM, has not been previously modeled and is essential for determining which electrolyzer achieves the lowest levelized cost of fuel.

Technology	Carbon efficiency (%)
SOE	67
RWGS reactor	91
FT synthesis	91

Table 4.5: Carbon efficiency overview

4.1.5. Fixed OPEX and Lifetime

The fixed operational expenditures and lifetime for all technologies are presented in the table below. DAC has a high fixed OPEX of 10% primarily due to sorbent replacement. However, when operating at lower hours, the sorbent's lifetime is extended. To reflect this, OPEX is assumed to scale linearly with operational hours, reducing to 5% when operational hours are halved to 4000.

The OPEX for PEM electrolysis was derived from literature sources that included stack replacement costs for simplicity (Grahn et al., 2022; Sherwin, 2021). For solid oxide co-electrolysis, OPEX was set at 4% (Choe et al., 2022), excluding stack replacement, as the system's lifetime, currently estimated at 10 years, matches the stack's lifetime. This is shorter than the 24-year lifetime of PEM due to issues with stack degradation, reflecting the technology's novelty (Becattini et al., 2021; Choe et al., 2022; Höglund, 2024; IEA, 2019; Martin et al., 2023; Seymour et al., 2023). For fuel synthesis, the operational expenditure is estimated at 4% with a system lifetime of 25 years (International Energy Agency, 2019; Grahn et al., 2022; Seymour et al., 2023; Sherwin, 2021).

Technology	OPEX (%)	Lifetime (years)
DAC	10	20
PEM	7	24

SOE	4	10
RWGS reactor	4	25
FT synthesis	4	25

Table 4.6: Overview of technology specific OPEX and lifetime

4.1.6. Economic assumptions

The following outlines key economic assumptions used in this model, including values for storage, heat integration, electricity price, discount rate, and operational hours. These assumptions are summarized in table 4.5 below.

Storage

Storage is not considered in this model, despite the well-established need for electricity storage in managing renewable energy intermittency. Including storage would require additional component sizing and transform the model into a more complex mixed optimization problem, which falls outside the scope of this study.

Heat Integration

The thermal energy demands of the endothermic RWGS reactor are supplied by the exothermic FT synthesis process. Rojas-Michaga et al. (2023) demonstrated that FT synthesis waste heat additionally meets DAC requirements. Similarly, for solid oxide co-electrolysis, the FT synthesis heat is assumed to meet high-temperature demands, as the RWGS reactor is bypassed. Therefore, the thermal energy price was set to zero.

Electricity Price

An electricity price of €60/MWh, representing the levelized cost of renewable electricity, was assumed in line with EU estimates (IEA, 2021). Large-scale projects such as eSAF production plants typically purchase electricity directly before the meter, avoiding network-associated costs but potentially requiring additional storage expenses.

Discount Rate

The discount rate is set at 8%, representing the the Weighted Average Cost of Capital (WACC). The WACC reflects the true cost of financing by considering the balance between debt and equity in the capital structure, and it accounts for the risks associated with the project. This approach helps capture the required returns for investors and lenders, ensuring consistency with broader financial strategies. Additionally, WACC includes tax benefits from debt, providing a more realistic assessment of the project's economic feasibility, making it a crucial component of Levelized Cost of Fuel calculations for eSAF projects (Franc-Dąbrowska et al., 2021).

Operational Hours

Fuel synthesis is assumed to run continuously for 8,000 hours annually. Although storage of hydrogen, CO_2, or syngas could facilitate intermittent operation, the high CAPEX of DAC and both electrolysis technologies and expensive storage supports the assumption of continuous operation to improve cost efficiency by distributing capital expenses over larger production volumes.

Parameter	Value	Unit
Thermal energy price	0	€/MWh
Electricity price	60	€/MWh
Discount rate	8	%
Operational hours	8000	Hours/year

Table 4.7: Economic parameters

4.2. Levelized Cost Analysis

Section 4.2 addresses the second sub-question, **How do the identified technologies perform in their overall costs?** by first calculating the CO_2 costs for DAC and other alternatives. These costs serve as a crucial input for determining the Levelized Cost of Fuel. The LCOF is then calculated for various technological pathways, incorporating different carbon sources, electrolysis technologies, and fuel synthesis methods. These are compared against the cost of fossil kerosene, factoring in the forecasted carbon prices under the EU Emissions Trading System.

4.2.1. Levelized cost of CO2

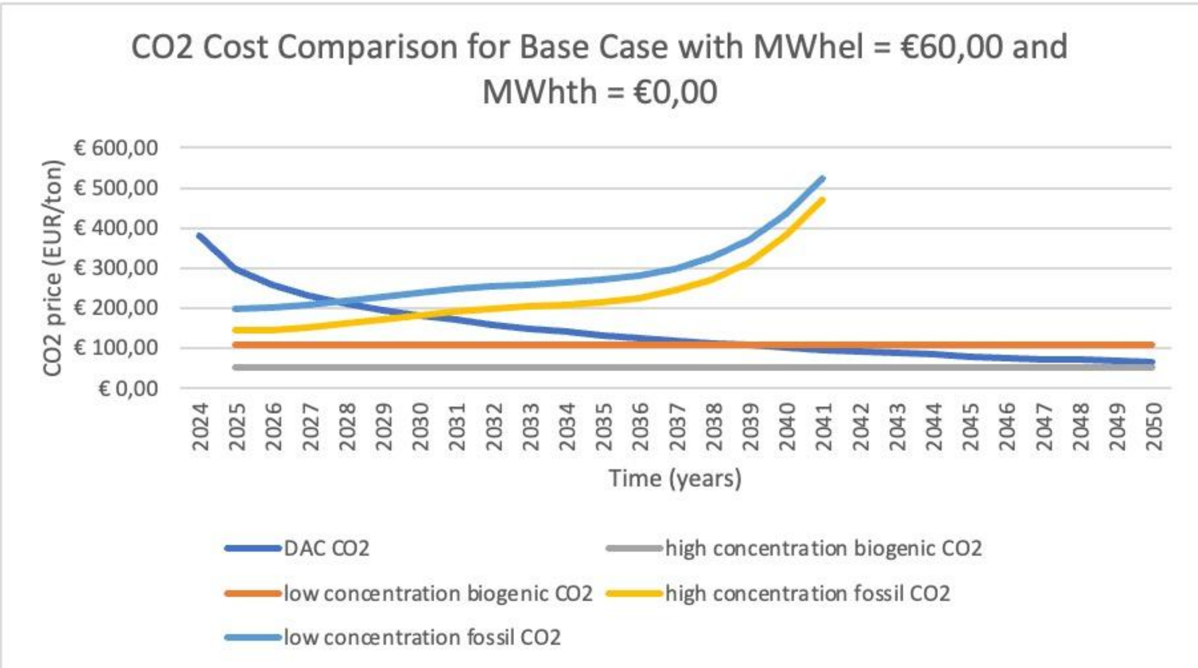


Figure 4.6: CO_2 cost comparison for base case comparing DAC and the proposed CO_2 sources from table 4.4. The base case assumes MWhel = €60,00 and MWhth = €0,00

Figure 4.6 illustrates a comparison of CO_2costs from various sources, including DAC, biogenic CO_2, and fossil PSC CO_2, across different concentrations over the period 2024-2050. It shows that the cost of CO_2 captured via direct air capture remains higher than other CO_2 sources until 2028. From 2028 onward, DAC becomes cheaper than low-concentration fossil CO_2, and by 2030, it is less expensive than high-concentration fossil CO_2. The rising cost of CO_2under the EU ETS drives up the costs for fossil-based CO_2 sources, which is already a significant cost component in 2025, with prices nearing €100/ton. DAC surpasses low-concentration biogenic CO_2 in cost efficiency for the first time in 2040. While DAC CO_2 prices approach those of high-concentration biogenic CO_2, the latter remains the cheapest option throughout the data set at 52,80 €/ton.

To maintain clarity in the next section, only DAC and high-concentration biogenic CO_2 were compared in the technological pathways analysis, as high-concentration biogenic CO_2 remains the most cost-effective CO_2 source. Differences between other CO_2 sources will be referenced from Figure 4.6.

4.2.2. Levelized cost of eSAF Outlook

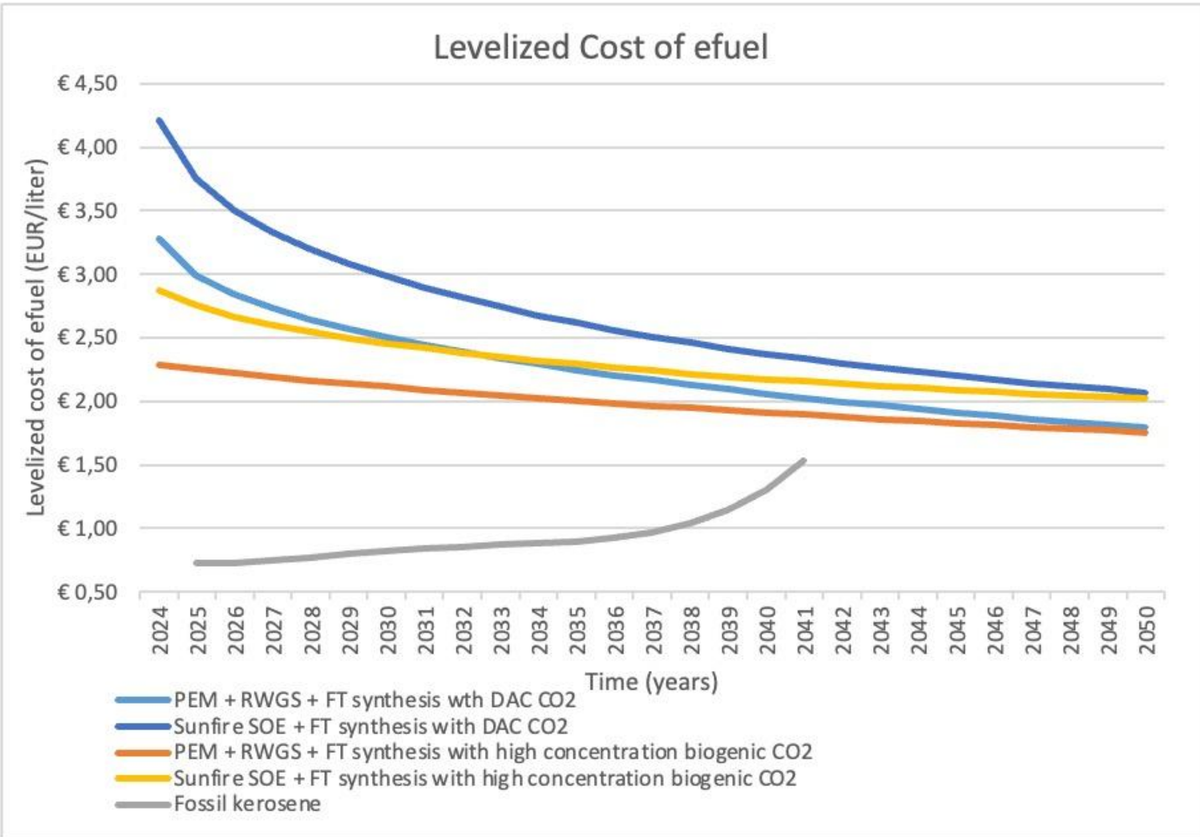


Figure 4.7: Levelized cost of e-fuel for base case with MWhel = €60,00 and MWhth = €0,00

Figure 4.7 presents the alternative technological routes and feedstocks studied, alongside the fossil kerosene price, which includes EU ETS costs. As anticipated from earlier results, the most expensive alternative, represented by the dark blue line, includes DAC. Despite experiencing the largest cost reduction, from €4.20/liter to €2.07/liter, DAC combined with co-electrolysis and Fischer-Tropsch synthesis remains the costliest route throughout the period up to 2050. Depending on whether EU ETS costs are applied to fossil kerosene, which may not occur until the free allocation of credits ends in 2026, this alternative is currently 6 to 9 times more expensive than fossil kerosene.

On the other hand, the cheapest current eSAF option is PEM + RWGS + FT with biogenic CO_2, indicated by the orange line, with a levelized cost of €2.27/liter in 2024. This technology is currently 4 to 5 times more expensive than fossil jet fuel and remains the most cost-effective throughout the timeline.

The light blue line, which shows PEM + RWGS + FT with DAC, is initially more expensive than co-electrolysis + FT with biogenic CO2 (yellow line). However, by 2033, it becomes more cost-effective than yellow.

The levelized cost of fossil kerosene is described by the dark grey line seen moving upwards until 2041. This can be attributed to the EU ETS price, as no other data is incorporated into this price besides an average EU jet fuel price based on the Jet Fuel Price Monitor from IATA (*Jet Fuel Price Monitor*, n.d.). Due to an increasing amount of uncertainty in future EU ETS price predictions and limited data on such predictions, the levelized cost of jet fuel is depicted until 2041.

By 2050, the levelized cost of eSAF is projected to approach either €1.80 or €2.00 per liter, depending on the electrolysis technology used, with PEM being the more cost-effective option. When compared to the furthest projected fossil kerosene price estimate, which is 2041, all eSAF production pathways in 2050 are expected to range from 1 to 2 times the cost of fossil kerosene.

4.3. Levelized Cost Breakdown

To address the third sub question, " **What are the key cost drivers within each eSAF technology, and how do these components evolve over time?**", the following section presents a detailed breakdown of the levelized cost of eSAF for the years 2024, 2035, and 2050. Several production pathways are analyzed, incorporating different electrolysis technologies combined with either direct air capture or biogenic CO_2 sources. An alternative representation of the results is provided in Appendix H. The normalized cost breakdown per technological pathway highlights the distribution of individual cost components and offers insights into how these components evolve over time, helping to identify the key parameters that most significantly impact the levelized cost of that specific technology. Following this, a sensitivity analysis was conducted to examine the impact of economic model parameters, ensuring a comprehensive understanding of their effects on the techno-economic performance of eSAF.

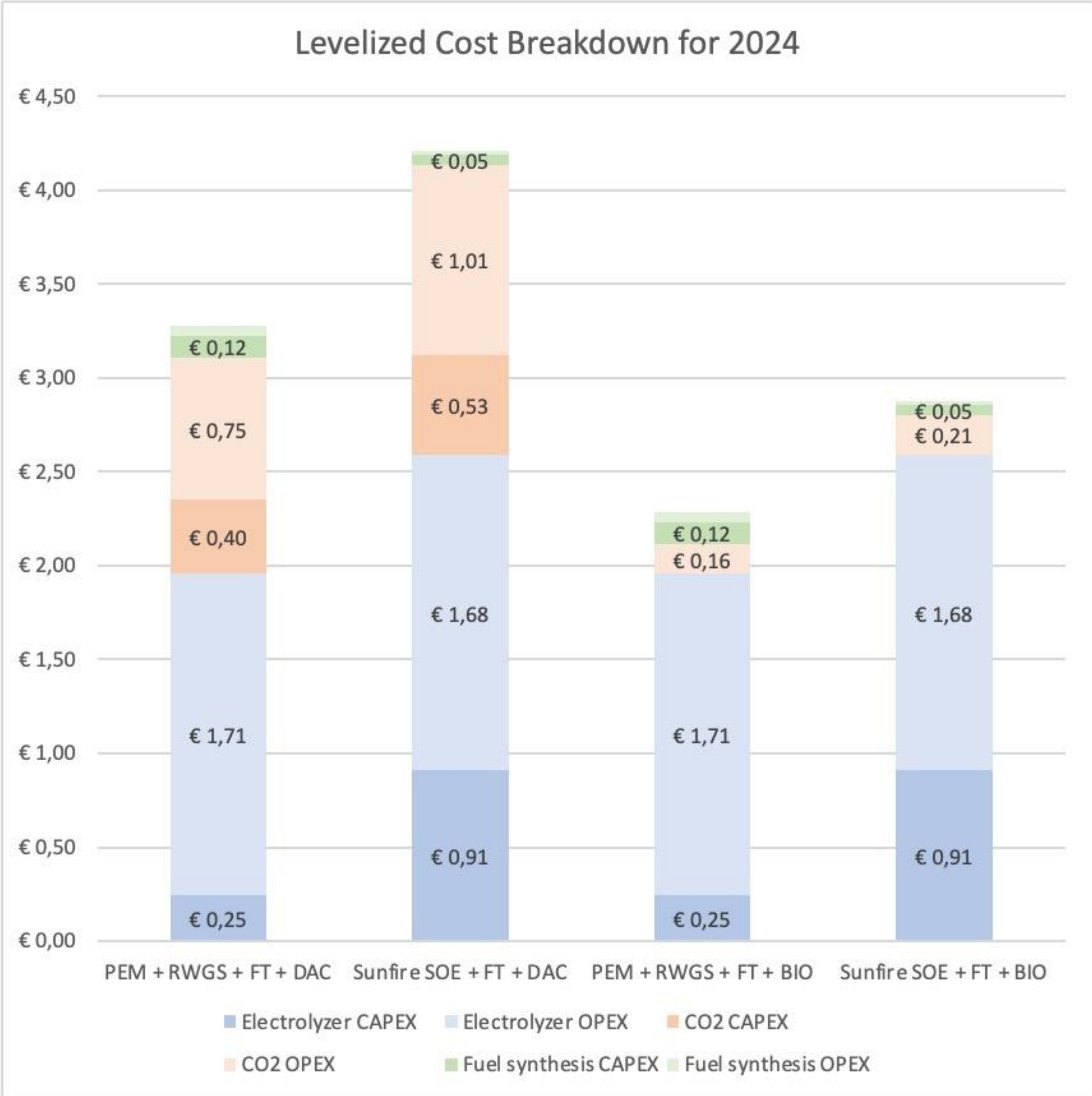


Figure 4.8: Levelized cost breakdown for 2024. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 sourcing (orange) and fuel synthesis (green).

In all technological pathways described above, costs are primarily driven by the electrolyzer, represented by the light and dark blue sections, ranging between 59,7% (PEM +RWGS + FT + DAC) and 90,11% (Sunfire SOE + FT + BIO). Specifically, the operating expenditures of the electrolyzer constitute the largest cost component. The CO_2 costs in the first two pathways (column 1 and 2) are higher than those in the last two, as these pathways incorporate direct air capture. DAC-related CO_2 costs are predominantly OPEX, whereas biogenic CO_2 is classified entirely as OPEX. While there are capital expenditures associated with CO_2 capture equipment, these were not distinguished from operating expenditures in the capture data. Since CO_2 capture forms the largest portion of biogenic CO_2-related costs, and additional costs for purification, liquefaction, and transport are relatively small, these are not individually detailed.

When comparing PEM technology (columns 1 and 3) with SOE technology (columns 2 and 4), PEM emerges as the more cost-effective option. Although SOE has slightly lower OPEX costs (€1,68 vs €1,71), its CAPEX is more than four times higher. Additionally, the PEM pathways require less CO_2, as evidenced by the lower CO_2 costs in column 1 compared to column 2, and similarly in column 3 compared to column 4.

Fuel synthesis costs contribute the least to the levelized cost of eSAF. The operational expenditures for fuel synthesis are too small to be labeled in Figure 5.5 but account for €0.02 or €0.05 per liter of eSAF, with the higher costs associated with the use of a reverse water-gas shift reactor, corresponding with higher fuel synthesis CAPEX. While fuel synthesis is not OPEX-dominated, both electrolysis and CO_2 capture are OPEX-heavy across all pathways, making the levelized cost of eSAF predominantly OPEX-driven.

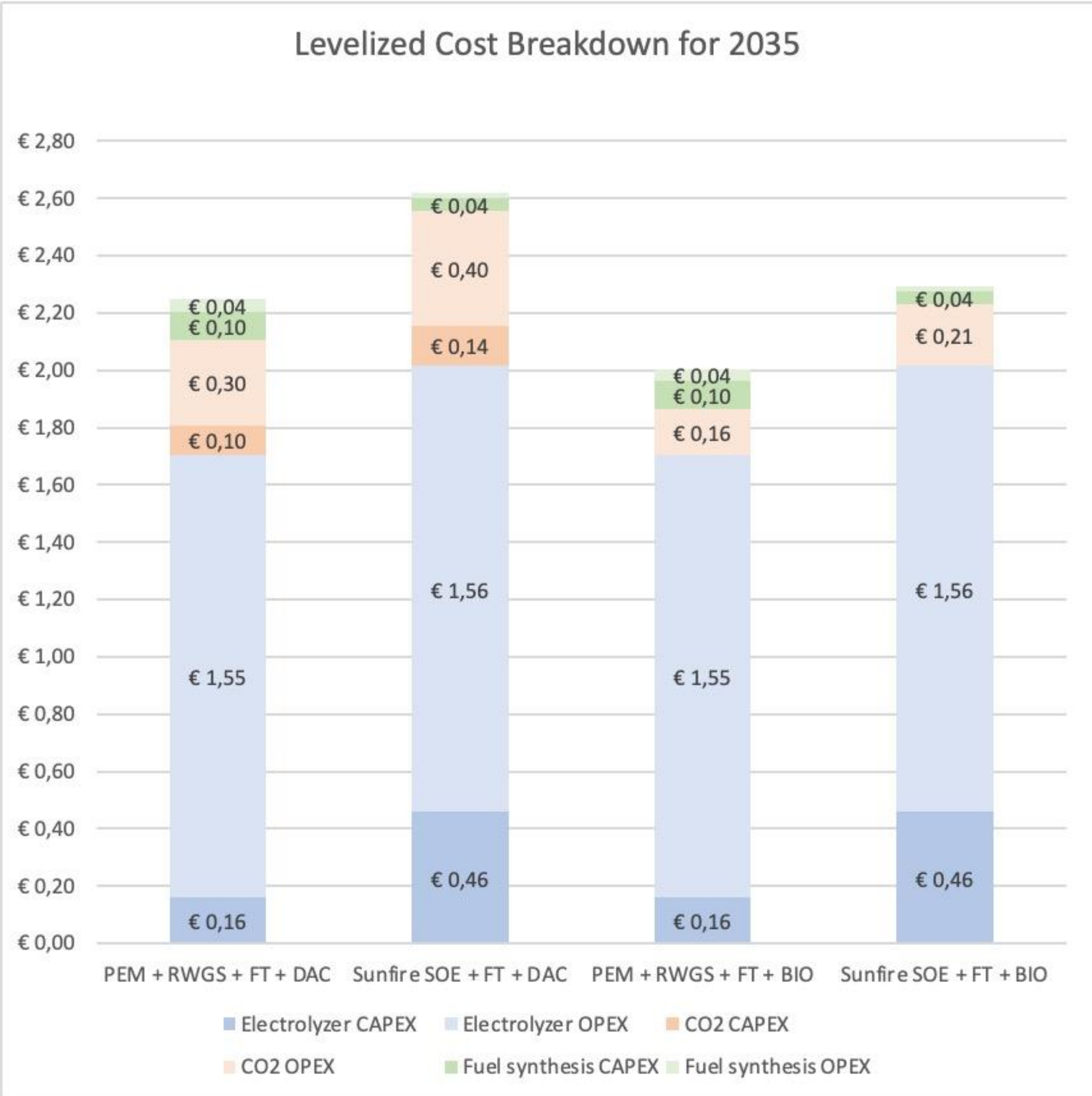


Figure 4.9: Levelized cost breakdown for 2035. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 sourcing (orange) and fuel synthesis (green).

Looking at Figure 5.6 and comparing it to 2024, PEM + RWGS + FT + DAC and Sunfire SOE + FT + DAC experience the largest cost reductions, primarily driven by decreasing CAPEX and OPEX for DAC CO_2. Proportionally, the CAPEX reduction is greater than the OPEX reduction, leading to a higher relative share of OPEX compared to CAPEX for DAC, as compared to 2024 levels. Since DAC sees the most significant decrease in costs, an even larger proportion of the total costs are now attributed to the electrolyzer. For pathways incorporating DAC in 2035, the electrolyzer's cost share increases substantially, rising from 59.7% to 75.9% for PEM + RWGS + FT + DAC, and from 60.7% to 77.1% for Sunfire SOE + FT + DAC.

When examining Figure 4.7, it can be observed that PEM + RWGS + FT with DAC was initially more expensive than co-electrolysis + FT with biogenic CO_2. However, by 2033, it becomes more cost-effective. Figure 4.9 illustrates that this shift is driven by technological advancements in DAC and PEM, compared to a constant biogenic CO_2 price and slower cost reductions for SOE.

Consistent across all pathways, the electrolyzer cost breakdown shows a decreasing share of CAPEX while the share of OPEX rises. As noted above, DAC becomes increasingly OPEX-dependent due to the larger reduction in CAPEX, further shifting the overall cost structure toward operational expenditures, reinforcing the growing dominance of OPEX. Conversely, for pathways utilizing biogenic CO_2 (third and fourth columns), the total share of costs (CAPEX + OPEX) attributed to electrolysis decreases compared to 2024, reflecting the different cost dynamics associated with biogenic CO_2 capture.

SOE OPEX costs are now also higher than PEM OPEX costs. This shift further amplifies the cost differences between the two technologies, with SOE facing both higher OPEX and significantly greater CAPEX compared to PEM. This contributes to PEM remaining the more cost-effective option overall.

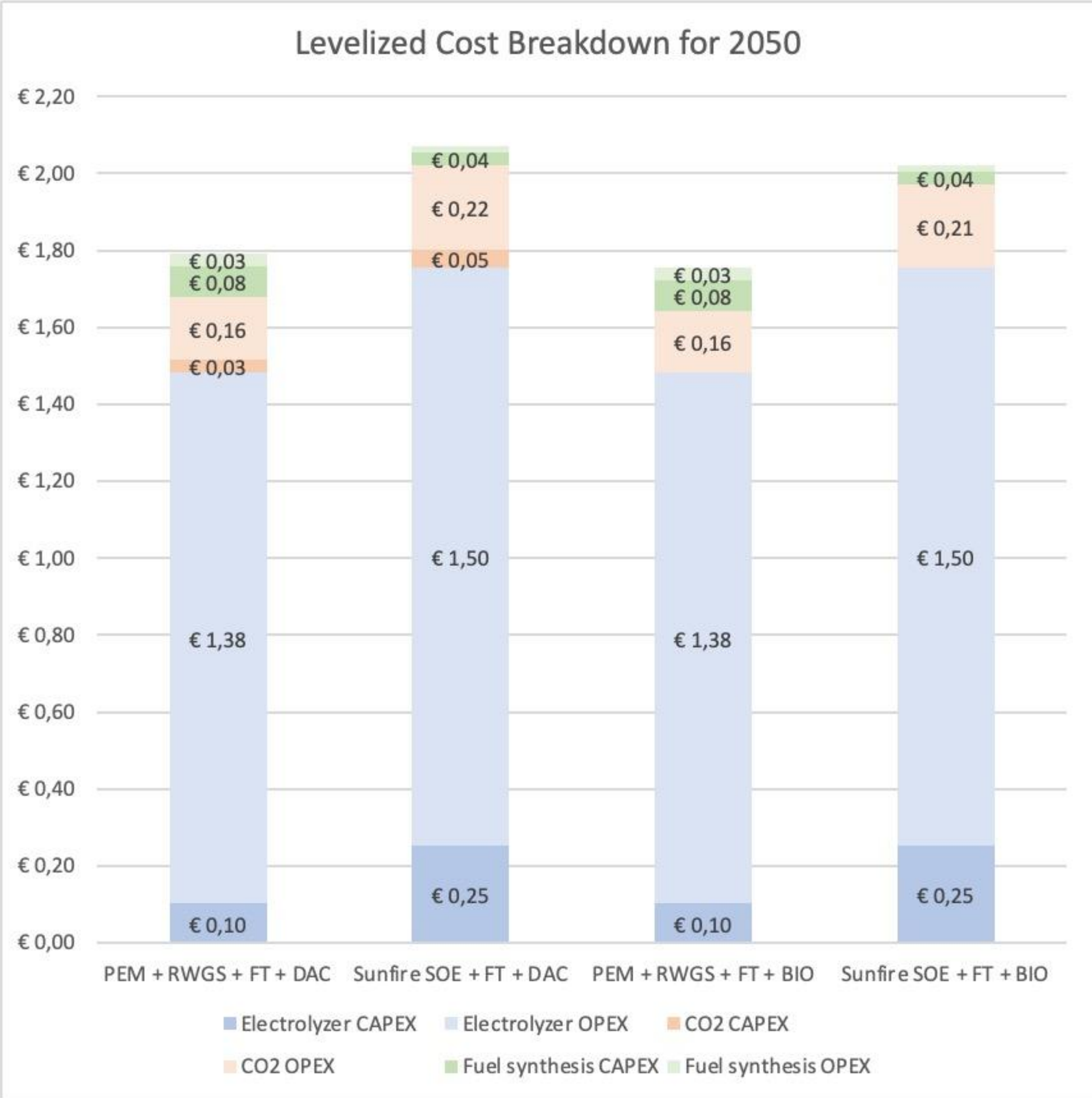


Figure 4.10: Levelized cost breakdown for 2050. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 sourcing (orange) and fuel synthesis (green).

Figure 5.7 presents the cost breakdown for the year 2050 and illustrates why the levelized costs for eSAF are grouped around specific price levels based on the electrolysis technology used, as noted in Section 4.2.2. This occurs due to two factors: first, DAC CO_2 costs approach biogenic CO_2 costs, narrowing the cost differences between pathways that use different CO_2 sources but the same electrolysis technology. Second, pathways utilizing co-electrolysis (columns 2 and 4) require more CO_2, resulting in higher CO_2 costs, but this is nearly offset by the additional fuel synthesis costs associated with the RWGS reactor needed for the technology pathways in columns 1 and 3. As a result, electrolysis technology becomes the defining cost component. Additionally, the shift toward a higher proportion of OPEX in the overall cost structure continues.

4.4. Sensitivity Analysis

4.4.1. Levelized cost of CO_2

In Appendix I, various model scenarios are examined to assess the impact of different factors on CO_2 pricing. The first scenario explores the case where insufficient waste heat is available, requiring the purchase of additional waste heat at €10/MWh. The second and third scenarios analyze CO_2 costs under different electricity prices, specifically €80/MWh and €40/MWh, both within the range reported in the literature. Additionally, upper and lower bounds for the EU ETS price are tested. Lastly, the effect on CO_2 prices when DAC operates for 4,000 hours per year is modeled. The scenarios are summarized in the table below.

Parameter	**Unit**	**Base Case**	**Thermal energy**	**Upper Bound electricity**	**Lower Bound Electricity**	**Upper Bound EU ETS**	**Lower Bound EU ETS**	**4000 Operational Hours**
Electricity price	€/MWhel	60	60	**80**	**40**	60	60	60
Thermal energy price	€/MWhth	0	**10**	0	0	0	0	0
EU ETS price	€/ton CO2	EU ETS trendline	EU ETS trendline	EU ETS trendline	EU ETS trendline	**SA UB trendline**	**SA LB trendline**	EU ETS trendline
Run time	Hours per year	8000	8000	8000	8000	8000	8000	**4000**

Table 4.8: Parameters for the levelized cost of CO_2: sensitivity analysis

The key takeaway is that in all scenarios that result in higher DAC CO_2 costs, DAC still becomes cost competitive with fossil-based CO_2 sources before 2036. This is notable as 2036 marks the earliest phase-out of certain fossil-based CO_2 sources. Additionally, the lowest CO_2 price, €50,20, is achieved by high-concentration biogenic CO_2 in the lower bound electricity scenario where the electricity price is set at €40/MWh. In this same scenario, DAC CO_2 nearly reaches cost parity with high-concentration biogenic CO_2 in 2050.

The most significant negative impact on DAC CO_2 prices occurs when operational hours drop from 8,000 to 4,000 annually. This delays the cost advantage over low- and high-concentration fossil alternatives to 2032 and 2035, respectively. In this scenario, DAC only surpasses low-concentration biogenic CO_2 in 2046, compared to 2039 in the base case. Also, In 2050, DAC CO_2 costs are €87,51 more than €20,- higher than the cost per ton in the base case.

While a 50% reduction in operational hours may seem extreme, it is realistic given the variability in renewable energy capacity factors. Offshore wind in Europe typically has a 30% capacity factor, onshore wind around 20%, and solar PV averages 10% (Bolson et al., 2022). These figures are European averages, and higher capacity factors do exist in certain regions with more favorable wind or solar conditions. Yet, even when integrating these renewable sources into a hybrid energy system, projecting DAC facilities to operate for 4,000 hours annually may still be an optimistic estimate.

4.4.2. Levelized cost of eSAF

The table below outlines the economic parameters used in the sensitivity analysis. Electricity prices were selected based on values reported in the literature and are sufficiently varied to show their impact on costs. Discount rates of 6% and 10% were used to reflect common values for renewable energy projects and higher-risk electrolysis and CCS projects, respectively (Burchardt et al., 2023; Irena, 2020).

Parameter	Unit	Base Case	Upper Bound Electricity	Lower Bound Electricity	Upper Bound WACC	Lower Bound WACC	4000 Operatio-nal Hours
Electricity price	€/MWhel	60	**80**	**40**	60	60	60
WACC	%	8	8	8	**10**	**6**	8
Run time	Hours per year	8000	8000	8000	8000	8000	**4000**

Table 4.9: Parameters for the levelized cost of eSAF: sensitivity analysis

Electricity Price

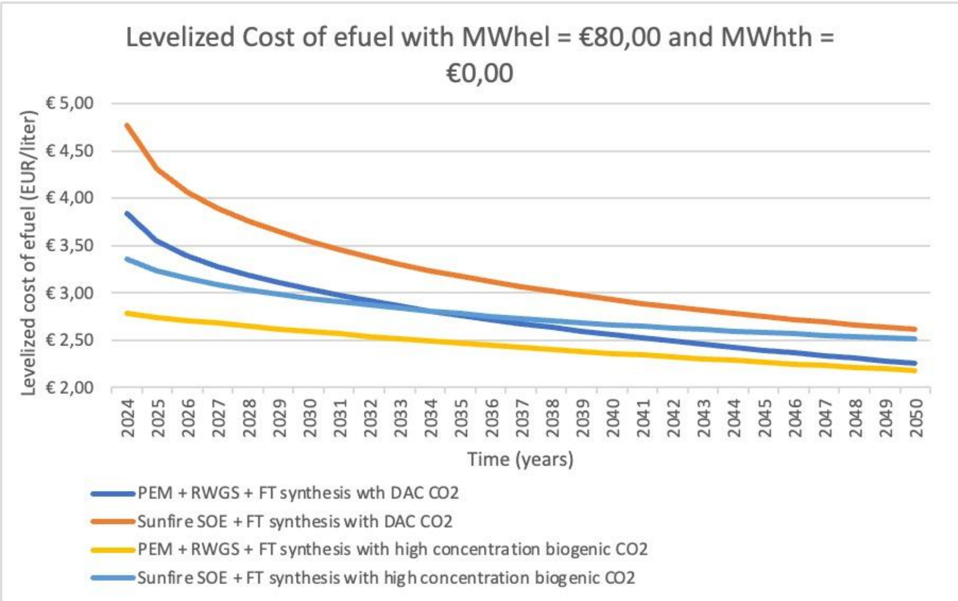


Figure 4.11: Levelized cost of e-fuel for Upper Bound Electricity case with MWhel = €80,00 and MWhth = €0,00

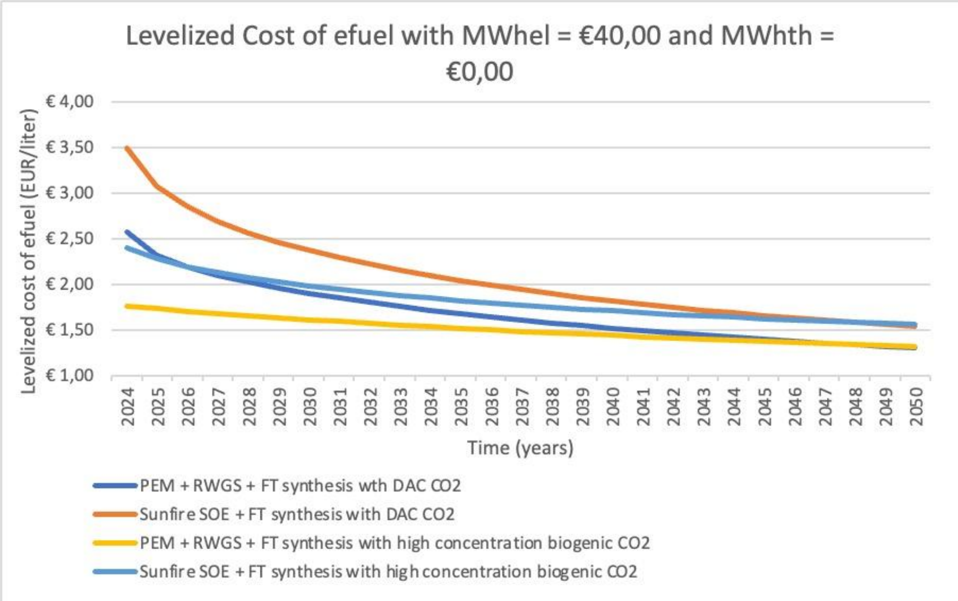


Figure 4.12: Levelized cost of e-fuel for Lower Bound Electricity case with MWhel = €40,00 and MWhth = €0,00

In 2024, the Upper Bound Electricity case led to costs ranging from 2.78 €/liter to 4.77 €/liter. When the electricity price was decreased to €40/MWh, costs ranged between 1.76 €/liter and 3.49 €/liter, compared to our base case range of 2.27 €/liter to 4.13 €/liter. By 2050, costs diverged in a pattern similar to the base case. This effect was amplified in the lower electricity price scenario and reduced in the higher price scenario, as also indicated by the shift of the intersection point between the dark (PEM + RWGS + FT + DAC) and light blue (Sunfire SOE + FT + BIO) lines. When looking out to 2050, a higher electricity price resulted in costs per liter ranging from 2.18 €/liter to 2.61 €/liter, while the lower bound electricity price led to costs between 1.31 €/liter and 1.55 €/liter.

Weighted Average Cost of Capital

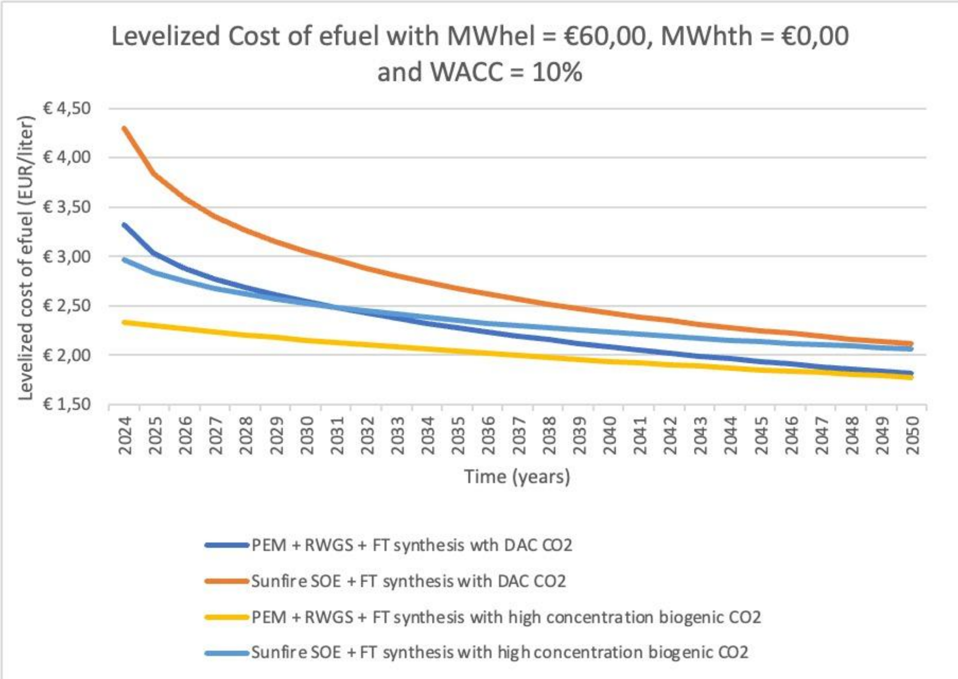


Figure 4.13: Levelized cost of e-fuel for Upper Bound WACC case with MWhel = €60,00 and MWhth = €0,00 and WACC = 10%

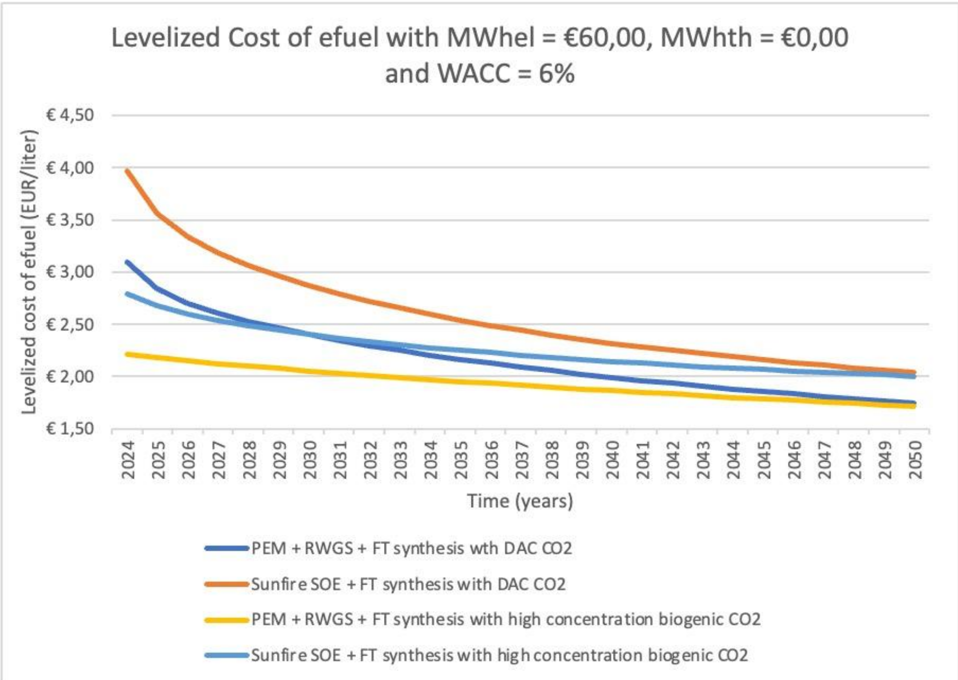


Figure 4.14: Levelized cost of e-fuel for Lower Bound WACC case with MWhel = €60,00 and MWhth = €0,00 and WACC = 6%

For 2024, costs ranged between 2.33 €/liter and 4.30 €/liter with a WACC of 10%, and between 2.21 €/liter and 3.97 €/liter with a WACC of 6%. By 2050, a WACC of 10% resulted in costs ranging from 1.78 €/liter to 2.12 €/liter, while a 6% WACC led to a cost range of 1.72 €/liter to 2.04 €/liter.

Operational Hours

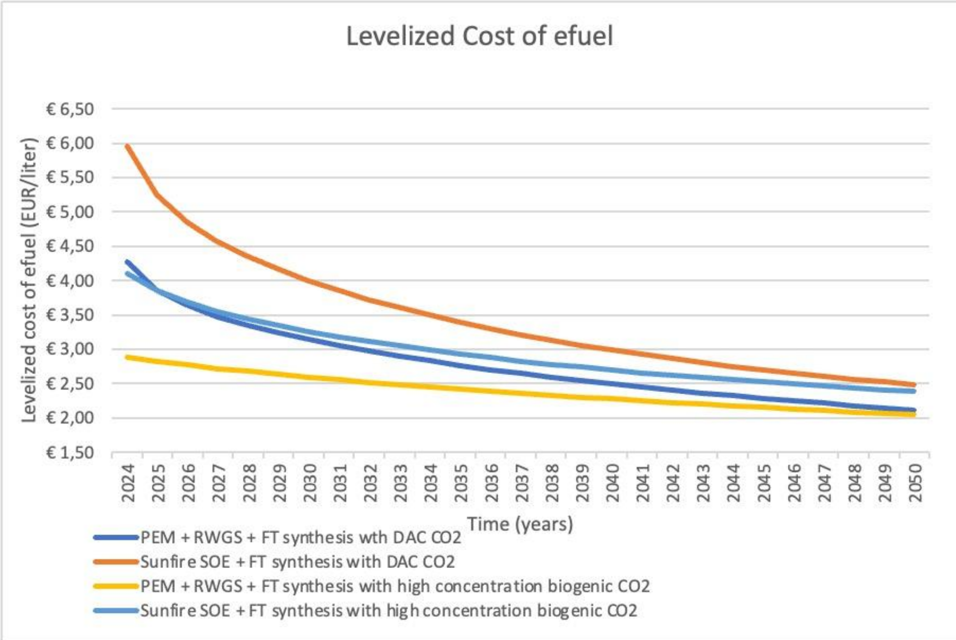


Figure 4.15: Levelized cost of e-fuel for 4000 Operational Hours with MWhel = €60,00 and MWhth = €0,00

Reducing the number of operational hours had a negative impact on all technologies. In 2024, the largest effect was observed on Sunfire SOE + FT + DAC (orange), followed by Sunfire SOE + FT + BIO (light blue), PEM + RWGS + FT + DAC (dark blue), and finally PEM + RWGS + FT + BIO (yellow). Costs for 2024 ranged between 2.88 €/liter and 5.96 €/liter. By 2050, technologies utilizing PEM converged slightly above 2 €/liter, while those incorporating SOE converged below 2.50 €/liter.

Technological Development: SOE

The efficiency of solid oxide electrolysis differs from that of co-electrolysis through SOE because, in co-electrolysis, additional energy is required to convert CO2 into CO. This process benefits from shared thermal energy, improving overall efficiency by reducing energy losses compared to separate conversions of water and CO2. However, while efficiency data for SOE is available, we found little to no data on the current and future efficiencies of co-electrolysis. Consequently, our co-electrolysis efficiency is based on the Sunfire model and remains constant, leading to an unequal comparison with PEM efficiencies beyond 2024, as PEM effiencies are modeled to improve. As electrolyzer OPEX was identified as the largest contributor to costs, the carbon efficiency was calculated, and electrical efficiency data was retrieved from a feasibility study on syngas production through SOE conducted by ISPT (Institute for Sustainable Process Technology) and TNO (van ’t Noordende et al., 2023). These parameters were incorporated into the model as an additional technology option to provide insights into the sensitivity of solid oxide electrolyzer performance specifications. The data can be found in the table below.

	Sunfire		**ISPT**	
CO2 input	730	kg/h	190	ton/h

Syngas output	750	nm^3/h	110	ton/h
Carbon efficiency	67	%	80	%
Electrical efficiency	82	%	92	%

Table 4.10: Performance specs of the different solid oxide electrolyzers

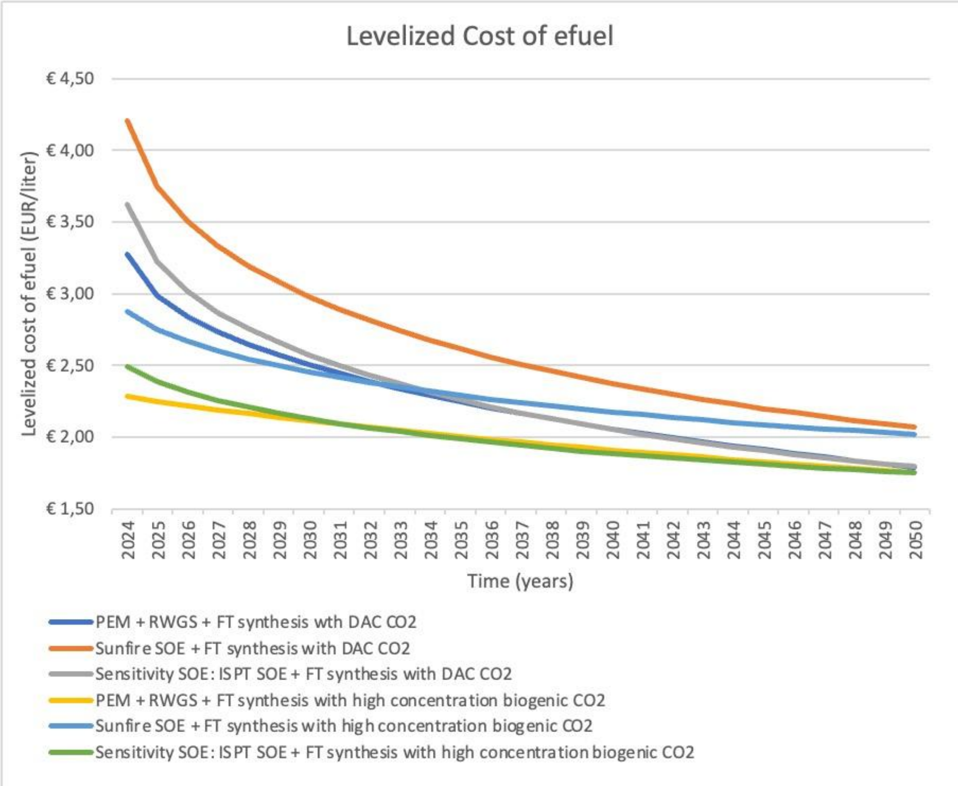


Figure 4.16: Levelized cost of e-fuel with additional solid oxide electrolyzer

On the short term, the ISPT SOE + FT + BIO (green line) reaches cost parity with the lowest levelized cost highlighted by yellow in 2032 at 2,07 €/liter. From 2035 onwards, ISPT SOE + FT + DAC (grey line) and PEM + RWGS + FT + DAC (dark blue) exihibits a similar converging pattern. In 2050, all 4 technologies approach a similar price point, ranging between 1.75 and 1.80 €/liter, depending on whether DAC is used or not. From 2034 onwards, grey outperforms its competing solid oxide electrolysis technology coupled with cheaper biogenic CO2 (light blue).

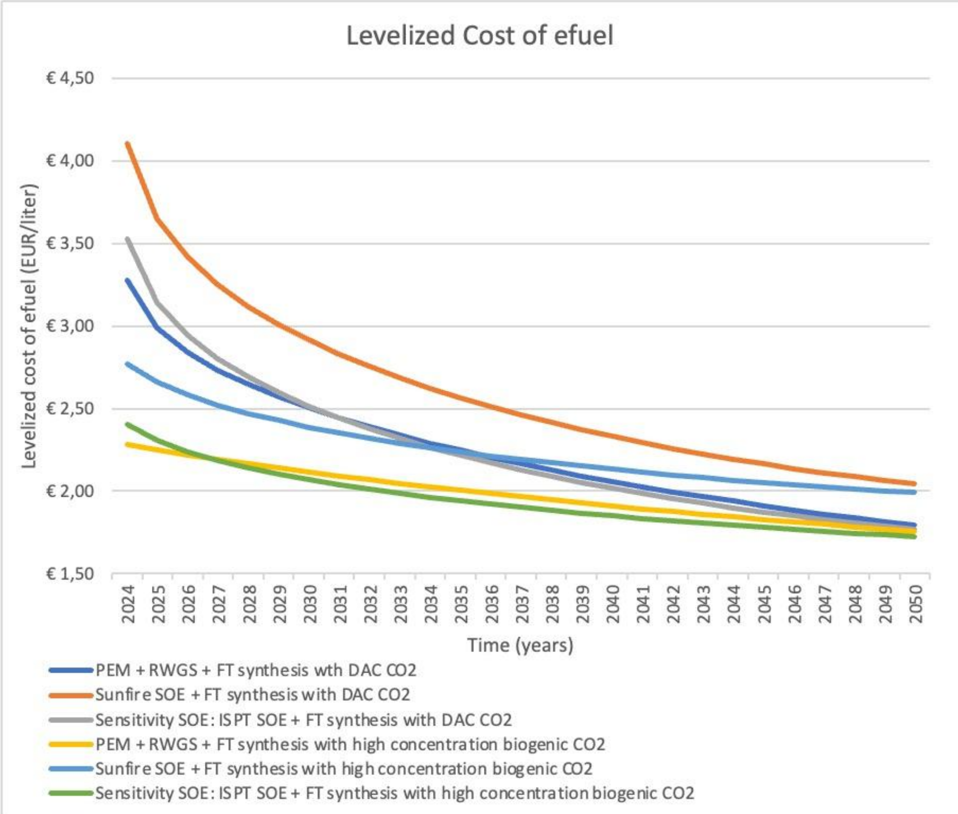


Figure 4.17: Levelized cost of e-fuel with additional solid oxide electrolyzer and lifetime of all SOE technologies extended to 20 years

The ISPT report identified cell degradation as a critical factor in reducing costs (van ’t Noordende et al., 2023). This directly impacts electrolyzer CAPEX, the second-largest cost component after OPEX, as it determines the operational lifetime of the technology. In the graph above, the assumption of an extended SOE technology lifetime from 10 to 20 years has been made to enable a more equal comparison with PEM technologies. As a result of this extended lifetime, OPEX has been also adjusted to account for necessary stack replacements, similar to the PEM approach. Figure 4.17 shows how this assumption results in ISPT SOE + FT + BIO (green line) having the lowest levelized cost of e-fuel from 2027 onwards, reaching a low of 1.73 €/liter by 2050.

4.5. Wrap up

Chapter 4 presented the core findings of the thesis, addressing the techno-economic performance and cost drivers of sustainable aviation fuel (SAF) production pathways. The chapter evaluated competing technologies based on the levelized costs of fuel, incorporating direct air capture (DAC) and biogenic CO_2 sources while comparing electrolysis and synthesis technologies, such as proton exchange membrane (PEM) electrolysis, solid oxide electrolysis (SOE), and Fischer-Tropsch (FT) synthesis. It detailed the underlying assumptions, model framework, and cost components, including carbon sourcing, purification, and transport. Sensitivity analyses highlighted the impact of factors such as electricity price, operational hours, and technology lifetimes on SAF costs. The results revealed key cost drivers, with DAC-related CO_2 costs and electrolysis expenditures dominating, and identified PEM as the most cost-effective electrolysis technology under the given assumptions. The chapter concluded with insights into how advancements in DAC, SOE, and CO_2 efficiencies could influence the future competitiveness of SAF pathways.

5. Discussion

5.1 delves into the interpretation of the results, providing an analysis of the findings from both the socio-technical and techno-economic perspectives. Following this, the methodology and data are critically examined in 5.2, with separate reflections on the limitations encountered in the socio-technical and techno-economic analyses. Concluding in 5.3 discusses the academic relevance of the study and identifies future research areas that could substantiate the conclusions or broaden the scope of this research.

5.1. Interpreting Results

5.1.1. General Remarks

While the technologies included in the techno-economic analysis were derived from the socio-technical analysis, the costs of alternative technologies were not modeled. Consequently, it cannot be definitively stated that the most cost-effective option is among the technologies analyzed here, particularly given the limitations of the socio-technical analysis, which will be discussed later in this chapter. For a thorough assessment, it is essential to evaluate the costs of other potentially viable technologies as well. Preliminary analysis suggests that CSP holds high potential and should be further investigated prior to making investment decisions, ensuring a comprehensive consideration of cost-effective SAF options. Additionally, methanol pathways should be assessed as it is possible this technology is certified soon (Eyberg et al., 2024).

The analysis found that the most feasible short-term option for eSAF production is locating plants in regions with an electricity grid with over 90% renewables, like Norway or Iceland. However, not all projects can be situated in these areas due to the need for increased capacity. While self-generating renewable energy could be cheaper than grid purchases, it requires costly storage, and intermittent operation may be more economical, though this has not been analyzed alongside capital-intensive DAC.

In the future, coupling eSAF production with nuclear energy should be reconsidered, given the EU's pressing need to expand grid capacity to meet 2050 aviation mandates. This raises the question of whether allocating the currently limited renewable electricity supply for CO_2 capture from air is the most efficient approach, particularly when CO_2 from hard-to-abate sectors is readily available and being emitted. Our analysis indicated that this approach is economically viable under the modeled DAC technological advancements and projected increases in EU ETS prices. However, the potential for future regulatory adjustments to stabilize the EU ETS market could undermine the economic case for DAC (Kopernikus-Projekt Ariadne, 2023). Furthermore, economic viability does not imply greater CO_2 reduction potential, as greater reductions could be achieved by capturing fossil CO_2 from point sources and directly using renewable electricity in alternatives like electric vehicles.

The IPCC climate plan incorporates DAC as a crucial measure to address historical emissions and mitigate temperature overshoots resulting from delayed transitions (Masson-Delmotte et al., 2018). Similarly, IATA emphasizes the necessity of removing 500 million tons of carbon annually to offset aviation emissions, highlighting a role for DAC specifically for permanent removal, excluding its use in fuel production (Appendix E). In a net-zero framework, scaling both DAC and fossil CO_2 capture—whether for eSAF production or carbon storage—is critical to achieving overall emissions reductions. However, once transitional fossil CO_2 is no longer permitted, DAC should already be developed and scaled to ensure the continued economic viability of eSAF production. Identifying locations without alternative CO_2 sources strengthens the business case for DAC.

That said, discussions around eSAF production should focus more on hydrogen production rather than DAC usage relative to other CO_2 sources. Electrolyzers, required for hydrogen production, are extremely energy-intensive and account for the majority of renewable energy demand in eSAF production. In contrast, DAC consumes significantly less electricity and will remain essential for scaling net-negative emissions technologies to address historical emissions and mitigate temperature overshoots. Efficiently allocating renewable energy resources to decarbonization efforts with the highest global warming reduction potential, alongside expanding renewable energy capacity, is essential. This is particularly important for energy-intensive and relatively inefficient processes such as eSAF production (Appendix F).

5.1.2. Techno-Economic Analysis

The techno-economic analysis assessed the levelized cost of eSAF in €/liter, comparing it with the cost of fossil kerosene including EU ETS costs. The objective was to identify the most cost-effective eSAF technologies over time, factoring in technological progress and evolving policies. The most economical technology, PEM + RWGS + FT with biogenic CO_2, was priced at €2.27/liter and consistently remained the least expensive option, though still 4 to 5 times higher than the cost of fossil jet fuel. In contrast, DAC combined with co-electrolysis and Fischer-Tropsch synthesis remained the priciest route, dropping from €4.20/liter to €2.07/liter by 2050 but costing 6 to 9 times more than fossil kerosene at current prices, contingent on EU ETS implementation expected by 2026. By 2033, PEM + RWGS + FT with DAC became more cost-effective than co-electrolysis + FT with biogenic CO_2, due to improvements in DAC and PEM technology. By 2050, eSAF costs are expected to range between €1.80 and €2.00 per liter, with technologies incorporating PEM emerging as the more economical option. Electrolysis technology will become the primary cost driver, as DAC CO_2 costs converge with biogenic CO_2 costs. Although co-electrolysis pathways require more CO_2, higher CO_2 costs are nearly offset by lower fuel synthesis costs without a RWGS reactor, emphasizing the role of electrolysis as the defining cost component.

When analyzing the cost structure and its evolution over time, a distinct pattern emerges. System OPEX and electrolyzer costs dominate overall expenses. For technologies utilizing DAC, the share of electrolyzer costs increases over time, driven by a decreasing share of CAPEX and rising share of OPEX. This shift occurs because efficiency improvements in DAC technology increase the amount of CO_2 captured per machine, reducing CAPEX per ton of CO_2 while lowering OPEX through decreased energy consumption. Consequently, the electrolyzer's cost share grows, meaning its cost and performance improve at a lower rate than DAC. This effect is more pronounced with SOE, as no efficiency gains are modeled. In contrast, for technologies using biogenic CO_2, the overall share of the electrolyzer costs diminishes over time, as there are no other components experiencing significant efficiency gains. This results in an almost stable cost distribution compared to DAC technologies throughout the years.

When examining CO_2 costs, biogenic CO_2 remains the most cost-effective option across the data, although DAC could achieve comparable prices by 2050 if electricity costs drop to €40/MWh. Biogenic CO_2 is preferred over DAC, with the choice between the two in the future depending significantly on the availability of high-concentration biogenic CO_2 sources (Williams, 2015). This effect is expected to intensify as fossil CO_2 sources become more expensive or phased out due to rising carbon prices or regulatory constraints. However, costs for low-volume capture and transport of CO_2 can reach up to €100/ton, particularly in regions without established carbon infrastructure, according to industry expert interviews (McKenna et al., 2024). By eliminating the need for CO_2 transport, DAC enables eSAF facilities to be strategically located near renewable energy sources and export ports, reducing logistical and infrastructure challenges. Consequently, carbon feedstock options should be assessed locally for new eSAF sites, as high-concentration biogenic CO_2 priced at approximately €50/ton represents a modeled minimum.

DAC CO_2 becomes more cost-effective than fossil-based alternatives in all sensitivity scenarios by 2036. Consequently, if transitional legislation aims to mandate the use of DAC and biogenic CO_2 over fossil sources, it would have limited impact according to our calculations and sensitivity analysis, as DAC becomes more cost-effective before these mandates take effect. Thus, to be meaningful, this legislation should be advanced or reconsidered altogether. However, the current system of free allowances under the EU ETS allows industries to supply fossil CO_2 at a lower cost because they do not pass along the full EU ETS price to CO_2 consumers. This effectively subsidizes fossil CO_2, creating a competitive disadvantage for DAC and biogenic CO_2. This imbalance could delay the transition to DAC as a primary carbon source for eSAF, hindering its development and broader adoption as a sustainable aviation fuel solution.

Possible interventions to eliminate the unfair advantage of fossil sectors receiving free allowances when supplying CO_2 feedstock include accelerating the phase-out of free allowances under the EU ETS, which would remove the implicit subsidy benefiting fossil CO_2 sources and create a more level playing field for DAC and biogenic CO_2. Another approach could involve providing subsidies for DAC to reduce costs and boost adoption by eSAF producers. Additionally, implementing a policy that mandates the passing of total carbon prices to downstream carbon capture and utilization processes would ensure the environmental cost of using fossil CO_2 is reflected in pricing. Finally, establishing a reward system for prevented emissions when using carbon-neutral options, such as biogenic or DAC CO_2, instead of fossil CO_2 in CCU applications would incentivize the shift to sustainable carbon sources.

The sensitivity analysis highlighted the urgent need for low-cost electricity. Although periods of free electricity occur in the Netherlands during sunny conditions, primarily due to an oversupply of PV capacity relative to flexible demand, reliable and cost-effective storage solutions are essential to ensure a stable and affordable electricity supply year-round. For projects like this, maintaining consistent electricity would require oversizing a hybrid PV and wind farm to charge storage systems, enabling energy availability even during low wind or solar conditions. These additional costs should be integrated into the levelized cost of renewable electricity. This is especially important in the near term, as most technologies still have high capital expenditures that are more negatively impacted by reduced operating hours.

To meet future demand, substantial investments in capacity expansion, infrastructure, and storage are needed, particularly as other sectors also electrify to achieve decarbonization goals.

The sensitivity analysis also demonstrated the impact of SOE specifications on costs. Although cost data could be averaged from literature given the minimal adjustments needed for SOE to perform co-electrolysis, information on electrical efficiency was limited, and carbon efficiency has rarely been researched due to the traditionally lower value assigned to carbon as feedstock. Higher carbon efficiency, however, reduces CO_2 requirements, significantly affecting costs when integrated with DAC. Combined with higher electrical efficiency, an SOE with specifications as outlined in the ISPT report was shown to meet levels of the most cost-effective option by 2032 in our base case. Although the report's specifications for SOE technology may not yet be fully attainable, they underscore the significant potential of SOE. This technology might prove even more promising than the current analysis suggests, as no efficiency improvements were modeled for SOE. In contrast, PEM technology incorporated efficiency gains, with electrolyzer efficiency improving from 63% to 71% in 2050. Additionally, with improved stack lifetime, SOE becomes the preferred electrolysis option based on techno-economic analysis from 2027 onward, highlighting the need for continuous development of this technology.

A final note on interpreting results for all novel technologies in this study is that all projected cost declines rely on a CAPEX degression curve aligned with future price forecasts. Achieving these forecasted prices requires continuous investment and adoption of improved technologies. Consequently, while cost estimates are most accurate for 2024, without ongoing advancements, costs may remain elevated longer than anticipated, underscoring the need for continuous innovation to realize the technological progress essential to reach cost estimations outlined in this study.

5.2. Reflection on Method and Data Limitations

5.2.1. Socio-Technical Analysis

The TIS framework provided a robust structure for analyzing the socio-technical system of eSAF technologies. By conducting a literature review to map the technological landscape and grouping technologies based on their function, the approach allowed for an organized assessment of various components using technical criteria. The approach's strengths included its ability to clearly link technological components to actor roles, aiding the actor analysis and identifying regulatory bodies for the institutional analysis. Examining the networks further accounted for the broader socio-technical environment. By developing criteria grounded in the problem statement and insights from technology, actor, policy, and network analyses, the method ensured a holistic evaluation of both technological performance and socio-political factors.

However, the criteria developed in this research are not exhaustive and would require expert validation before being applied to make investment decisions. There are undoubtedly additional criteria that have not been captured, and the relative importance of each criterion may vary, suggesting that some should carry more weight than others. Furthermore, the scores assigned to technological components were based on a relative comparison, which introduces subjectivity and invites further scrutiny. Similarly, identifying the threshold at which a technology was deemed "critical"—indicating it failed to meet the criteria in a significant and prohibitive way—also involved subjective judgment. A "critical" score meant the technology was excluded from further consideration in the TEA. While this approach needs refinement and consensus from industry experts, this research makes a start in assessing the strengths and weaknesses of each technology, how they compare, and what successful projects have in common.

An example of the non-exhaustiveness of the criteria is the omission of cost-effectiveness for different electricity options. While we used the levelized cost of electricity of renewable electricity in general for the cost analysis, cost-effectiveness was not captured in any criteria and, therefore, not included in the analysis. This omission was primarily due to the complexity of calculating these costs, especially when comparing options like heat from CSP, with electricity from intermittent renewables and stable nuclear energy. Accurately assessing costs would require incorporating storage and flexibility measures necessary to meet system requirements, which introduces further layers of complexity. Designing a comprehensive plant that accounts for these factors is a research topic in itself and was beyond the scope of this study.

5.2.2. Techno-Economic Analysis

Limitations of this method largely stem from model structure and data constraints. Model limitations concern how variables are represented within the model. This includes assumptions about their behavior, the formulas or functional relationships applied, and decisions about which variables are static or dynamic. While the model design choices were justified and generally aligned with literature, they may not represent the only valid approach. Forecasting inherently grows less reliable over time, as uncertainty increases. Introducing randomness into forecasts using a Monte Carlo simulation could enhance robustness by applying a normal distribution to certain price ranges, although setting these price ranges experiences similar issues.

Model Limitations

Model limitations were primarily related to assumptions about cost evolution, depreciation, and selectively applied efficiency gains. LCOF calculations faced challenges in estimating depreciation periods for emerging technologies, as their lifespans remain uncertain, adding risk to long-term forecasts. The CAPEX degression curve, designed based on future price forecasts, relied heavily on the chosen formula, meaning that CAPEX values between forecast points were shaped by the curve’s chosen trajectory. Even the values for forecasted years depended on how well the curve fit the available data points, affecting the projected cost trajectory.

Another limitation involved treating certain costs, like electricity, as static rather than dynamic, despite the potential for significant shifts due to geopolitical or market factors, as seen during the Russia-Ukraine conflict. Efficiency gains were also modeled selectively: while DAC received detailed CAPEX degression modeling, only linear improvements were applied to electrolysis and fuel synthesis technologies. For SOE, neither carbon nor electrical efficiency gains were included at a model level. This lack of modeled efficiency improvements for SOE was due to data constraints, as no adequate data was available to support these improvements—a point further discussed in the data limitations section. Additionally, the comparison of industrial data for DAC and SOE with theoretical data for biogenic CO_2, PEM and fuel synthesis may have introduced an inconsistency, underscoring the need for more standardized data across all technologies to ensure reliable projections.

Data Limitations

Data limitations in this analysis were influenced by both the scope, quantity and quality of the data sources. Our review was based on a limited selection of articles, which may not fully encompass the range of existing studies. Different search terms or methodologies could have led to alternative articles, potentially introducing different values into the model. Additionally, not all data points were directly comparable, as scaling factors varied between sources. While some studies presented values optimized for size, others did not account for such adjustments, leading to inconsistencies.

Several specific data limitations apply, which is not uncommon for emerging technologies like solid oxide co-electrolysis, direct air capture and RWGS reactors. For co-electrolysis, cost data for solid oxide electrolysis could be applied due to minimal technology adjustments needed for syngas production. However, efficiency data could not be directly used, as the energy output of syngas differs from hydrogen. Additionally, carbon efficiency, a metric not widely used as carbon is often treated as a waste product rather than valuable feedstock, was unavailable.

Short-term DAC efficiency data, though current, was sourced exclusively from a single industry partner, Skytree, potentially introducing bias. Similarly, limited cost data for certain components, like the RWGS reactor, forced reliance on a small number of sources, which may have impacted the robustness of cost forecasts, though this was a minor cost component. Furthermore, while some sources provided detailed near-term performance data, reliable long-term data for future efficiency gains and technological improvements was scarce. As a result, while short-term cost estimates (e.g., for 2024) are likely accurate, long-term forecasts carry greater uncertainty, underscoring the evolving nature of these technologies and the need for ongoing research and data collection.

5.3. Academic Relevance & Future Research

This research contributes to the academic understanding of sustainable aviation fuel pathways by providing actionable insights into the feasibility and a tool to research cost dynamics of SAF technologies. By introducing accurate DAC data and integrating it with novel co-electrolysis technologies, alongside comparisons to alternative pathways, these contributions set the first steps for advancing SAF deployment and serve as a springboard for future research. Future research should extend the socio-technical analysis by incorporating industry expert interviews. Additionally, the criteria used for evaluating alternatives should be expanded and weighted to better capture socio-political and technical factors, improving the robustness of future assessments.

Further exploration is required to assess biogenic CO_2 availability, its proximity to renewable energy hotspots and more detailed levelized cost. Investigating CO_2 transportation costs, especially in regions lacking pipeline infrastructure, is essential. This includes costs for evaluating the feasibility and costs of pipeline construction or alternative transportation methods like via trucks, which could significantly impact the scalability of eSAF production.

the costs of capture equipment (CAPEX) must be examined in more detail, as biogenic CO_2 costs are not entirely composed of OPEX, contrary to some simplified assumptions.

Solid oxide electrolysis performance in co-electrolysis presents another critical area of study. Improved data on SOE electrical and carbon efficiencies are necessary, along with a detailed evaluation of stack lifetime, which is currently assumed to be 10 years but may be shorter for emerging technologies. These insights would refine cost projections and enable a more accurate assessment of SOE's potential.

Optimization of plant size and energy storage solutions, particularly for renewable energy and eSAF production systems, is also a priority. Studies should address molar and heat flow dynamics and the efficiency of syngas production, which involves both hydrogen and carbon monoxide. The high-temperature requirements for SOE were assumed to be met by the exothermic FT synthesis in the analysis. However, if this integration does not materialize as expected, the overall efficiency of SOE could drop significantly, as additional external energy would be required to maintain the necessary operating temperatures. Establishing a clearer definition for co-electrolysis efficiency in these contexts would aid in evaluating system performance.

Additionally, more detailed cost and performance data are needed for reverse water gas shift reactors, which are often modeled as part of a single process with Fischer-Tropsch synthesis. Assumptions made in this analysis to allocate efficiency gains and cost reductions between RWGS and FT should be validated through further study to ensure accuracy.

Finally, future work should analyze the factors driving long-term electricity price reductions, such as renewable energy expansion, grid and storage development, and policy incentives, while considering potential external disruptions. These studies would improve the accuracy of long-term cost projections and help ensure the economic feasibility of eSAF technologies at scale, as these are largely dependent on the electricity price.

6. Conclusion

This thesis combined a socio-technical and a techno-economic analysis. The socio-technical analysis used a literature review to examine technologies, actors, institutions, and networks, identifying technologies for further study and criteria for successful EU implementation. The subsequent techno-economic analysis evaluated the costs of selected technologies and feedstocks through a levelized cost analysis. Together, these analyses addressed the main research question: **How can sustainable aviation fuel (SAF) be developed within the EU, specifically considering technologies that incorporate direct air capture (DAC)?**

6.1. Sub Questions and Key Findings

SQ 1: Which sustainable aviation fuel (SAF) technologies are promising for short-term viability in the EU, considering the current socio-technical system?

To analyze how technologies interacted with the socio-technical system, a literature review provided an overview of relevant technologies, followed by an assessment of the actors, institutions, and networks supporting their functionality, as outlined in the first step of the Technological Innovation System (TIS) framework. Insights from these analyses and the problem statement informed the development of technical requirements for assessing the technologies. This led to the selection of fossil, biogenic (BIO) and direct air capture (DAC) carbon sources coupled with proton exchange membrane electrolysis (PEM), reverse water-gas shift (RWGS) reactor, and Fischer-Tropsch (FT) synthesis, as well as solid oxide co-electrolysis (SOE) with Fischer-Tropsch (FT) synthesis, for further study.

Non-technical requirements essential for short-term implementation were derived from the socio-technical analyses. The actor and network analysis emphasized that the development of new sustainable aviation fuel (SAF) capacity should, at a minimum, involve fuel conversion technology providers, knowledge institutes, and airlines. Additionally, energy providers, feedstock suppliers, and infrastructure providers play crucial roles and are highly interconnected, highlighting the importance of collaboration across the supply chain. High costs, economies of scale, narrow profit margins, and low initial demand necessitated collective investments, with IATA potentially coordinating efforts, particularly in EU states with specific synthetic sustainable aviation fuel (eSAF) regulations. Strategically, eSAF production sites should prioritize proximity to renewable energy generation to reduce grid congestion and to fueling infrastructure to minimize logistical costs. Renewable-heavy grids in regions like Iceland or Norway were identified as ideal short-term locations, addressing intermittency despite higher costs. Locating facilities in areas without alternative carbon sources strengthened the business case for direct air capture by reducing reliance on limited carbon infrastructure. The policy analysis highlighted the need for a level playing field between green and fossil-based carbon sources, as free allowances under the EU ETS could unfairly favor fossil CO_2. Timely phasing out of these credits is necessary to support DAC and biogenic CO_2 adoption. While short-term efforts focus on leveraging renewable-heavy grids, coupling eSAF production with nuclear energy presents a potential long-term strategy for providing stable, low-carbon energy, aligning with the EU's 2050 mandates.

SQ 2: How do the identified technologies perform in their overall costs?

A levelized cost analysis (LCA) was conducted to calculate the cost of sustainable aviation fuel (SAF). Data on the performance of these technologies was sourced from literature, while direct air capture (DAC) data was provided by Skytree.

The section begins by calculating CO_2 costs for DAC and other alternatives, which are essential inputs for determining the levelized cost of fuel. In this analysis, DAC CO_2 costs were initially higher than other sources but became cheaper than low-concentration fossil CO_2 by 2028 and high-concentration fossil CO_2 by 2030. Rising EU ETS carbon prices, nearing €100/ton by 2025, significantly increased fossil CO_2 costs. DAC surpassed low-concentration biogenic CO_2 in cost efficiency by 2040, while high-concentration biogenic CO_2 remained the most cost-effective option throughout at €52.80/ton. This prompted the focus on DAC and high-concentration biogenic CO_2 in further analyses, as these represent the most competitive and relevant options for the technological pathways.

The analysis compared the levelized cost of various eSAF technologies and feedstocks with fossil kerosene, which included EU ETS costs. The most expensive option, DAC combined with solid oxide co-electrolysis (SOE) and Fischer-Tropsch (FT) synthesis, saw the largest cost reduction from €4.20/liter to €2.07/liter by 2050 but remained the costliest route throughout the period, currently 6 to 9 times more expensive than fossil kerosene. The cheapest pathway, proton exchange membrane electrolysis (PEM) coupled with reverse water-gas shift (RWGS) reactor, Fischer-Tropsch (FT) synthesis and biogenic CO_2, was priced at €2.27/liter in 2024 and remained the most cost-effective, though still 4 to 5 times more expensive than fossil jet fuel. By 2033, proton exchange membrane electrolysis (PEM) coupled with reverse water-gas shift (RWGS) reactor, Fischer-Tropsch (FT) synthesis and DAC became more economical than solid oxide co-electrolysis (SOE) with Fischer-Tropsch (FT) synthesis and biogenic CO2. By 2050, all synthetic sustainable aviation fuel (eSAF) pathways are expected to cost between €1.80 and €2.00/liter, with proton exchange membrane electrolysis (PEM) technology emerging as the most economical and eSAF prices ranging from 1 to 2 times the cost of fossil kerosene. Since the trajectory of EU ETS prices, particularly beyond 2041—the limit of current forecasts in this model—remains uncertain, regulatory adjustments to the EU ETS market dynamics should be closely monitored. Such adjustments will play a critical role in determining direct air capture's competitiveness against fossil CO_2 sources and the economic viability of synthetic sustainable aviation fuel compared to fossil kerosene.

SQ 3: What are the key cost drivers within the identified SAF technologies, and how do these components evolve over time?

To address the third sub-question on key cost drivers within eSAF pathways and their evolution over time, the analysis presented a detailed levelized cost assessment for 2024, 2035, and 2050, incorporating CAPEX and OPEX of various electrolyzer types, CO_2 sources (DAC or biogenic), and fuel conversion technologies. A normalized cost breakdown highlighted the distribution and evolution of cost components per pathway.

For 2024, costs across all pathways were dominated by electrolyzer contributions, with OPEX as the largest component. This OPEX share grew over time, particularly for solid oxide electrolysis (SOE) technologies, as their efficiency remained constant, unlike proton exchange membrane electrolysis (PEM), which improved. In 2024, solid oxide electrolysis OPEX costs were lower than proton exchange membrane electrolysis but were outweighed by its significantly higher CAPEX costs. Since biogenic CO_2 prices remained constant while DAC costs declined, biogenic pathways experienced a greater decrease in the share of other components. For DAC pathways, rising electrolyzer OPEX shares offset declining CAPEX shares, resulting in a growing combined share of electrolyzer costs, whereas biogenic CO_2 pathways saw a slight reduction in the total share of electrolyzer costs through 2050. Fuel synthesis costs contributed minimally to the total cost, highlighting the OPEX-heavy nature of both electrolysis and CO_2 capture as the primary determinants of synthetic sustainable aviation fuel (eSAF) levelized costs.

A sensitivity analysis assessed the impact of economic model parameters on the levelized cost of CO_2 and the techno-economic performance of eSAF. In all scenarios, DAC CO_2 costs became competitive with fossil-based CO_2 sources before the 2036 phase-out of certain fossil alternatives, prompting reconsideration of these transitional timelines. The lowest CO_2 price of €50.20 was achieved by high-concentration biogenic CO_2 under a low electricity price scenario (€40/MWh), where DAC nearly reached cost parity by 2050. However, biogenic CO_2 availability remains location-dependent due to limited capture incentives and high potential transport costs in regions lacking CO_2 infrastructure. A reduction in operational hours from 8,000 to 4,000 annually had the most significant negative effect, delaying cost competitiveness with alternatives and raising 2050 DAC costs by over €20/ton compared to the base case. Given the capacity factors of renewable energy sources, even 4,000 operational hours annually may be an optimistic assumption under hybrid energy systems.

Within the limits of the sensitivity analysis, an electricity price of €40/MWh resulted in the lowest LCOF at €1.76/liter for 2024. Conversely, a reduction in operational hours to 4000 caused the largest price increase under current conditions, as the high CAPEX of current systems meant that costs were distributed over fewer hours, significantly raising the levelized cost of fuel.

To further explore key cost drivers, Institute for Sustainable Process Technology (ISPT) solid oxide co-electrolysis (SOE) performance data were analyzed, focusing on electrical and carbon efficiency, as well as extended technology lifetimes. This analysis addressed the significant impact of electrolyzer OPEX, the largest cost component, and CAPEX through technology lifespan, offering insights into how improvements in solid oxide electrolysis performance could enhance the economic feasibility of sustainable fuel production. While prices converge to similar price levels in 2050, does solid oxide co-electrolysis (SOE) becomes the preferred electrolysis option under these conditions based on techno-economic analysis from 2027 onward, highlighting the need for continuous development of this technology.

To further explore key cost drivers, Institute for Sustainable Process Technology (ISPT) solid oxide co-electrolysis (SOE) performance data were analyzed with a focus on electrical and carbon efficiency, as well as extended technology lifetimes, given that electrolyzer costs constitutes the largest cost component. This analysis provided insights into how performance improvements in solid oxide co-electrolysis could enhance the economic feasibility of sustainable aviation fuel production. Although prices for all pathways converge by 2050, solid oxide co-electrolysis emerged as the preferred electrolysis option under these conditions based on techno-economic analysis from 2027 onward, emphasizing the critical need for continued development of this technology.

6.2. Answering the Main Research Question

How can sustainable aviation fuel (SAF) be developed within the EU, specifically considering technologies that incorporate direct air capture (DAC)?

The EU has recognized the need to reduce emissions in the aviation sector, implementing mandates to support its decarbonization. However, the high costs of emerging technologies, combined with limited airline investment, have created a chicken-and-egg problem that hinders the scaling of installed capacity. Addressing these challenges requires solutions that are sustainable, cost-effective, aligned with regulatory targets, and scalable to meet future demand. Identified technological pathways were assessed based on their ability to meet these criteria, address renewable electricity challenges, and integrate with direct air capture systems.

Without reiterating what has already been addressed by answering the sub-questions, this research primarily contributed by offering practical criteria to support the industry in establishing successful sustainable aviation fuel (SAF) projects and identifying regulatory issues requiring attention from policymakers, backed by sensitivity analysis findings. While the levelized cost analysis aligned with existing literature, it also provided accurate DAC data for other researchers, highlighting the critical role of carbon efficiencies in fuel production and their impact on the costs of advanced pathways like co-electrolysis. Comparative analysis offered new insights into how this technology could become a leading option if key barriers, such as efficiency improvements and cost reductions, are addressed. From a systemic perspective, long-term strategies to reduce costs should prioritize expanding grid capacity and implementing storage solutions to address renewable energy intermittency effectively.

7. Bibliography

Abdulkareem-Alsultan, G., Asikin-Mijan, N., & Taufiq-Yap, Y. H. (2020). Future aviation biofuel, efficiency and climate change. In *Green energy and technology* (pp. 505–522). https://doi.org/10.1007/978-981-15-5667-8_20

Anderson, T. R., Hawkins, E., & Jones, P. (2016). CO2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour*, *40*(3), 178–187. https://doi.org/10.1016/j.endeavour.2016.07.002

Andika, R., Nandiyanto, A. B. D., Putra, Z. A., Bilad, M. R., Kim, Y., Yun, C. M., & Lee, M. (2018). Co-electrolysis for power-to-methanol applications. *Renewable and Sustainable Energy Reviews, 95*, 227–241. https://doi.org/10.1016/j.rser.2018.07.030

Amhamed, A. I., Al Assaf, A. H., Le Page, L. M., & Alrebei, O. F. (2024). Alternative sustainable aviation fuel and energy (SAFE)-A Review with selected simulation cases of study. *Energy Reports, 11*, 3317-3344. https://doi.org/10.1016/j.egyr.2024.03.002

Bachmann, T. M. (2020). Considering environmental costs of greenhouse gas emissions for setting a CO2 tax: A review. *Science of the Total Environment*, *720*, 137524. https://doi.org/10.1016/j.scitotenv.2020.137524

Ballal, V., Cavalett, O., Cherubini, F., & Watanabe, M. D. B. (2023). Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios. *Fuel, 338*, 127316. https://doi.org/10.1016/j.fuel.2022.127316

Becattini, V., Gabrielli, P., & Mazzotti, M. (2021). Role of carbon capture, storage, and utilization to enable a net-zero-CO2-emissions aviation sector. *Industrial & Engineering Chemistry Research, 60*(18), 6848-6862. https://dx.doi.org/10.1021/acs.iecr.0c05392?ref=pdf

Benson, C. L., & Magee, C. L. (2014). On improvement rates for renewable energy technologies: Solar PV, wind turbines, capacitors, and batteries. *Renewable Energy, 68*, 745–751. https://doi.org/10.1016/j.renene.2014.03.002

Bergero, C., Gosnell, G., Gielen, D., Kang, S., Bazilian, M., & Davis, S. J. (2023). Pathways to net-zero emissions from aviation. *Nature Sustainability*, *6*(4), 404–414. https://doi.org/10.1038/s41893-022-01046-9

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy, 37*(3), 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Bolson, N., Prieto, P., & Patzek, T. (2022). Capacity factors for electrical power generation from renewable and nonrenewable sources. *Proceedings of the National Academy of Sciences, 119*(52). https://doi.org/10.1073/pnas.2205429119

Branker, K., Pathak, M. J. M., & Pearce, J. M. (2011). A review of solar photovoltaic levelized cost of electricity. *Renewable and sustainable energy reviews, 15*(9), 4470-4482.

Carbon Gap. (n.d.). *The different types of carbon removal technologies*. carbongap.org. https://carbongap.org/infographics/?utm_source=substack&utm_medium=email

Burchardt, J., Hegnsholt, E., Holm, M., Klose, F., Ritter, D., & Schönberger, S. (2023). *Turning the European Green Hydrogen Dream into Reality: A Call to Action* [Report]. Boston Consulting Group. https://media-publications.bcg.com/Turning-the-European-Green-H2-Dream-into-Reality.pdf

Chiaramonti, D. (2019). Sustainable Aviation Fuels: the challenge of decarbonization. *Energy Procedia*, *158*, 1202–1207. https://doi.org/10.1016/j.egypro.2019.01.308

Choe, C., Cheon, S., Gu, J., & Lim, H. (2022). Critical aspect of renewable syngas production for power-to-fuel via solid oxide electrolysis: Integrative assessment for potential renewable energy source. *Renewable and Sustainable Energy Reviews, 161*, 112398. https://doi.org/10.1016/j.rser.2022.112398

Cifuentes-Faura, J. (2022). European Union policies and their role in combating climate change over the years. *Air Quality, Atmosphere, & Health, 15*(8), 1333–1342. https://doi.org/10.1007/s11869-022-01156-5

Council of the EU. (2023). *RefuelEU aviation initiative: Council adopts new law to decarbonise the aviation sector* [Press release]. https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/

Creswell, J. W. (1994). *Research Design: Qualitative, quantitative, and mixed methods approaches*. http://www.revistacomunicacion.org/pdf/n3/resenas/research_design_qualitative_quantitative_and_mixed_methods_approaches.pdf

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A. J., & Sheikh, A. (2011). The case study approach. *BMC Medical Research Methodology*, *11*(1). https://doi.org/10.1186/1471-2288-11-100

D'Adamo, I., Gastaldi, M., Giannini, M., & Nizami, A. (2024). Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen. *Environmental Research*, 118163. https://doi.org/10.1016/j.envres.2024.118163

Dietrich, R., Adelung, S., Habermeyer, F., Maier, S., Philippi, P., Raab, M., & Weyand, J. (2024b). Technical, economic and ecological assessment of European sustainable aviation fuels (SAF) production. *CEAS Aeronautical Journal, 15*(2), 161–174. https://doi.org/10.1007/s13272-024-00714-0

DiMartino, B. B. (2023). Direct Air Capture as a Carbon Removal Solution: Analyzing Scale-Up, Cost Reduction, and Pathways for Acceleration (Doctoral dissertation, Massachusetts Institute of Technology). MIT Theses. https://hdl.handle.net/1721.1/152729

Dray, L., Schäfer, A., Grobler, C., Falter, C., Allroggen, F., Stettler, M., & Barrett, S. R. H. (2022). Cost and emissions pathways towards net-zero climate impacts in aviation. *Nature Climate Change*, *12*(10), 956–962. https://doi.org/10.1038/s41558-022-01485-4

Erriu, R., Marcucci, E., & Gatta, V. (2024). Facilitating a sustainable aviation fuel transition in Italy. *Energies, 17*(14), 3388. https://doi.org/10.3390/en17143388

European Biogas Association. (2022). *Biogenic CO2 from the biogas industry*. https://www.europeanbiogas.eu/wp-content/uploads/2022/10/Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf

European Commission. (2021). *The European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2022). *European Green Deal: New rules agreed on applying the EU emissions trading system in the aviation sector* (Press Release IP/22/7609). European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7609

European Commission. (2023). *Commission sets out rules for renewable hydrogen.* Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/ip_23_594

European Commission. (2023). *What is the Innovation Fund?* Retrieved from https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/what-innovation-fund_en

European Commission. (2024). *Horizon Europe.* Research and Innovation. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

European Commission. (n.d.). *EU Emissions Trading System (EU ETS).* Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (n.d.) *Innovation Fund*. Climate Action. https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund_en

European Commission. (n.d.) *ReFuelEU Aviation.* Mobility and Transport. https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en

European Commission & Directorate-General for Energy. (2023). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS State of the Energy Union Report 2023. In *europa.eu.* https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52023DC0650

European Commission, Joint Research Centre, Tumara, D., Uihlein, A., & Hidalgo Gonzalez, I. (2024). *Shaping the future CO_2 transport network for Europe* (JRC136709). Publications Office of the European Union. https://doi.org/10.2760/582433

European Parlement. (2022). *Amendments adopted by the European Parliament on 7 July 2022 on the proposal for a regulation of the European Parliament and of the Council On Ensuring a level playing field for Sustainable Air Transport (COM(2021)0561 – C9-0332/2021 – 2021/0205(COD))*. europarl.europa.eu. https://www.europarl.europa.eu/doceo/document/TA-9-2022-0297_EN.html

European Union. (2024). *Invest EU.* InvestEU. https://investeu.europa.eu/index_en

European Union Aviation Safety Agency. (2022). *EUROPEAN AVIATION ENVIRONMENTAL REPORT 2022*. https://doi.org/10.2822/309946

Eyberg, V., Dieterich, V., Bastek, S., Dossow, M., Spliethoff, H., & Fendt, S. (2024). Techno-economic assessment and comparison of Fischer–Tropsch and Methanol-to-Jet processes to produce sustainable aviation fuel via Power-to-Liquid. *Energy Conversion and Management, 315*, 118728. https://doi.org/10.1016/j.enconman.2024.118728

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science*, *10*(6), 1389–1426. https://doi.org/10.1039/c7ee00465f

Farmer, J. D., & Lafond, F. (2016). How predictable is technological progress? *Research Policy, 45*(3), 647–665. https://doi.org/10.1016/j.respol.2015.11.001

Federal Aviation Administration. (2020). *Engine Fuel and Control - Semi-Synthetic Jet Fuel*. FAA Aviation Safety. https://www.avfuel.com/Portals/0/SAF%20SAIB.pdf

Fiorini, A. C. O., Angelkorte, G. B., Portugal-Pereira, J., Bergman-Fonte, C., De Souza Vicente, C., Morais, T. N., Carvalho, L. S., Zanon-Zotin, M., Szklo, A., Schaeffer, R., & Portugal-Pereira, J. (2023). Sustainable aviation fuels must control induced land use change: an integrated assessment modelling exercise for Brazil. *Environmental Research Letters*, *18*(1), 014036. https://doi.org/10.1088/1748-9326/acaee1

Franc-Dąbrowska, J., Mądra-Sawicka, M., & Milewska, A. (2021). Energy Sector Risk and Cost of Capital Assessment—Companies and Investors Perspective. *Energies, 14*(6), 1613. https://doi.org/10.3390/en14061613

Franco, A., & Giovannini, C. (2023). Routes for Hydrogen Introduction in the Industrial Hard-to-Abate Sectors for Promoting Energy Transition. *Energies*. https://doi.org/10.20944/preprints202307.1419.v1

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*(8–9), 1257–1274. https://doi.org/10.1016/s0048-7333(02)00062-8

Grimme, W. (2023). The Introduction of Sustainable Aviation Fuels—A discussion of challenges, options and Alternatives. *Aerospace, 10*(3), 218. https://doi.org/10.3390/aerospace10030218

Habermeyer, F., Weyand, J., Maier, S., Kurkela, E., & Dietrich, R. (2024). Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-03671-y

Heiniger, M., Mistry, H., & Brunner, C. (2024). *Carbon catch-up | Navigating decarbonization in aviation with carbon removal solutions* [Video]. Climeworks. https://climeworks.com/navigating-decarbonization-in-aviation-with-carbon-removal-solutions

Hekkert, M., Negro, S., Heimeriks, G., & Harmsen, R. (2011). Technological Innovation System Analysis: A manual for analysts. Utrecht University, 16.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., & Smits, R. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting & Social Change/Technological Forecasting and Social Change, 74*(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Hepperle, M. (2012). Electric Flight - Potential and Limitations. https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf

Herz, G., Reichelt, E., & Jahn, M. (2018). Techno-economic analysis of a co-electrolysis-based synthesis process for the production of hydrocarbons. *Applied Energy, 215*, 309–320. https://doi.org/10.1016/j.apenergy.2018.02.007

Höglund, R. (2024). Removals are better than some reductions - The case of electrofuels for aviation. *Marginal Carbon.* https://marginalcarbon.substack.com/p/removals-are-better-than-some-reductions

International Energy Agency. (2019). The future of hydrogen. In *Report Prepared by the IEA for the G20, Japan*. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

International Energy Agency. (2021). Net Zero by 2050: A roadmap for the global energy sector. In *International Energy Agency*. https://iea.blob.core.windows.net/assets/063ae08a-7114-4b58-a34e-39db2112d0a2/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf

International Energy Agency. (2023). Tracking Clean Energy Progress 2023. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Intergovernmental Panel on Climate Change. (2022). Summary for Policymakers. In *Climate Change 2022 Mitigation of Climate Change Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009157926.001

IRENA. (2020). Green hydrogen cost reduction: *Scaling up electrolysers to meet the 1.50C climate goal.* International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Jamasb, T., & Kohler, J. (2007). Learning curves for energy technology: a critical assessment. http://www.dspace.cam.ac.uk/handle/1810/194736

Jet fuel Price Monitor. (n.d.). https://www.iata.org/en/publications/economics/fuel-monitor/

Kahn, M. E., Mohaddes, K., Ng, R. N. C., Pesaran, M. H., Raissi, M., & Jin, Y. (2021). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics*, *104*, 105624. https://doi.org/10.1016/j.eneco.2021.105624

Kalkuhl, M., & Wenz, L. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, *103*, 102360. https://doi.org/10.1016/j.jeem.2020.102360

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis and Strategic Management, 10*(2), 175–198. https://doi.org/10.1080/09537329808524310

Kopernikus-Projekt Ariadne. (2023). MSR through 2030: *Impact on market liquidity and considerations for the 2026 reform*. Potsdam Institute for Climate Impact Research. https://ariadneprojekt.de/media/2023/12/Ariadne-Documentation_ETSWorkshopBruessel_December2023.pdf

Kumar, A., Madden, D. G., Lusi, M., Chen, K., Daniels, E. A., Curtin, T., Perry, J. J., & Zaworotko, M. J. (2015). Direct air capture of CO2 by physisorbent materials. *Angewandte Chemie International Edition*, *54*(48), 14372–14377. https://doi.org/10.1002/anie.201506952

Lawmaker proposes raising EU green jet fuel target to 100% by 2050. (2022). Euractiv. https://www.euractiv.com/section/biofuels/news/lawmaker-proposes-raising-eu-green-jet-fuel-target-to-100-by-2050/

Leech, N. L., & Onwuegbuzie, A. J. (2010b). Guidelines for conducting and reporting mixed research in the field of counseling and beyond. *Journal of Counseling & Development, 88*(1), 61–69. https://doi.org/10.1002/j.1556-6678.2010.tb00151.x

Lin, B., & Ge, J. (2020). To harvest or not to harvest? Forest management as a trade-off between bioenergy production and carbon sink. *Journal of Cleaner Production*, *268*, 122219. https://doi.org/10.1016/j.jclepro.2020.122219

Liu, C. M., Sandhu, N., McCoy, S., & Bergerson, J. (2020). A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production. *Sustainable Energy and Fuels*, *4*(6), 3129–3142. https://doi.org/10.1039/c9se00479c

Liu, D., Guo, X., & Xiao, B. (2019). What causes growth of global greenhouse gas emissions? Evidence from 40 countries. *Science of the Total Environment*, *661*, 750–766. https://doi.org/10.1016/j.scitotenv.2019.01.197

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (Eds.). (2018). *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Cambridge University Press. https://doi.org/10.1017/9781009157940

Mannion, P., Parry, E., Scott, J., & Patel, M. (2024). *Carbon removals: How to scale a new giga ton industry*. McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/carbon-removals-how-to-scale-a-new-gigaton-industry?utm_source=substack&utm_medium=email#/

Markowitsch, C., Lehner, M., & Maly, M. (2023). Evaluation of process structures and reactor technologies of an integrated power-to-liquid plant at a cement factory. *Journal of CO2 Utilization, 70*, 102449. https://doi.org/10.1016/j.jcou.2023.102449

Martín, J. S., Neumann, A., & Ødegård, A. (2023). Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model. *Renewable & Sustainable Energy Reviews, 186*, 113637. https://doi.org/10.1016/j.rser.2023.113637

Martin, G., Oikonomopoulou, E., & Walsh, P. (2024). *LOW-CARBON FUELS: DECODING EU LEGISLATION FOR THE TRANSPORT SECTOR.* Clifford chance. https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2024/02/low-carbon-fuels-decoding-eu-legislation-for-the-transport-sector.pdf

McDonald, A., & Schrattenholzer, L. (2001). Learning rates for energy technologies. *Energy Policy, 29(*4), 255–261. https://doi.org/10.1016/s0301-4215(00)00122-1

McKenna, B., Poehler, A., Qin, K., Lam, Y., & Tempke, R. (2024). *Global availability of biogenic CO_2 and implications for maritime decarbonization*. Maersk Mc-Kinney Møller Center for Zero Carbon Shipping. Retrieved from https://cms.zerocarbonshipping.com/media/uploads/documents/Global-Availability-of-Biogenic-CO2-and-Implications-for-Maritime-Decarbonization.pdf

McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy*, *3*(3), 032001. https://doi.org/10.1088/2516-1083/abf1ce

Micheli, M., Moore, D. C., Bach, V., & Finkbeiner, M. (2022). Life-Cycle Assessment of Power-to-Liquid Kerosene Produced from Renewable Electricity and CO2 from Direct Air Capture in Germany. *Sustainability, 14*(17), 10658. https://doi.org/10.3390/su141710658

Mikhaylov, A., Moiseev, N., Алешин, К. А., & Burkhardt, T. (2020). Global climate change and greenhouse effect. *Entrepreneurship and Sustainability Issues*, *7*(4), 2897–2913. https://doi.org/10.9770/jesi.2020.7.4(21)

Mitchell, J. F. B. (1989). The "Greenhouse" effect and climate change. *Reviews of Geophysics*, *27*(1), 115–139. https://doi.org/10.1029/rg027i001p00115

Moretti, C., Patil, V., Falter, C., Geissbühler, L., Patt, A., & Steinfeld, A. (2023). Technical, economic and environmental analysis of solar thermochemical production of drop-in fuels. *Science of the Total Environment, 901*, 166005. https://doi.org/10.1016/j.scitotenv.2023.166005

Mutrelle, C. (2024). The challenges of scaling up e-kerosene production in Europe*. In Transport & Environment.* https://www.transportenvironment.org/uploads/files/2024_01_E-kerosene_Tracker_TE_2024-04-29-155012_cevi.pdf

National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: a research agenda*. The National Academies Press. https://doi.org/10.17226/25259

National Oceanic and Atmospheric Administration. (2023). Greenhouse gases continued to increase rapidly in 2022. *www.noaa.gov*.

Neuwirth, M., Fleiter, T., Manz, P., & Hofmann, R. (2022). The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to Germany. *Energy Conversion and Management*, *252*, 115052. https://doi.org/10.1016/j.enconman.2021.115052

Nguyen, T., Abdin, Z., Holm, T., & Mérida, W. (2019). Grid-connected hydrogen production via large-scale water electrolysis. *Energy Conversion and Management, 200*, 112108. https://doi.org/10.1016/j.enconman.2019.112108

van 't Noordende, H., Van Berkel, F., & Stodolny, M. (2023). Next Level Solid Oxide Electrolysis. In *Institute for Sustainable Process Technology*. Institute for Sustainable Process Technology (ISPT). Retrieved July 2, 2024, from https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

Ordóñez, D. F., Halfdanarson, T., Ganzer, C., Shah, N., Mac Dowell, N., & Guillén-Gosálbez, G. (2022). Evaluation of the potential use of e-fuels in the European aviation sector: a comprehensive economic and environmental assessment including externalities. *Sustainable Energy & Fuels, 6*(20), 4749–4764. https://doi.org/10.1039/d2se00757f

Oyewo, A. S., Lopez, G., ElSayed, M., Galimova, T., & Breyer, C. (2024). Power-to-X Economy: Green e-hydrogen, e-fuels, e-chemicals, and e-materials opportunities in Africa. *Energy Reports, 12*, 2026–2048. https://doi.org/10.1016/j.egyr.2024.08.011

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*, n160. https://doi.org/10.1136/bmj.n160

Paez, A. (2017). Grey literature: An important resource in systematic reviews. *Journal of Evidence-Based Medicine*. https://doi.org/10.1111/jebm.12265

Paltsev, S., Morris, J., Kheshgi, H. S., & Herzog, H. J. (2021). Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. *Applied Energy*, *300*, 117322. https://doi.org/10.1016/j.apenergy.2021.117322

Peacock, J., Cooper, R., Waller, N., & Richardson, G. (2024). Decarbonising aviation at scale through synthesis of sustainable e-fuel: A techno-economic assessment. *International Journal of Hydrogen Energy*, *50*, 869–890. https://doi.org/10.1016/j.ijhydene.2023.09.094

Pio, D., Vilas-Boas, A., Araújo, V., Rodrigues, N. F. C., & Mendes, A. (2023). Decarbonizing the aviation sector with Electro Sustainable Aviation Fuel (eSAF) from biogenic CO2 captured at pulp mills. *Chemical Engineering Journal*, *463*, 142317. https://doi.org/10.1016/j.cej.2023.142317

Prats-Salvado, E., Monnerie, N., & Sattler, C. (2022). Techno-Economic assessment of the integration of direct air capture and the production of solar fuels. *Energies, 15*(14), 5017. https://doi.org/10.3390/en15145017

Purolite. (2024, June 18). Purolite announces development agreement with Skytree to commercialize CO_2 capture technology. Purolite. https://www.purolite.com/index/Company/News-and-Events/news/skytree-development-agreement

Rivard, E., Trudeau, M., & Zaghib, K. (2019). Hydrogen Storage for mobility: a review. Materials, 12(12), 1973. https://doi.org/10.3390/ma12121973

Rojas-Michaga, M. F., Michailos, S., Cardozo, E., Akram, M., Hughes, K. J., Ingham, D., & Pourkashanian, M. (2023). Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. *Energy Conversion and Management, 292*, 117427. https://doi.org/10.1016/j.enconman.2023.117427

Roundtable on Sustainable Biomaterials. (2024). *Power-to-X: a new pathway for SAF* [Video]. Youtube. https://www.youtube.com/watch?v=Rpr81taU1wU

Ruokonen, J., Nieminen, H., Dahiru, A. R., Laari, A., Koiranen, T., Laaksonen, P., Vuokila, A., & Huuhtanen, M. (2021). Modelling and cost estimation for conversion of green methanol to renewable liquid transport fuels via olefin oligomerisation. *Processes, 9*(6), 1046. https://doi.org/10.3390/pr9061046

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrão, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P., & Vogt, J. (2014). Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres*, *119*(22). https://doi.org/10.1002/2014jd022098

Sacchi, R., Becattini, V., Gabrielli, P., Cox, B., Dirnaichner, A., Bauer, C., & Mazzotti, M. (2023). How to make climate-neutral aviation fly. *Nature Communications, 14*(1). https://doi.org/10.1038/s41467-023-39749-y

Salomone, F., Giglio, E., Ferrero, D., Santarelli, M., Pirone, R., & Bensaid, S. (2019). Techno-economic modelling of a Power-to-Gas system based on SOEC electrolysis and CO2 methanation in a RES-based electric grid. *Chemical Engineering Journal, 377*, 120233. https://doi.org/10.1016/j.cej.2018.10.170

Seymour, K., Held, M., Stolz, B., Georges, G., & Boulouchos, K. (2023). Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe. *Sustainable Energy & Fuels, 8*(4), 811–825. https://doi.org/10.1039/d3se00978e

Sherwin, E. D. (2021). Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis. *Environmental Science & Technology, 55*(11), 7583–7594. https://doi.org/10.1021/acs.est.0c07955

Shi, X., Lin, Y., & Chen, X. (2022). Development of sorbent materials for direct air capture of CO2. *MRS Bulletin, 47*(4), 405–415. https://doi.org/10.1557/s43577-022-00320-7

Short, W., Packey, D., & Holt, T. (1995). A manual for the economic evaluation of energy efficiency and renewable energy technologies. https://doi.org/10.2172/35391

Shukla, J., Verma, M., & Misra, A. (2017). Effect of global warming on sea level rise: A modeling study. *Ecological Complexity*, *32*, 99–110. https://doi.org/10.1016/j.ecocom.2017.10.007

Sick, V., Stokes, G. M., Mason, F., Yu, Y., Van Berkel, A., Daliah, R., Gamez, O., Gee, C., & Kaushik, M. (2022). Implementing CO2 capture and utilization at scale and speed. In *Deep Blue (University of Michigan)*. https://doi.org/10.7302/5825

Sivaramanan, S. (2015). Global Warming and Climate change, causes, impacts and mitigation. *Central Environmental Authority*, *2*(4). http://doi.org./10.13140/RG.2.1.4889.7128

Sunfire GmbH. (2023). Sunfire SynLink SOEC factsheet. https://www.sunfire.de/files/sunfire/images/content/Produkte_Technologie/factsheets/Sunfire-Factsheet-SynLink-SOEC_2023Nov.pdf

Su-Ungkavatin, P., Tiruta-Barna, L., & Hamelin, L. (2023). Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. *Progress in Energy and Combustion Science*, *96*, 101073. https://doi.org/10.1016/j.pecs.2023.101073

Timmons, D., & Terwel, R. (2022). Economics of aviation fuel decarbonization: A preliminary assessment. *Journal of Cleaner Production*, *369*, 133097. https://doi.org/10.1016/j.jclepro.2022.133097

Tremel, A. (2018). Electricity-based fuels. In *SpringerBriefs in applied sciences and technology*. https://doi.org/10.1007/978-3-319-72459-1

United Nations. (n.d.-a). *The Paris Agreement | United Nations*. https://www.un.org/en/climatechange/paris-agreement

United Nations. (n.d.). *UN Climate Change Working together for climate ambition*. United Nations Framework Convention on Climate Change. https://unfccc.int/

Vitousek, P. M. (1994). Beyond Global Warming: Ecology and global change. *Ecology*, *75*(7), 1861–1876. https://doi.org/10.2307/1941591

Williams, C. L., Westover, T. L., Emerson, R. M., Tumuluru, J. S., & Li, C. (2015). Sources of biomass feedstock variability and the potential impact on biofuels production. *BioEnergy Research, 9*(1), 1–14. https://doi.org/10.1007/s12155-015-9694-y

World Bank Group, (2024). *GDP (current US$).* Retrieved in on January 18, 2024, from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

World Nuclear Association. (2024). *Nuclear power in the European Union - World Nuclear Association.* https://world-nuclear.org/information-library/country-profiles/others/european-union

Yeh, S., & Rubin, E. S. (2012). A review of uncertainties in technology experience curves. *Energy Economics, 34*(3), 762-771. https://doi.org/10.1016/j.eneco.2011.11.006

Zang, G., Sun, P., Elgowainy, A. A., Bafana, A., & Wang, M. (2021). Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process. *Journal of CO2 Utilization, 46*, 101459. https://doi.org/10.1016/j.jcou.2021.101459

Zeeshan, M., Kidder, M. K., Pentzer, E., Getman, R. B., & Gurkan, B. (2023). Direct air capture of CO2: from insights into the current and emerging approaches to future opportunities. *Frontiers in Sustainability*, *4*. https://doi.org/10.3389/frsus.2023.1167713

Zheng, Y., Wang, J., Yu, B., Zhang, W., Chen, J., Qiao, J., & Zhang, J. (2017). A review of high temperature co-electrolysis of H2O and CO2to produce sustainable fuels using solid oxide electrolysis cells (SOECs): advanced materials and technology. *Chemical Society Reviews, 46*(5), 1427–1463. https://doi.org/10.1039/c6cs00403b

8. Appendix

Appendix A: overview of the synonyms used in the preliminary literature review, as well as the final query.

Key search term	**Synonyms**
DAC	Direct air capture, air-based carbon capture, carbon dioxide removal from air, atmospheric carbon capture, carbon removal from atmosphere, and direct CO2 capture
eSAF	Efuel, e-fuel, electrofuel, aviation, eSAF, synthetic aviation fuel, Power to liquid, PtL, electricity to liquid, jet fuel, ekerosene, electro-fuel, and synthetic kerosene

Figure 8.1: Key search terms and corresponding synonyms

Search query: ("direct air capture" OR "Air-based Carbon Capture" OR "Carbon Dioxide Removal from Air" OR "Atmospheric Carbon Capture" OR "Carbon Removal from Atmosphere" OR "Direct CO2 Capture") AND ("efuel" OR "e-fuel" OR "electrofuel" OR "aviation" OR "eSAF" OR "synthetic aviation fuel" OR "Power to liquid" OR "PtL" OR "electricity to liquid" OR "jet fuel" OR "ekerosene" OR "electro-fuel" OR "synthetic kerosene")

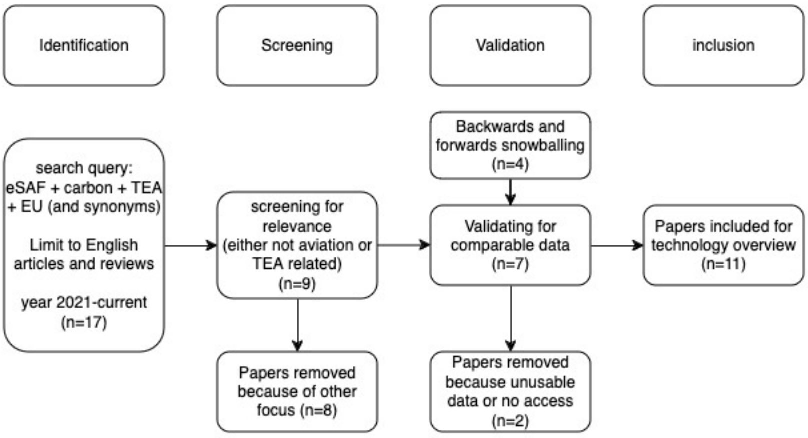
Appendix B: list of final 23 articles for the literature gap + reason for exclusion. Green = selected. Orange = excluded

Publication Year	Document Title	Authors	ISSN	Journal Title	Reason for exclusion
2024	Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen	D'Adamo I., Gastaldi M., Giannini M., Nizami A.-S.	139351	Environmental Research	
2023	Technical, economic and environmental analysis of solar thermochemical production of drop-in fuels	Moretti C., Patil V., Falter C., Geissbuhler L., Patt A., Steinfeld A.	489697	Science of the Total Environment	
2023	Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model	Martin J., Neumann A., Odegard A.	13640321	Renewable and Sustainable Energy Reviews	
2023	Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment	Rojas-Michaga M.F., Michailos S., Cardozo E., Akram M., Hughes K.J., Ingham D., Pourkashanian M.	1968904	Energy Conversion and Management	
2023	Integrated capture and solar-driven utilization of CO2 from flue gas and air	Kar S., Rahaman M., Andrei V., Bhattacharjee S., Roy S., Reisner E.	25424351	Joule	Focus on coversion to syngas
2023	Near-Term Suitability Assessment of Deploying DAC System at Airport: A Case Study of 52 Large Airports in China	Wang F., Wang P., Xu M., Li X., Tan W., Li H.	20734433	Atmosphere	Focus on finding suitable DAC location in China
2023	Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios	Ballal V., Cavalett O., Cherubini F., Watanabe M.D.B.	162361	Fuel	
2023	Techno-economic competitiveness of renewable fuel alternatives in the marine sector	Mukherjee A., Bruijnincx P., Junginger M.	13640321	Renewable and Sustainable Energy Reviews	Focus on marine sector
2022	Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals	Galimova T., Ram M., Bogdanov D., Fasihi M., Khalili S., Gulagi A., Karjunen H., Mensah T.N.O., Breyer C.	9596526	Journal of Cleaner Production	Focus on CO2 demand in point source industries
2022	Economic and Environmental Barriers of CO2-Based Fischer-Tropsch Electro-Diesel	Medrano-Garcia J.D., Charalambous M.A., Guillen-Gosalbez G.	21680485	ACS Sustainable Chemistry and Engineering	Focus on e-diesel
2022	Life-Cycle Assessment of Power-to-Liquid Kerosene Produced from Renewable Electricity and CO2 from Direct Air Capture in Germany	Micheli M., Moore D., Bach V., Finkbeiner M.	20711050	Sustainability (Switzerland)	
2022	Techno-Economic Assessment of the Integration of Direct Air Capture and the Production of Solar Fuels	Prats-Salvado E., Monnerie N., Sattler C.	19961073	Energies	
2022	Atmospheric CO2 as a resource for renewable energy production: A European energy law appraisal of direct air capture fuels	Schaller R., Markus T., Korte K., Gawel E.	20500386	Review of European, Comparative and International Environmental Law	Focus on Renewable Energy Directive
2022	Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals	Oshiro K., Fujimori S.	3062619	Applied Energy	Focus on hydrogen
2021	Climate change mitigation measures for global net-zero emissions and the roles of CO2 capture and utilization and direct air capture	Akimoto K., Sano F., Oda J., Kanaboshi H., Nakano Y.	26662787	Energy and Climate Change	No open access
2021	Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis	Sherwin E.D.	0013936X	Environmental Science and Technology	
2021	Role of carbon capture, storage, and utilization to enable a Net-Zero-CO2-emissions aviation sector	Becattini V., Gabrielli P., Mazzotti M.	8885885	Industrial and Engineering Chemistry Research	
2021	Scaling CO2 Capture With Downstream Flow CO2 Conversion to Ethanol	Pace G., Sheehan S.W.	26249553	Frontiers in Climate	Focus on different CO2 capture techniques at higher concentration, minimal rol DAC
2021	Technical principles of atmospheric carbon dioxide reduction and conversion: economic considerations for some developing countries	Roduner E., Rohwer E.R.	1618954X	Clean Technologies and Environmental Policy	Focus on developing countries
2020	Dynamically operated Fischer–Tropsch synthesis in PtL—Part 2: Coping with real PV profiles	Loewert M., Riedinger M., Pfeifer P.	23057084	ChemEngineering	Focus on load flexibility of F-T synthesis
2020	A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production	Liu C.M., Sandhu N.K., McCoy S.T., Bergerson J.A.	23984902	Sustainable Energy and Fuels	
2020	Direct capture of carbon dioxide from air via lime-based sorbents	Samari M., Ridha F., Manovic V., Macchi A., Anthony E.J.	13812386	Mitigation and Adaptation Strategies for Global Change	Focus on lime-based sorbents
2018	A Process for Capturing CO2 from the Atmosphere	Keith D.W., Holmes G., St. Angelo D., Heidel K.	25424351	Joule	Focus on DAC process involving fossil fuels, excludes fuel synthesis and very outdated

Appendix C: Overview of the selected literature. Purple = techno-economic analysis of standard production pathway. Blue = techno-economic analysis of novel production pathway. Green = life cycle analysis. Purple/green = combined techno-economic and life cycle analysis. Purple/blue = combination of standard and novel production pathway

Publication Year	Document Title	Authors	Journal Title	Abstract	Model	Scenario analysis	Pilot	Site specific	energy supply specific	fuel specific	Fuel production	fuel price	entire value chain	worth mentioning
2024	Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen	D'Adamo I., Gastaldi M., Giannini M., Nizami A.-S.	Environmental Research	[illegible]	yes		no	yes	yes, pv (an no electricity costs when buying from the grid)	no (just diesel)	Fischer-Tropsch	baseline = 3.7 €/L (new term not specified)	[illegible]	LCO analysis, disregard electricity costs in certain steps, disregards production costs, doesn't specify different fuel sectors
2023	Technical, economic and environmental analysis of solar thermochemical production of drop-in fuels	Moretti C., Patil V., Falter C., Geissbühler L., Patt A., Steinfeld A.	Science of the Total Environment	[illegible]	yes	yes	no	yes, 2 locations	yes, solar thermochemical heat	FT jet, FT diesel, methanol, gasoline via methanol, dimethyl ether and hydrogen	Multiple, also FT via RWGS and fuel upgrading	2.5 €/L (cheapest location and 2030)		LCO, focus on novel production method, not on e-fuels produced from CO2 and hydrogen via electrolysis and renewables
2023	Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model	Martin J., Neumann A., Ødegård A.	Renewable and Sustainable Energy Reviews	[illegible]	yes	yes	no	yes, 3 case studies in Norway	yes, high full load hours of stable renewable from norwegian grid	hydrogen, ammonia and eDiesel (not specific eFuel)	Simplified FT	2.14 €/L (hydro in 2025)	[illegible]	[illegible]
2023	Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment	Rojas-Michaga M.F., Michailos S., Cardozo E., Akram M., Hughes K.J., Ingham D., Pourkashanian M.	Energy Conversion and Management	[illegible]	yes	yes	no	yes, Teesside, UK	yes, off-shore wind. grid used as virtual storage excess elec --> grid injection. Lower power gen --> buy electricity taken from grid	yes, jet fuel	FT via RWGS and fuel upgrading	5.16 GBP/kg = 6.03 €/kg = 4.824 €/liter with density of 0.8 kg/L		[illegible]
2023	Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios	Balal V., Cavalett O., Cherubini F., Watanabe M.D.B.	Fuel	[illegible]	yes	yes	no	no	yes, 3 European energy mixes (EU average, Norway and Poland)	yes, jet fuel	FT via RWGS	no	LCA only OPEX components	[illegible]
2022	Life Cycle Assessment of Power-to-Liquid Kerosene Produced from Renewable Electricity and CO2 from Direct Air Capture in Germany	Micheli M., Moore D., Bach V., Finkbeiner M.	Sustainability (Switzerland)	[illegible]	yes		no	yes, Germany	2 different mixes	yes, jet fuel	FT via RWGS and fuel upgrading			[illegible]
2022	Techno-Economic Assessment of the Integration of Direct Air Capture and the Production of Solar Fuels	Prats-Salvado E., Monnerie N., Sattler C.	Energies	[illegible]	yes	yes	no	yes, Riyadh	yes, solar thermochemical heat	yes, methanol	not specified or in scope of study, fuel production after syngas formation already well established technology according to paper	0.89 €/liter methanol	no, disregards fuel production	[illegible]
2021	Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis	Sherwin E.D.	Environmental Science and Technology	[illegible]	yes, linear programming optimization	yes	no	yes, arizona for solar and wyoming for wind	yes, variable renewable	yes, jet fuel	FT via RWGS and fuel upgrading	$4.41–$4.90 per liter --> 3.87-4.28 €/liter	[illegible]	[illegible]
2021	Role of carbon capture, storage, and utilization to enable a Net-Zero-CO2-emissions aviation sector	Becattini V., Gabrielli P., Mazzotti M.	Industrial and Engineering Chemistry Research	[illegible]	yes	yes	no		yes, renewable with LCOE	yes, jet fuel	FT via electrochemical reduction of CO2 to CO	4.89 €/liter		[illegible]
2020	A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production	Liu C.M., Sandhu N.K., McCoy S.T., Bergerson J.A.	Sustainable Energy and Fuels	[illegible]	yes		yes, Carbon engineering in BC	yes	yes, generic low-CI grid like near the CE pilot project	yes, e-diesel	FT via RWGS and fuel upgrading		cradle-to-grave scope	[illegible]

Appendix D: Structured literature review



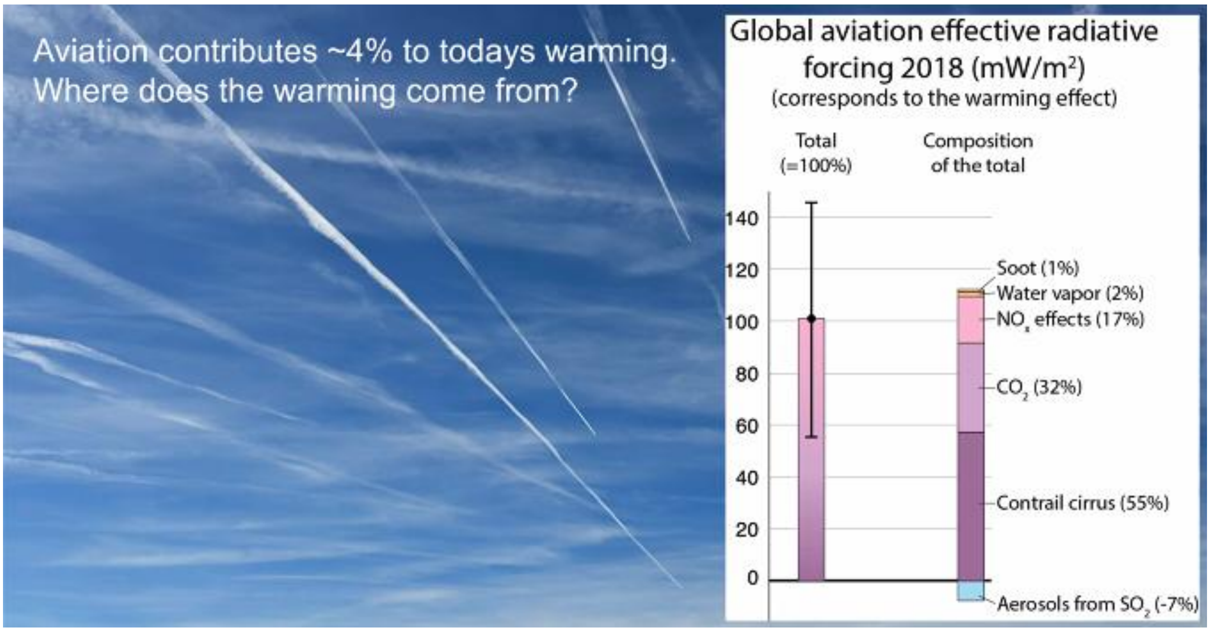
TITLE-ABS-KEY((efuel OR e-fuel OR esaf OR electrofuel OR electro-fuel OR ekerosene OR e-liquid OR e-kerosene OR power-to-liquid OR ptl OR p-t-l OR power-to-x OR ptx OR p-t-x OR (e AND fuel) OR (electro AND fuel) OR (aviation AND fuel) OR (power AND to AND liquid) OR (power AND to AND x) OR (electricity AND fuel)) AND (techno-economic OR economic OR tea OR (levelized AND cost) OR (techno AND economic)) AND (carbon OR CO2 OR (carbon AND dioxide)) AND (EU OR Europe OR (European AND union)) AND (aviation OR flight OR kerosene OR jet OR (air AND travel))) AND PUBYEAR > 2020 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re"))

***** = backwards or forwards snowballing

Number	**Author**	**Year**	**Technology**
1	Oyewo et al.	2024	Solar, alkaline, DAC CO2, FT, methanol, and ammonia
2	Sacchi et al.	2023	PEM, DAC CO2, RWGS + FT
3	Habermeyer et al.	2023	Biomass + additional H2, FT (biogenic e-fuel)
4	Grimme	2023	Biomass gasification + FT, HEFA, ATJ
5	Ordóñez et al.	2022	Solar + wind, PEMEL, fossil PSC and DAC, RWGS + FT
6	Ruokonen et al.	2021	Green methanol to jet-fuel
7*	Grahn et al.	2022	Overview
8*	Seymour et al.	2023	Solar + wind, PEMEL, DAC CO2, RWGS + FT
9*	Peacock et al.	2024	Nuclear, renewables, SOE, PEM, DAC, RWGS + FT, HEFA, gas/FT, ATJ
10*	Hoglund et al.	2024	PEMEL, PSC and DAC, RWGS + FT, HEFA, gasification, AtJ

Appendix E: Webinar: Navigating decarbonization in aviation with carbon removal solutions 13/06/2024
Speakers: Melanie Heiniger (Swiss Airlines), Hemant Mistry (IATA), Cyril Brunner (ETH zurich) and Climeworks

Summary: 800 million tons of DAC CO2 needed for the aviation industry according to IATA. Largest issue is scaling this technology in time to meet set targets. The continued use of fossil fuel and offsetting this with CDR is the cheaper option, but representatives of the industry agree this is not the way forward as it postpones needed tech cost down and improvements. In the regulational space, there are some developments taking place that strengthen the position of PtL, and thus DAC. The Aviation Reduction Act is something we should look into as well.



- CO2 is responsible for 2% of CO2, but aviation is responsible for 4% of global warming, with only a third being attributed to CO2 emissions
- Largest challenge is long distance flight: only possible with SAF 2.0 (synthetic aviation fuels, e-fuels) with carbon dioxide removal (SAF 1.0 = biofuels)

IATA net zero by 2050 roadmap
- 500 million tons by 2050 needed for carbon removal: excluding DAC capacities for PtL
- Additional 200 million ton needed for PtL, in line with other reports mentioning total of 800 million tons for aviation
- Billions of tons of DAC needed to decarbonize other industries as well

Why are Swiss and Lufthansa investing in direct air capturing now?
- 7 years before project initiation → first CDR
- Technology needs to be scaled up
  - Huge challenge to scale within time we have left to meet targets

Regulation

What do you expect in the evolution of regulation/when will CDR be included in compliance frameworks such as carbon removal and carbon farming framework?

- Carbon removals not accepted in EU ETS, could happen for 2026
- UK in movement now
- Approval of progress for being credible in international removal for IATA
- Alignment of international standards essential, including accountability towards science based targets
- Aviation reduction act

Synthetic aviation fuels vs fossil use + cdr

- More attractive to prolong use of fossil fuels offset with DAC:
- Uses less energy
- Cheaper
- But postpones scaling investments that need to be made eventually to stimulate SAF production

Conclusion:
SAF most important lever for aviation industry stakeholders and preferred pathway. Predicting costs down and rate of learning is difficult, only possible by investing in projects today and scaling up asap.

Appendix F: Power-to-x webinar 06/06/2024 notes
Speakers: Courtney Unruh (Alaska Airlines), Andy Stevenson (Twelve) and Carolina Grassi (RSB)
https://www.youtube.com/watch?v=Rpr81taU1wU

Summary: Power-to-liquid most potential, scalable technology with largest reduction potential. No reliance on limited feedstock and modular plants can be installed anywhere. Different technologies are currently being used and developed, with RWGS (reverse water gas shift) the most common. As long as the last step is Fischer-Tropsch conversion, the fuel can be blended with fossil fuel because FT is ASTM certified. Currently a combination of challenges hinders scaling the technology, mostly the limit of renewable electricity availability. Combination of advancements need to be made and aligned. In order to qualify as electrofuel (with actual CO2 reduction), certain requirements regarding renewable energy and hydrogen production have to be met, which is something Skytree should pay attention to when orchestrating a new e-fuel project with such partners.

Why is Alaska airlines interested in power to liquid?

- Large amount of emission reductions per liter of fuel
- No reliance on limited feedstock supply
- Plants are modular with a small footprint, can be installed anywhere

Andy Stevenson, VP of Commercial, (Twelve)

Advantages of power-to-x:

- Best scalable, depends on scale of renewable energy
- 10 x more energy per m2 compared to biomass
- Fischer-Tropsch is an ASTM certified pathway and qualifies for blending with fossil fuels (depends on catalyst)

Comparison of power-to-x processes:

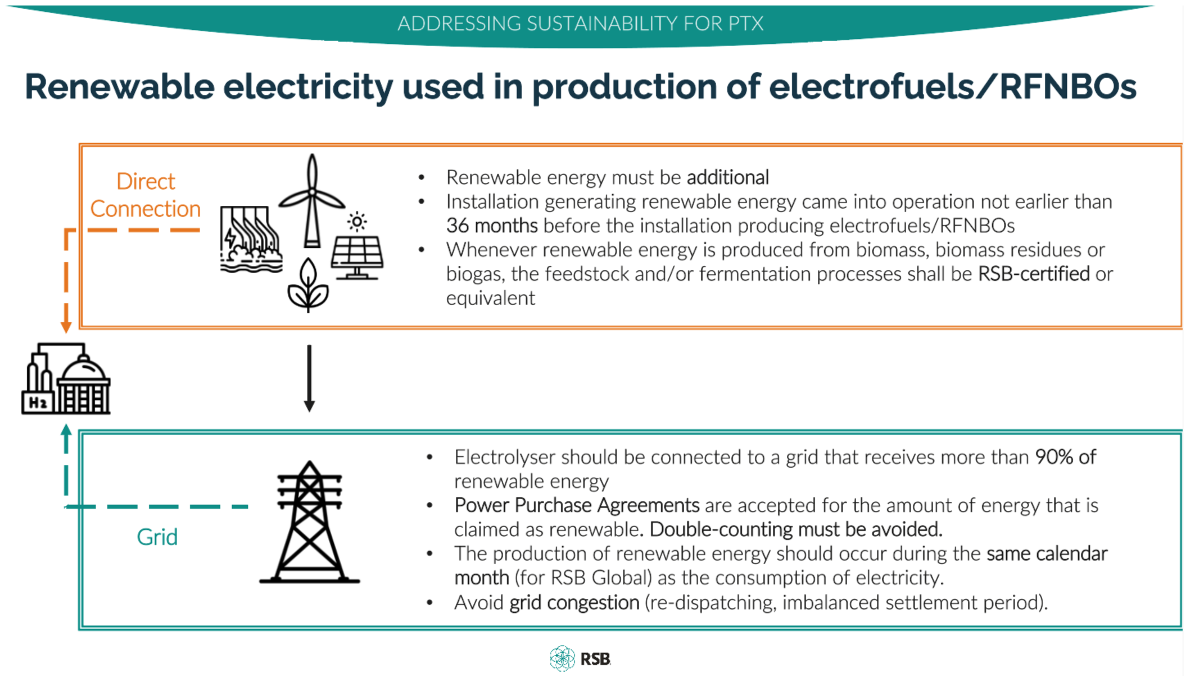
- RWGS is most advanced due to industry application. It is highly hydrogen intensive, so in an electrified energy system the use of electricity can be more applicable than hydrogen
- Methanol-to-jet
- Electrochemical reduction of CO2
    - Less hydrogen intensive
    - More electricity intensive
        - So highest carbon reduction potential
- Co-electrolysis of CO2 and water → syngas: hydrogen and CO synthesis from 1 electrolyzer
    - Uses heat (usually fossil)

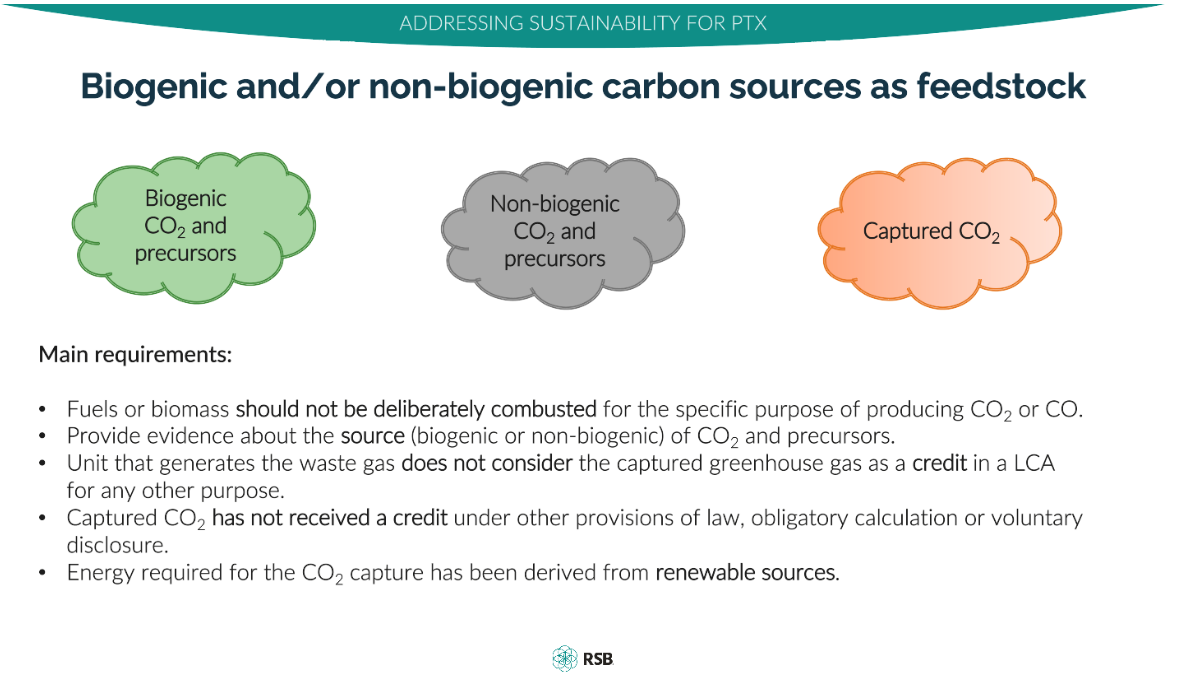
Challenges for scaling Power-to-Liquid:

- There is enough biogenic CO2 for 40 billion liters of eSAF
- Feedstock concentration/quality is low: cannot be directly used at the moment
- High cost of capture makes it infeasible
- Non-biogenic CO2 for P-t-L fuels are cheaper to capture (cement, ammonia, natural gas processing) but will not always be available in the future

- Feedstock challenges: competition for biogenic CO2
- Renewable energy integration more limiting

Key critical advancements that need to align for large scale adoption of Power-to-Liquid:
- Green hydrogen availability
- Cheaper carbon capture technologies
- Renewable energy abundance
- Biomass feedstocks
- FT and hydrotreating possible at smaller scale
- Incentives needed to bring us down cost curve of all technologie





ADDRESSING SUSTAINABILITY FOR PTX

RFNBOs/electrofuel should reduce GHG emissions

- Emission reductions of **70%** compared to the fossil fuel (usually 94 gCO_{2eq}/MJ).
- GHG methodologies described by regulatory market or others accepted by the voluntary market.

Emission sources:

- Production of electricity (CO_{2eq} emissions for RE from wind, solar, hydro and geothermal production are considered to be equal to zero),
- Water capturing and processing (e.g., desalination, deionization) - used in the electrolysis processes,
- Production of the fuel,
- Compression of the gas,
- Transport from the production of the fuel up to the fuel station/final distributor (including grid losses)
- Combustion of the fuel in use.

- For non-biogenic carbon sources - evidence that the carbon would be emitted into the atmosphere as local CO_2 emissions or other GHG in the absence of the utilisation.

RSB

Questions:
How does CO2 electrolysis compare to traditional electrolysis?
Energy efficiency of electro-chemical reduction of CO2 is currently behind RWGS, but no fundamental reason so expected to come down

Will eSAFs reach price parity in the upcoming 20 years?
Not trying to reach price imparity because fossil jet fuel subsidized: no carbon tax so try to reach level of jet fuel price + carbon tax

Appendix G: Pivot table containing announced eSAF project data in Europe.

Count of project	**Column Labels**									
Row Labels	**Airline**	**Electrolyzer manufacturer**	**Energy provider**	**Feedstock supplier**	**Fuel conversion technology provider**	**Fuel distributor**	**Infrastructure**	**Knowledge institute**	**Supporting organization**	**Grand Total**
Airline	22	7	14	6	13	3	13	1	1	80
Electrolyzer manufacturer	7		3	3	5	2	3	6	2	31
Energy provider	14	3	10	15	16	6	8	8	1	81
Feedstock supplier	6	3	15	6	18	11	5	14	4	82
Fuel conversion technology provider	13	5	16	18	24	7	18	8	2	111
Fuel distributor	3	2	6	11	7	8	6	6	3	52
Infrastructure	13	3	8	5	18	6	2	6	2	63
Knowledge institute	1	6	8	14	8	6	6	38	3	90
Supporting organization	1	2	1	4	2	3	2	3	2	20
Grand Total	**80**	**31**	**81**	**82**	**111**	**52**	**63**	**90**	**20**	**610**

Appendix H:

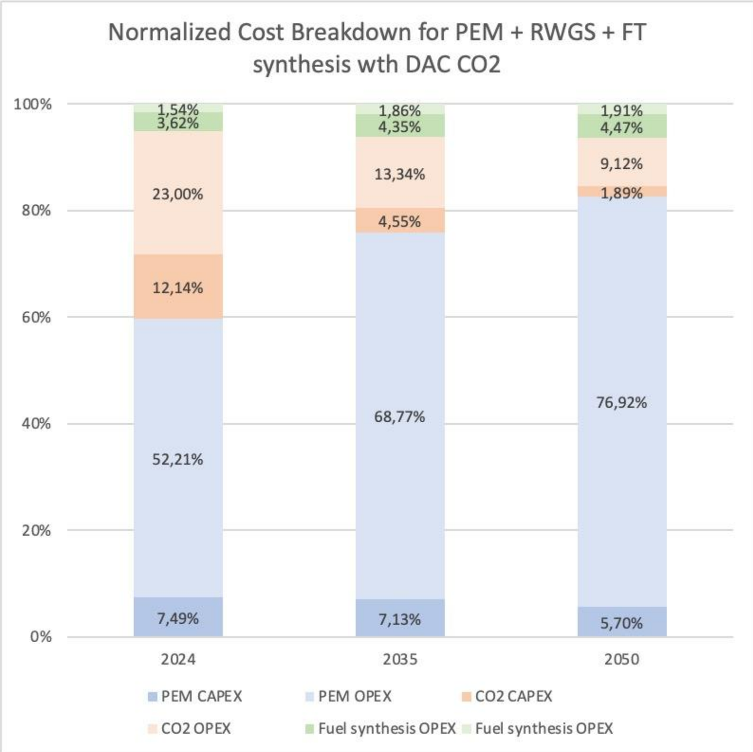


Figure 8.2: Normalized cost breakdown for PEM + RWGS + FT synthesis with DAC CO_2 in 2024, 2035 and 2050. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 (orange) and fuel synthesis (green).

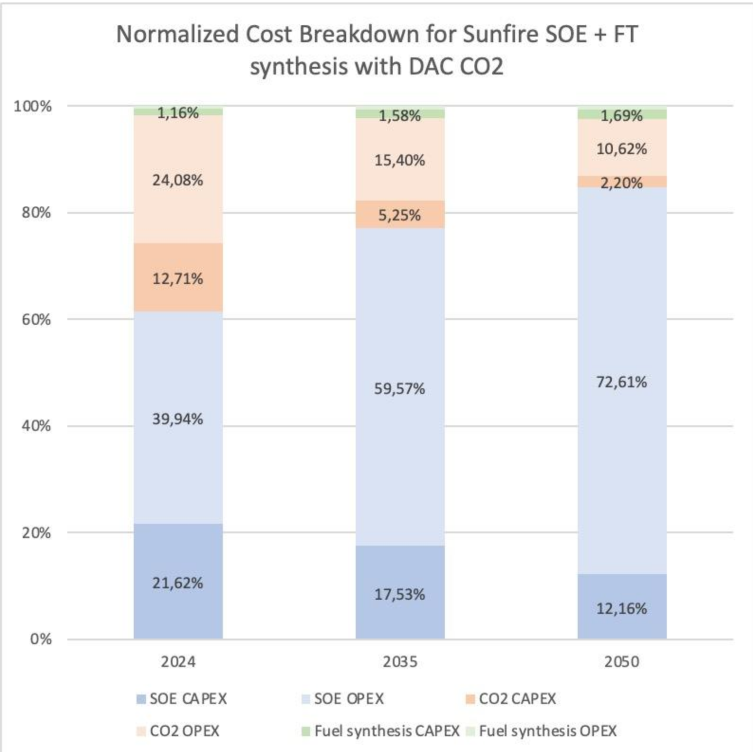


Figure 8.3: Normalized cost breakdown for Sunfire SOE + FT synthesis with DAC CO_2 in 2024, 2035 and 2050. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 (orange) and fuel synthesis (green).

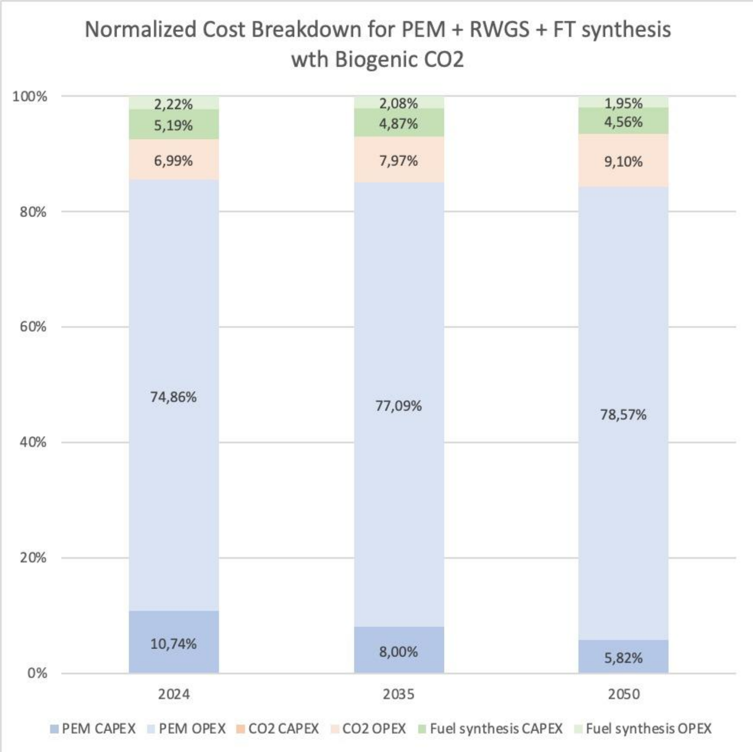


Figure 8.4: Normalized cost breakdown for PEM + RWGS + FT synthesis with Biogenic CO_2 in 2024, 2035 and 2050. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 (orange) and fuel synthesis (green).

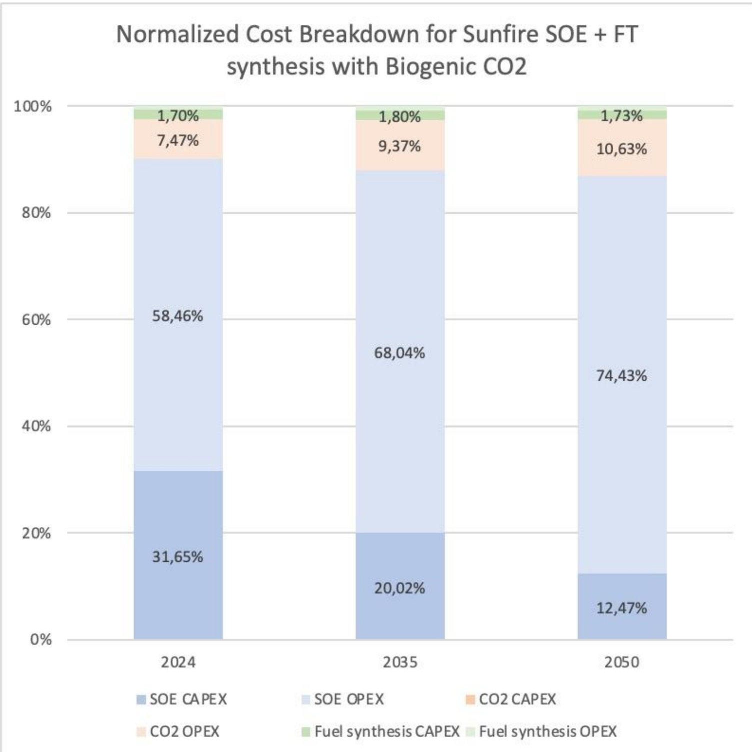


Figure 8.5: Normalized cost breakdown for Sunfire SOE + FT synthesis with Biogenic CO_2 in 2024, 2035 and 2050. Costs include CAPEX (dark) and OPEX (light) for Electrolysis (blue), CO_2 (orange) and fuel synthesis (green).

Appendix I: CO_2 prices for different scenarios

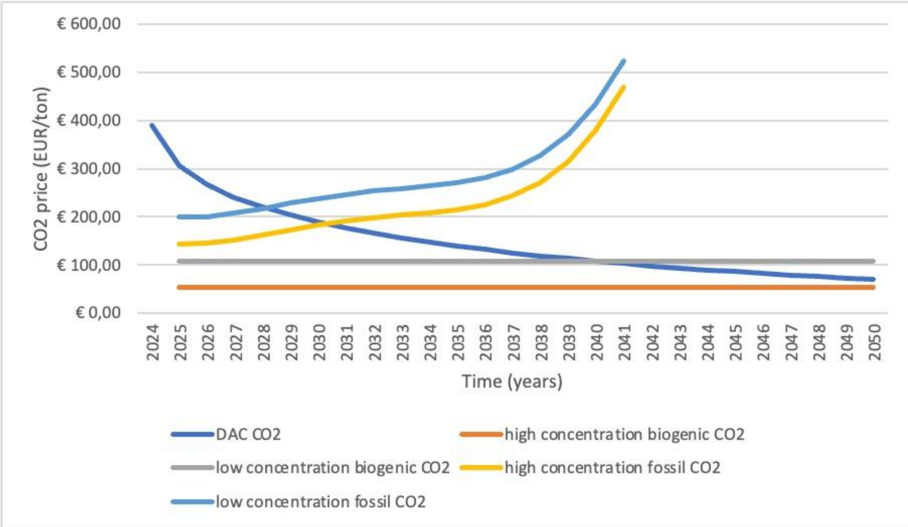


Figure 8.6: CO_2 cost comparison for thermal energy case with MWhel = €60,00 and MWhth = €10,00

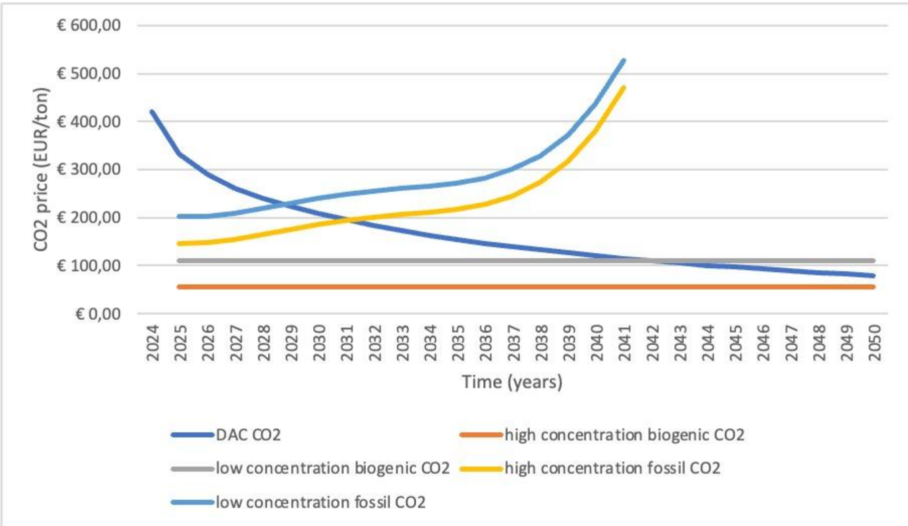


Figure 8.7: CO_2 cost comparison for higher bound electricity case with MWhel = €80,00 and MWhth = €00,00

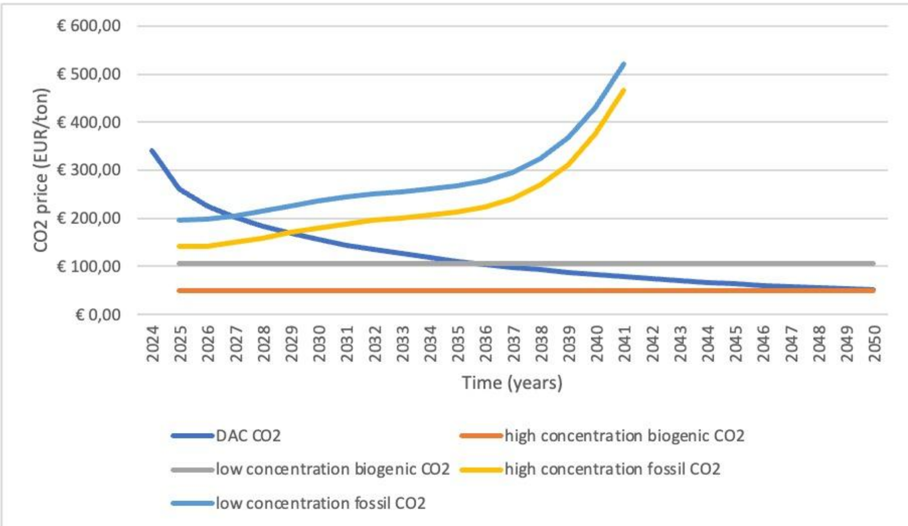


Figure 8.8: CO_2 cost comparison for lower bound electricity case with MWhel = €40,00 and MWhth = €00,00

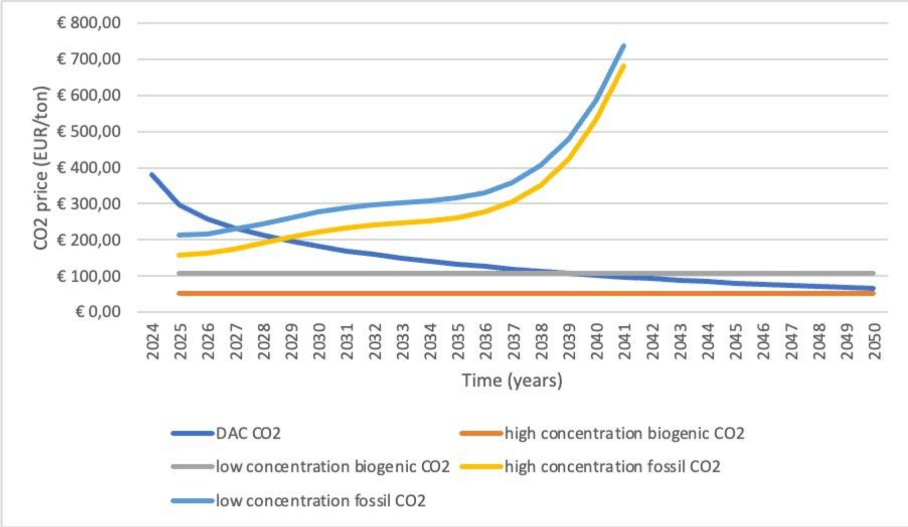


Figure 8.9: CO_2 cost comparison for EU ETS sensitivity analysis: upper bound

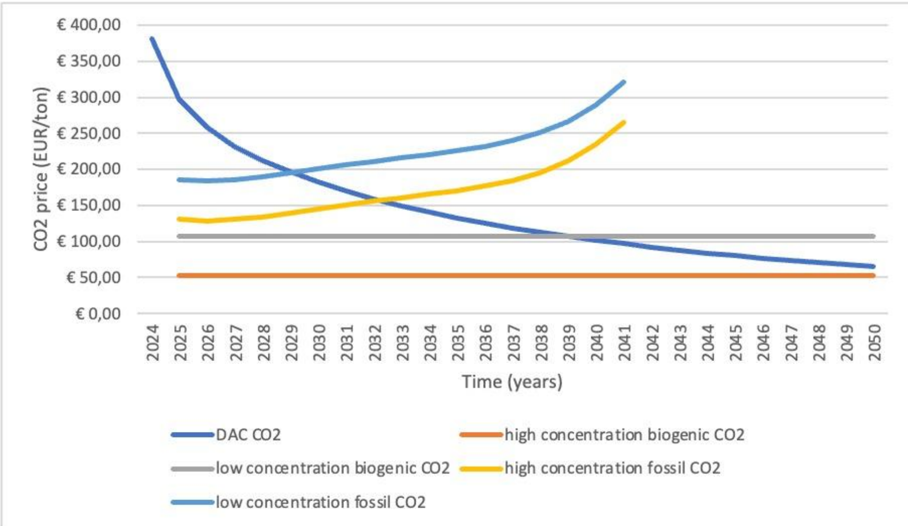


Figure 8.10: CO_2 cost comparison for EU ETS sensitivity analysis: lower bound

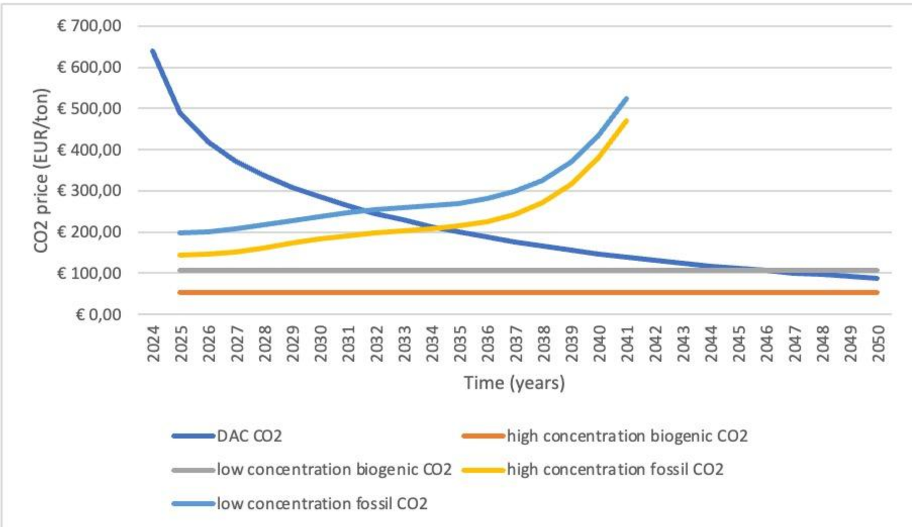


Figure 8.11: CO_2 cost comparison for intermittent electricity supply: 4000 operational hours