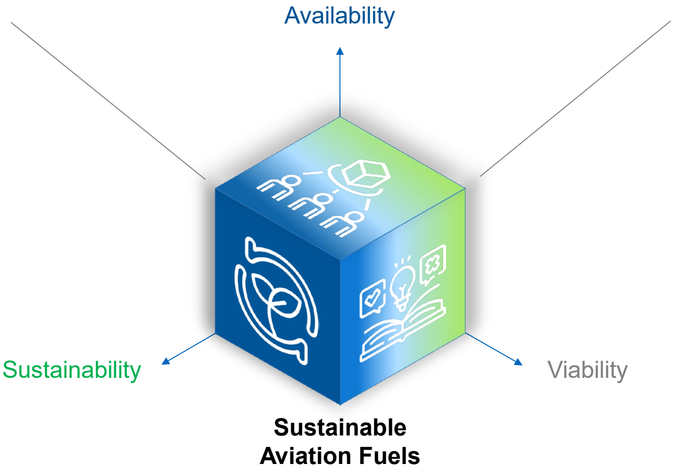
Resource-Constrained Pathways to Carbon-Neutral Aviation in Germany

Assessment of Sustainable Aviation Fuel (SAF) Strategies



In partial fulfilment of the requirements for the degree
Master of Science in Power Engineering
at the Chair of Renewable and Sustainable Energy Systems (ENS)
of the Technical University of Munich.

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Abstract

In the aviation sector, there is a collective vision for achieving "net-zero" operations by mid-century, aligning with global decarbonization targets such as COP21 and regional goals, such as the EU's "Fit for 55" Package and "ReFuelEU Aviation" directives. Despite this vision, it is acknowledged that the current pace of development and advancements may not be sufficient to meet the set targets within the given timeline. Cognizant of the need for GHG emission reduction in the aviation sector, the German government is actively advocating for measures to decrease overall emissions. This advocacy is anticipated to drive a substantial increase in demand for Sustainable Aviation Fuels (SAFs) in the years to come. The focus extends beyond traditional Power-to-Liquid fuels, with consideration given to the production of biogenic SAFs. The current status of the aviation sector entails a global or country-level analysis of specific requirements for fuels, infrastructure, and regulatory frameworks. While numerous publications delve into SAF production, there is a need for a comprehensive exploration of supply-side constraints, economic considerations, and other sustainability drivers within the sector. To address these gaps, this contribution aims to evaluate the potential of producing biogenic and non-biogenic SAFs in Germany. The analysis will encompass environmental, technical, and commercial aspects of various aviation fuel production pathways, adhering to approved ASTM D7566 standard and expected amendments.

The objective is to provide a thorough understanding of current and future SAF aspirations in Germany. Additionally, this investigation seeks to optimize emissions and costs, identifying potential pathways that may contribute to the decarbonization of aviation in Germany. The focus is on harnessing the potential of the German market to produce SAFs from indigenous biogenic feedstocks and e-fuels from renewable electricity. Importantly, this approach eliminates reliance on international imports of feedstocks or fuels, aligning with the country's commitment to developing a self-reliant energy market that supports its decarbonization targets. The findings underscore certain growth limitations, particularly regarding land use and regulatory frameworks in Germany. These constraints restrict the maximum potential of biogenic fuels to 12% (average) until 2050, with most scenarios falling short of exceeding 10% (average) energy substitution. Therefore, a significant contribution of non-biogenic SAF pathways is expected to meet the German aviation targets.

Keywords: Sustainable Aviation Fuels, Regional Demand, Biofuels, E-Fuels, Regulation

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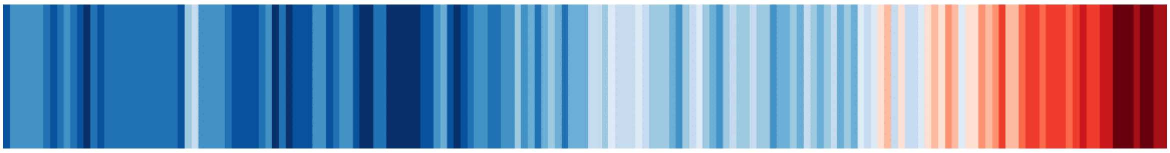
Foreword



"A picture is worth a thousand words."

- *Napolean Bonaparte (1769-1821)*

The work done originates from a place of passion, driven by an acute sense of responsibility, and frankly, from a sense of debt that we collectively owe to the generations to come. The decisions and policies we make right now, and the path we take would come under scrutiny by our successors – a realization that demands our collective attention.

I am certainly wishful that this scientific contribution, no matter how trivial, may guide someone, someday, somewhere, to make a decision that would enable us to steer away from the climate calamity that lies directly ahead of us.

The writing of this master thesis has been an enlightening journey and would have not been possible without the unrelenting love and support of my beloved parents, family, and friends.

In particular, I would like to thank Dr. Pablo Silva Oritz and Thushara Addanki for their continued support, patience, and more importantly their time. I am deeply obliged by your generosity and sense of professionalism.

For all the people involved, I extend my sincerest of gratitude.

Syed Zohaib Ahmed
December 2023

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Abbreviations

ACF	Annual Capacity Factor
AEL	Alkaline Electrolyser Cell
ASTM	American Society of Testing and Materials
ATJ	Alcohol-to-Jet
AvCPI	Aviation Consumer Price Index
BDL	German Aviation Association
BMDV	German Federal Ministry of Digital and Transport
BOE	Barrels of Oil Equivalent (1.7 MWh)
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CC	Carbon Capture
CCU	Carbon Capture Unit
CGH2	Compressed gaseous Hydrogen
CHJ	Catalytic Hydrothermolysis Jet Fuel
CIS	Carbon Intensity Score
COP21	21st Session of Conference of the Parties (Paris Agreement)
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPI	Consumer Price Index
DAC	Direct Air Capture (Carbon)
DENA	German Energy Agency
DESTATIS	Federal Statistical Office of Germany
DFS	Deutsche Flugsicherung GmbH
DIN	German Institute for Standardization
DME	Dimethyl Ether
EC	European Commission
EU ETS	European Emission Trading System
EU	European Union
Eurostat	European Statistical Office
FNR	Fachagentur Nachwachsende Rohstoffe e.V.
FOG	Fats, Oil, or Greases
FRL	Fuel Readiness Level
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GFT	Gasification + Fischer-Tropsch synthesis
GHG	Green-house Gases
GW	Gigawatt (1000 MW)
GWh	Gigawatt-hour (1000 MWh)
HEFA	Hydroprocessed Esters and Fatty Acids
HVO	Hydroprocessed Vegetable Oil
IATA	International Air Transport Association
ICAO	United Nations' International Civil Aviation Organization
IEA	International Energy Agency

ILUC	Indirect Land Use Change
IRENA	International Renewable Energy Agency
KJ	Kilojoules
KW	Kilowatt (1000 W)
LCA	Lifecycle Assessment
LCOE	Levelized Cost of Electricity
LH2	Liquid Hydrogen
LHV	Lower Heating Value/Net Heating Value
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquidized Petroleum Gas
MBM	Market-Based Measures
MEA	Mono Ethanolamine
MJ	Megajoule (1 million Joule)
MRA	Multivariate Regression Analysis
MW	Megawatt (1000 KW)
MWh	Megawatt-hour (1000 KWh)
NDC	Nationally Determined Contributions
NREL	US National Renewable Energy Laboratory
OPEX	Operation Expenditure
PDI	Personal Disposable Income
PEM	Proton Exchange Membrane Electrolyser Cell
PJ	Petajoules (1000 Gigajoules)
PV	Photovoltaics
RE	Renewable Electricity
REDII	EU Renewable Energy Directive II
RFNBO	Renewable Fuels of Non-Biological Origin
RPK	Revenue Passenger Kilometer
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuel
SIP	Synthesized Iso-paraffin
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
SPK	Synthetic Paraffinic Kerosene
SPS	Substitution Potential Score
TRL	Technology Readiness Level
TW	Terawatts (1000 GW)
UK	United Kingdom
US	United States
USD	United States Dollars ($)
WACC	Weighted Average Cost of Capital

1. Introduction

"Those who have the privilege to know have the duty to act."

- *Albert Einstein (1879-1955)*

1.1. Global Alignment to Sustainability

The perspective on climate change underwent a significant shift after the 21st session of Conference of the Parties (COP21) in 2015, also known as the *Paris Agreement*. Before COP21, climate change was recognized as a global problem – with limited consensus and commitment to address it comprehensively, with discussions and debate only limited to the scientific and academic circles. Post-COP21, there has been a growing recognition of climate change as an existential threat to humankind and all the species living on earth at large, requiring immediate and coordinated remedial action(s). COP21 represented a collective acknowledgment of the urgency to mitigate climate change's impacts, particularly for vulnerable nations and ecosystems. These actions were articulated in the Article 2 of COP21 as [1]:

1. Holding the increase in the global average temperature to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

2. Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;

3. Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development.

COP21 was hailed as a diplomatic success as it took more than 20 years after the Earth Summit – 1992 in Rio de Janeiro to come to a global, multilateral consensus on the severity and urgency of the climate crisis, including the largest emitters such United States, Europe, China, and India [2]. That being said, the implementation of these measures was left to the individual nations to decide, commit, and implement under nationally determined contributions (NDCs). It should not come to no one's surprise that this open-ended approach led to a variety of timelines and strategies to combat climate change; several nations with developed economies striving to decarbonize their economies and decouple them from emissions by 2050 or even sooner, while developing nations in Asia, Africa, and South America committing to reach these goals in the latter half of the 21st century. Germany being one of the most developed nations on the planet aims to achieve this goal by 2045 with an accelerated approach to have at least 42.5% sustainable energy mix by 2030 under the ambitious EU Renewable Energy Directives [3].

1.2. The Path Towards Sustainability in Aviation

While the COP21 agreement has provided a crucial roadmap for global climate change mitigation, it is disheartening to note that the emissions stemming from the aviation sector have received relatively limited attention in this forum [2]. This might be attributed to the fact that aviation's contribution to global emissions is relatively small, accounting for approximately 2% of the annual global emissions, totaling around 800 million metric tons (Mt) [4].

However, it is imperative that these emissions are not overlooked. The demand for aviation is projected to escalate in the coming years due to factors such as population growth, globalization, and improved living standards. As aviation demand increases, so too will its emissions. It is estimated that by 2050, due to decarbonization of other sectors, aviation sector will contribute 27% of the remaining global emissions [5]. Therefore, it is crucial to address this issue with thoughtful consideration and proactive measures, under a globally collaborative environment. This highlights the need for a global forum, which is presently being addressed by the International Civil Aviation Organization (ICAO) as a United Nation’s Agency and International Air Transport Association (IATA). These institutions are spearheading the discussion on global aviation sector’s decarbonization and its collateral impacts on the aviation markets.

However, the progress on this front is rife with bureaucracy, diplomacy, and sluggishness due to the involvement of multi-lateral, multi-national, multi-stakeholder agreements with competing, and often diverging interests. This has pushed regional agencies to implement their own remedies with significant backlash from the international community. A detailed account of these developments is presented in History

1.3. Aspirational Targets

Moving forward the IATA has called for a carbon-neutral growth from 2020 and 50% reduction by 2050 in reference to 2005 emission levels. These have been reiterated by ICAO in resolution A40-18 with a set of measures outlined to reach these “aspirational” goals. The ICAO expects emission savings from Sustainable Aviation Fuels (SAFs) in coordination with market-based measures (MBMs) under the CORSIA framework to provide almost two-thirds (2/3) of emission reduction by 2050, with the rest of the improvement provided in terms of operational improvements and aircraft technologies - this will offer 2% per annum (p.a.) fuel reduction [6]. However, ICAO acknowledges that the rate of development and incremental gains are diminishing and will not be sufficient to effectively meet these targets and recommended that, other approaches, including changes in aircraft configurations, mission specifications, air traffic management, operational improvements, sustainable aviation fuels, and market measures should be introduced [7].

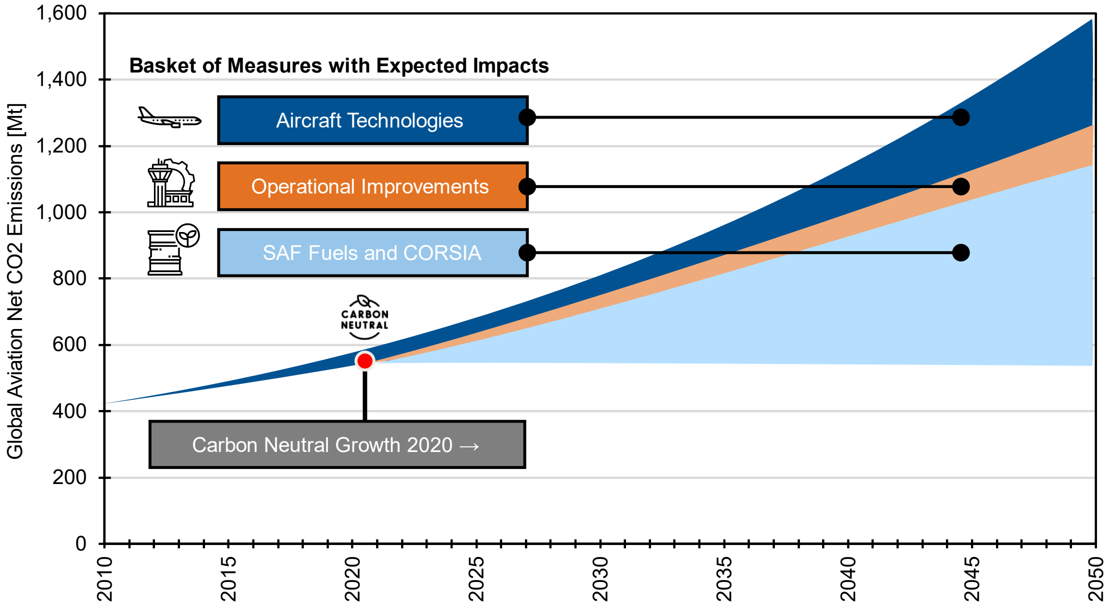

Figure 1: ICAO/IATA aspirational goals for carbon-neutral aviation growth with measures and their expected impact

Source: Original data by ICAO [6, 8], illustration by author

1.4. Market-Based Measures: CORSIA and EU ETS

In light of the Paris Agreement, ICAO resolutions, and the EU's commitment to internalize the cost of emissions, two market-based measures (MBMs) are particularly relevant to the aviation industry: the EU's **Emission Trading System** (EU ETS) and ICAO's **Carbon Offsetting and Reduction Scheme for International Aviation** (CORSIA). While these systems differ fundamentally in design, implementation, and scope, their shared objective is clear: to reduce global aviation emissions by internalizing the cost of emissions through a market-based pricing mechanism, primarily targeting carbon dioxide emissions. While EU ETS applies to the 27 member nations of the EU with mandatory participation, the geographical application of CORSIA is global with participation mostly being voluntary – EU member nations participate in both systems. One key aspect is that 2021 onwards, the allocation for aviation sector in EU ETS is being reduced linearly by 4.2% per annum. The key differences between these systems and their inclusion in the analysis is provided in Table 1 and status of countries in regards to their participation in MBMs are illustrated in Figure 2.

Table 1: Comparison of Market-Based Measures in relevance to the aviation sector: EU ETS and CORSIA

Source: Compiled from [2, 9–14]

Dimensions	EU ETS	CORSIA
Modality	Cap-and-trade	Offsetting
Coverage	Broad; covers various sectors including aviation	Specific to aviation section; focuses on international aviation emissions
Emission Cap	Sets a limit on emissions allowances issued with reduction over time	Aims to stabilize global emissions at 2020 levels.
Allocation	Airlines/Operators must buy allowances within the system. 4.2% p.a. reduction for the aviation sector 2021 onwards.	Requires airlines/operators to purchase offset credits or use CORSIA Eligible Fuels
Interoperability	EU ETS allowances not accepted under CORSIA	Credits not accepted under EU ETS
Emission Reduction Goal	Aims to reduce emissions by 61% in 2030 compared to 2005-levels	Aims to achieve carbon-neutral growth, with no net emissions increase post-2020
Cost Structure	The price of allowances is driven by supply and demand within the system	The cost of CORSIA eligible emission units varies depending on project category
Monitoring & Reporting	Both include similar *Monitoring, Reporting, and Verification (MRV)* systems to ensure robust and reliable emissions data	Airlines must draft *Emissions Monitoring Plans*, monitor emissions, report annually, and undergo third-party verification
Region	EU-27 (mandatory)	Global (voluntary)
Timeline	In place, currently in Phase 4 (2021-2030)	Pilot phase: 2021-2023 First phase: 2024-2026 Second phase: 2027-2035
Inclusion in the Energy Model	Yes, as a CO2 cost factor per unit of energy	Yes, as a CO2 Budget/Cap in certain scenarios

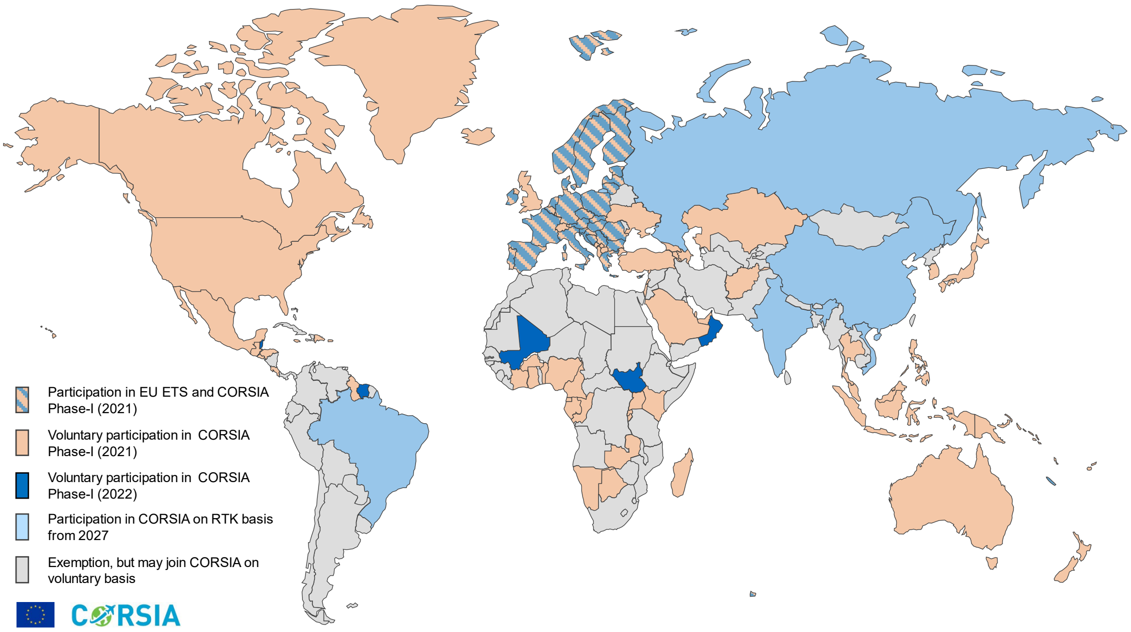

Figure 2: Country-wise participation status in Market-Based Measures (MBM) for CORSIA and EU ETS

Source: Author's own graphic based on data from [15, 16]

1.5. Original Contributions

During the literature review, it is observed that the existing research known to the author largely focuses on global- or country-level analyses, and reduced assessment has been done on the requirements specific to the aviation sector. On the other hand, several papers focus on the production of SAFs fail to address the supply-side constraints, economics, and other drivers of sustainability in the sector. However, with the active push from the EU and German government, and general guidelines from international bodies such as ICAO to reduce the overall emission of the sector, it is expected that the demand for SAFs would significantly increase. That being said, the sole topic of production, supply, and consumption of these fuels for aviation purposes in Germany is largely undiscussed and is often discussed in tandem with the transportation sector as whole – leading to many unaddressed concerns of the sector.

By this research, effort is expended to address the aviation sector in a manner that provides a clear analysis and understanding of the current and future aspirations of carbon-neutral aviation in Germany - taking into consideration technical and commercial aspects of decarbonization of various aviation fuels. Moreover, the research aims to optimize these parameters, in terms of cost and emissions, and obtain some probable pathways that may be undertaken to completely decarbonize the aviation sector by 2050.

1.6. Structure of the Thesis

The structure of the thesis can be broken down into 4 major segments, i.e., (1) data gathering and processing of acquired information, (2) translation of obtained data into inputs for the energy and demand model, (3) modelling of the aviation demand and energy requirements under various scenarios and finally (4) assimilating the results and drawing meaningful conclusions (see Figure 3).

For data collection, scientific papers, reports of international and national organizations, and, databases from trustworthy sources such as national and European statistic offices are selected. In addition to this, hourly timeseries of renewable generation is obtained from the tool developed at TUM-ENS called PyGRETA [17]. Wherever possible, region-specific values for Germany are used, and in the case of non-availability of such values European or global estimates are used consequently.

The data undergoes transformation and synthesis from diverse sources for analysis. Applying fundamental thermodynamic and chemistry principles, including stoichiometry calculations, yields numerical values. Key vectors in the analysis include regional energy generation potential, land usage and availability, crop cultivation and yields, fuel conversion processes, their technical and commercial viability, economic factors like capital requirements and operational costs, emissions intensities, and their alignment with global and regional emission targets. The modeling period spans from 2025 to 2050.

With these aspects taken into consideration, a comprehensive demand forecast model is developed using statistical tools based on regression analysis. Concurrently, the techno-economic inputs are used to develop an energy model to establish an optimal system expansion under cost and environmental considerations; based on the urbs energy modelling framework developed at TUM-ENS [18]. The results from these models provide a sustainability assessment framework for various SAF pathways envisaged to decarbonize aviation and an outlook for the coming 25 years of energy requirements of the aviation sector in Germany, with estimates for costs and incumbent emissions from the sector, and may serve as tool for policy development and decision-making.

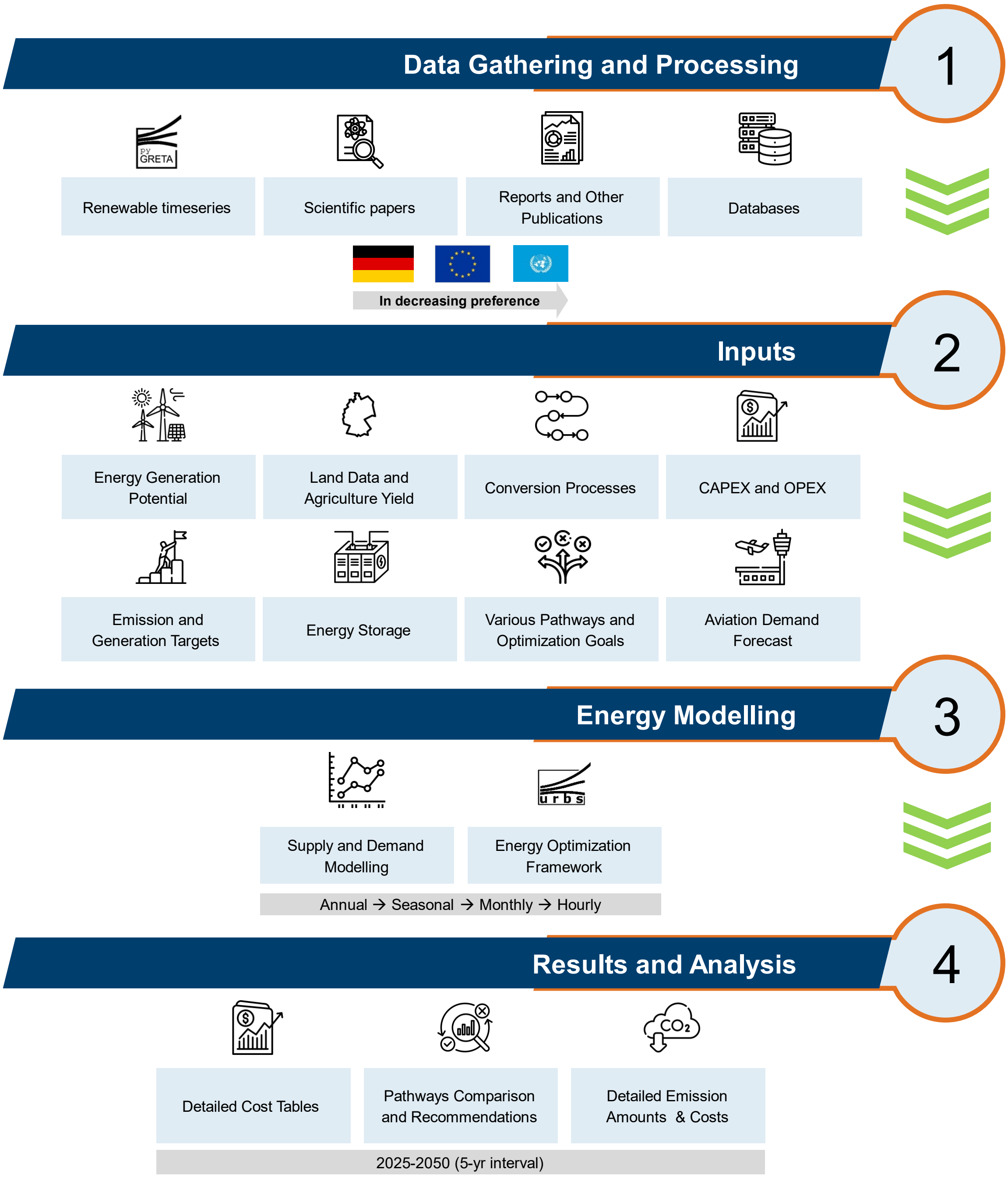

Figure 3: Graphical representation of the major segments of the research (thesis) along with key inputs and results

2. Status Quo in Germany

> *"When you don't know where you are going, all roads will take you there."*
>
> \- *Yiddish Proverb*

2.1. Aviation in Germany

The aviation in Germany is largely dominated by passenger traffic – in line with the global trends; in total approx. 2.3 million landings and take-offs were recorded in Germany in 2021 out of which 896,000 occurred at one of the 12 largest airports [19]. The largest/busiest airport in Germany, Frankfurt/Main, has reported an annual traffic of 70 million passengers in 2019 [20]. Apart from passenger traffic, approx. 5.5 million tons of freight is also transported through flights originating from or terminating in Germany [19]. The distribution of these flights is certainly not homogenous, with 65% of the flights occurring at the top 5 airports. Most of the passenger volume is presently handled by the top 2 airports, namely, Frankfurt/Main and Munich airport. Apart from the impact of COVID-19 pandemic on the global aviation industry, which is also reflected on the German sector, the number of flights occurring in Germany has remained relatively stable; fluctuating around the baseline value of 3 million flights per annum [19]. This trend is also observable in the overall energy demand of the sector.

2.1.1. Energy Consumption

In the context of Germany's transportation energy consumption, aviation-related fuels, specifically aviation jet fuel (kerosene) and petroleum, have historically accounted for a notable portion, ranging from 10% to 16% of the annual energy demand. According to the most recent data for the year 2021 published by Kraftfahrt-Bundesamt [19], this share was recorded at 11%. In absolute terms, this amounted to 258 PJ or 71.66 TWh of energy. Notably, this figure represents a substantial 40% decrease from the highest recorded value (2018) spanning a 20-year period, which stood at 437 PJ or 121.3 TWh. That being said, this share falls short in comparison to diesel and gasoline consumption; accounting for approx. 80% of the end-energy consumption, the rest being accounted by electricity and renewable fuels. In terms of growth, the aviation sector energy demand has increased steadily over the last 10- and 20 years at 1.69% and 2.22% CAGR[1] respectively. Meanwhile, the overall demand of the transport sector has observed negative growth over the last 20 years.

The aviation sector energy demand serves as one of the key variables to forecast the aviation demand for the period 2025-2050 and is further discussed in Chapter 4. However, due to major deviations caused by the COVID-19 pandemic the source data is terminated at 2019 values. The 2019 aviation energy consumption in Germany stood at 434 PJ or 120.5 TWh.

2.1.2. Aviation Related Emissions

Statistics published by the Eurostat [20] and European Alternative Fuels Observatory [21] highlights that the aviation demand in Europe has steadily risen by 60% over the period between 2005 and 2017, alongside a 24% improvement in the fuel efficiency during the same period. Thereby, gains in fuel efficiency have largely been negated by the increased demand from higher traffic resulting in overall higher emissions. These direct emissions from the aviation sector accounts for 3.8% of the total EU emissions which is higher than the global contribution of around 2%, and embodies approx. 14% of the total transport sector emissions in EU [21]. However, the emissions from on-ground activities and airport operations are largely ignored in these stats. The report published by German Aviation Association [22] classified the overall CO_2 footprint from aviation activities into 3 scopes. Scope 1 emissions directly account for the emissions as a result of the airport activities, encompassing energy production (heating, cooling, and electricity) and transportation of goods and people within the airport. Scope 2 emissions arise from purchased energy for airport operations. Together, they are responsible for 17% of the CO_2 footprint for aviation-related activities and are reported by the airports, the rest of the contribution (Scope 3) is attributed to the flight activities at the airport and fall in the domain of the airlines. Scope 3 emissions also includes transportation to the airport including personal and public transportation, in spite of this, due to the completely different order of magnitude in comparison to aircraft emissions these are not explicitly discussed further.

Most databases for fuel consumption and associated emissions known to the author focus on end-energy consumption as a function of energy or mass of the jet fuel and tend to ignore the scope 1 and 2 emissions. If these emissions are included in the analysis the resultant emission will be notably higher. However, for sake of simplicity, and the fact that

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[1] Compound Annual Growth Rate (CAGR) represent the mean growth rate over the specified period

scope 1 and 2 emissions can be eliminated through the decarbonization of the heating and electricity infrastructure which is already underway, thereby these are also excluded from this analysis.

According to the data published by Eurostat [20] it is evident that most flights are international in nature, either to EU countries or non-EU-countries. This is also corroborated by Siemons et al. [23] which claims that 94% of the refueling activities are carried out for international flights, with a 75:25 distribution for non-EU- to EU-bound flights. As aviation is predominantly supplied by fossil fuels, this translates into similar distribution for emissions. Figure 4 provides an illustrative summary of the above discussion. Based on the emission intensity of fossil fuel of 94 g_{CO2eq}/MJ or 0.3384 ton_{CO2eq}/MWh provided in Annex V of REDII (EU Renewable Energy Directive II) [3] and energy consumption discussed in previous sections, the overall emissions from fuel consumption equates to 40.8 Mt_{CO2eq}. The emission intensity provided in REDII is 6.4% higher than the “Well-to-Wheel” default values provided in EN 16258:2012/DIN EN 16258:2013 standard, which assumes an emission intensity of 88 g_{CO2eq}/MJ [24]. For modelling purposes, REDII values are used as the benchmark for the fossil-based fuel emissions.

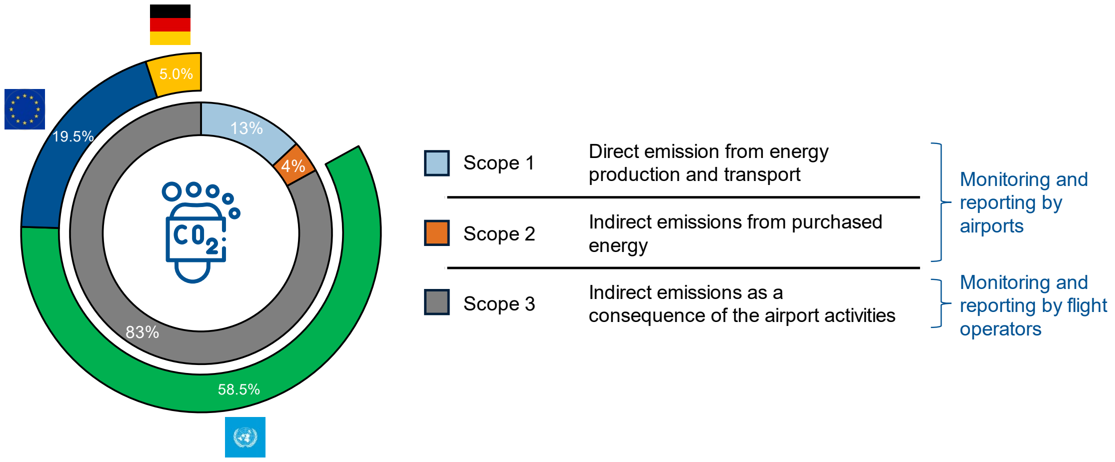

Figure 4: German aviation activities carbon footprint breakdown by scope and destination

Source: Originally reported by German Aviation Association (BDL) [22] and Siemons et al. [23], illustrations by the author

2.2. German Aviation in the Light of Climate Targets

2.2.1. Legislative Framework

The EU climate and energy policies directly affect the German climate target and are often transposed into German law. Thus, they cannot be isolated and have to be looked into from the perspective of overarching pan-EU climate targets and directives. Following the research, various estimates, targets, and milestones are discovered – with various dates and subsequent amendments which makes the estimation difficult. A case in point being the German government aim to reduce the greenhouse gas (GHG) emissions from 80% to 95% by 2050 compared to the 1990-baseline values. Thereby, variations in the analysis should be expected based on when it is conducted, published and when it is read. For the calculations, it is decided to utilize the targets outlined in three key EU directives: the "Fit for 55" Package, "REDII" Directive, and "ReFuelEU Aviation" Directive. These directives collectively establish the overarching goals of the EU to achieve a 55% reduction in GHG emissions by the year 2030. Furthermore, they provide specific guidance on achieving net-zero emissions by the year 2050, as well as sector-specific objectives.

2.2.2. Effects on the Aviation Sector

Based on the transport-related target set under REDII and 'Fit for 55' package, which are further complemented by more aviation specific guidelines under 'ReFuelEU Aviation', in Germany and EU, there is an obligation to have at least 2% SAF either by volume or mass in aviation fuel supply by 2025. This limit increases stepwise to 6% by 2030 following the goals derived from transport-related REDII targets, then increasing to 20% in 2035, 34% in 2040, 42% in 2045 and finally to 70% in 2050 respectively. This entails a pre-defined target specifically for e-fuels, with obligations starting at 1.2% in 2030 leading to 35% aviation fuels based on electricity by 2050 – side-by-side trend comparison is illustrated in Figure 5. Under these legislative mandates, for Germany, it is expected that a minimum of 200,000 tons p.a. of kerosene will be produced from Power-to-Liquid sources by 2030 [25]. Notwithstanding, the current supply of SAF in the EU only accounts to 0.05% of the annual jet fuel demand, with Frankfurt, Munich and Dusseldorf Airports in Germany being the few airports in EU to regularly offer SAF within their facilities [26].

In the context of aviation emissions in Germany, the current emissions level stands at 40.8 Mt_{CO2eq} (see section 2.1.2). According to Siemons et al. [23], aviation-related emissions in 1990 amounted to 14 Mt_{CO2eq}, indicating an alarming increase of nearly 290% over the past three decades. This substantial rise in emissions is a matter of grave concern, especially when juxtaposed with the ambitious emissions reduction targets outlined in the EU's "Fit for 55" initiative, which aims to achieve a substantial reduction in GHG emissions by 2030 and net neutrality by 2050. It is important to note that, in contrast to the desired trajectory, the German aviation sector is not merely falling behind but rather moving in the opposite direction. If the aviation sector had managed to decarbonize at a pace similar to what is envisaged for other modes of transportation, the resultant emissions would have been approximately 9 Mt_{CO2eq}. Figure 5 depicts the starkness of the diverging trend of envisaged-vis-à-vis observed emissions. This stark divergence from the decarbonization trajectory underscores the pressing need for comprehensive measures and strategies to curb emissions within the aviation sector, aligning it with the broader sustainability goals and climate targets outlined by the EU.

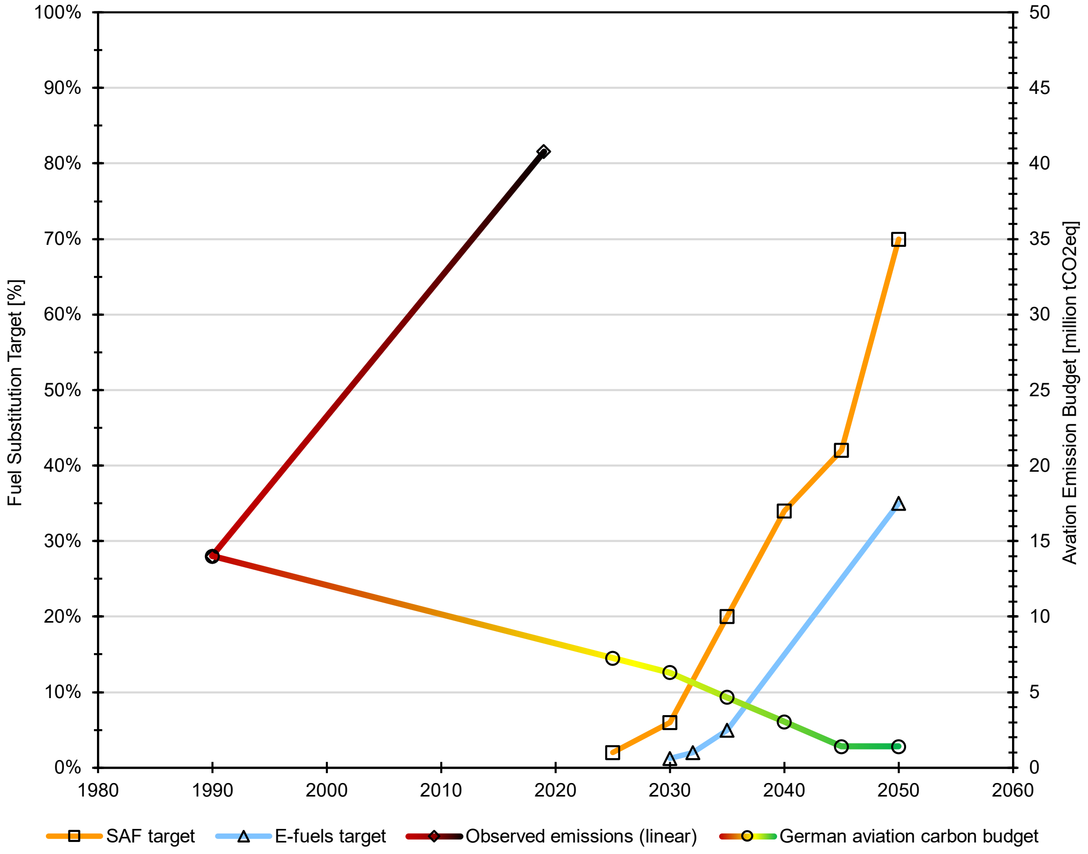

Figure 5: EU targets for Sustainable Aviation Fuels (SAF) and E-fuels (left axis) against German aviation carbon budget to achieve climate-neutrality by 2045 and the observed emission (right axis)

Source: Calculated by the author based on REDII, ReFuelEU Aviation and 'Fit for 55' targets [3, 23, 27, 28]

2.2.3. Existing SAF Production Facilities

From the production point of view, there exists only two commercial, one demonstration and two pilot projects to produce SAF in Germany, with only Power-to-Liquid (PtL) and Alcohol-to-Jet (ATJ) being the dominant technologies [26, 29]. These projects are, namely:

1. PtL– Shell, Wesseling (commercial)
2. PtL – Gevo/HCS, Speyer (demonstration)
3. PtL – Caphenia, Frankfurt (pilot)
4. ATJ-SPK – Global Bioenergies, Leuna (pilot)
5. PtL – Atmosfair, Emsland (commercial)

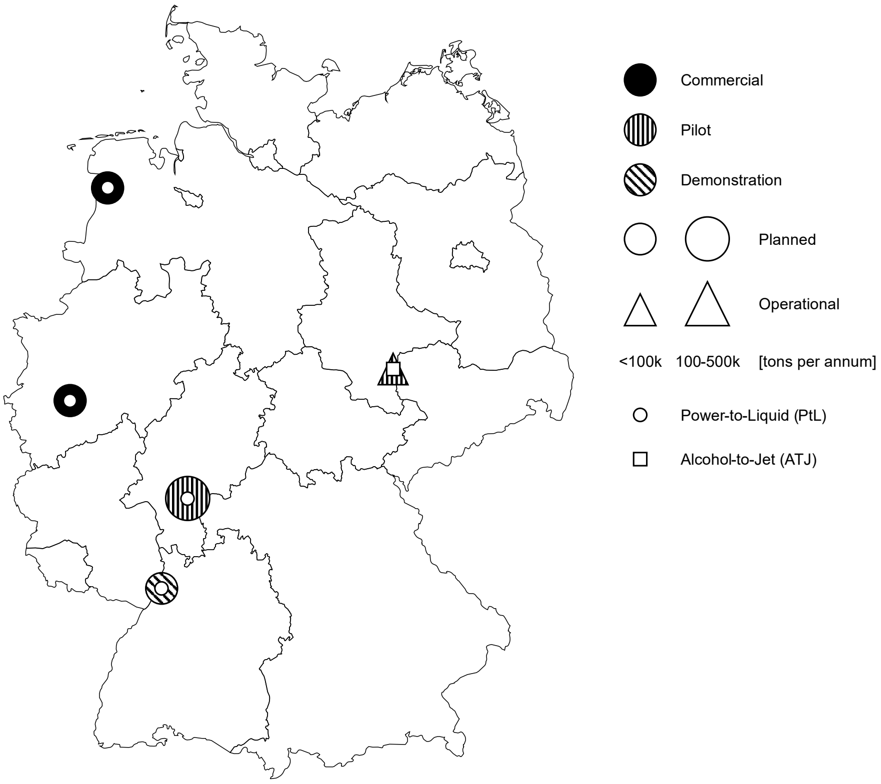

Figure 6: Approximate Location, Technology, Size and Status of Sustainable Aviation Fuel (SAF) production facilities in Germany

Source: Data from [26, 29], graphical representation by the author

Moreover, it is observed that only Fischer-Tropsch synthesis and alcohol synthesis is used to produce PtL kerosene in Germany, with methanol-to-olefins and subsequently olefins-to-distillate being used for alcohol synthesis [25]. PtL is observed to be the preferred technology for commercial plants in Germany.

2.3. Renewable Energy and Expansion Targets

Apart from the aviation sector, there is a constant push for the electrification of the German economy and decoupling the economic growth from the energy demand under various initiatives and regulations; most notably being the “Energiewende”. This has led to a significant increase in the demand of electricity in the partially electrified sectors, such as industry and transportation, and would further increase the demand due to the sectors which are not even electrified yet, such as heating. As depicted earlier, the aviation demand falls short in terms of the overall transport sector demand and even less significant when compared to the overall German energy demand. Despite being a trivial part of the overall emissions, the sector is poised to grow (see Chapter 4). Due to technical limitations, such as energy density, aging fleet, and global momentum, it is expected that the sector remains dependent on liquid fuels for the foreseeable future. Consequently, many resources researched during the course of the analysis classified aviation as a ‘**hard-to-abate’** sector in terms of electrification or potential to reduce GHG emissions, which may significantly limit the ability to reach the climate targets underlined in the Paris Agreement [30–36].

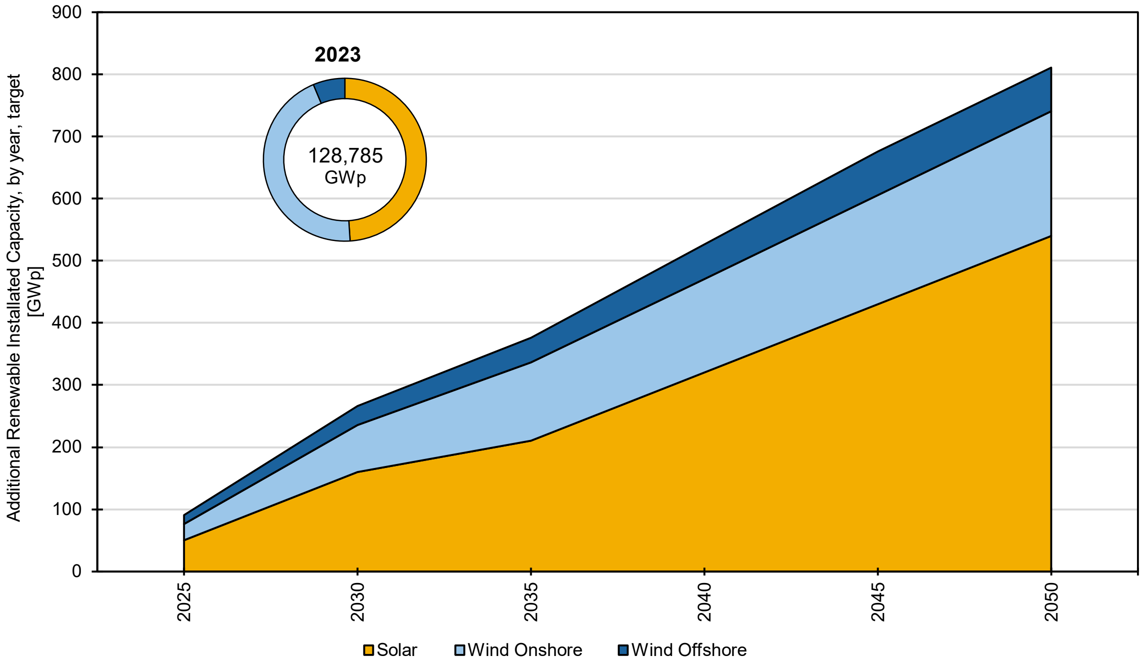

Figure 7: Germany renewable energy installations (Onshore-, Offshore wind, and Solar PV) status quo, planned expansions and assumed expansion

Source: Based on the plans provided in the Easter Package [37] and further assumptions made by the author

Based on datasets provided by the German Federal Statistics Office [38], renewable sources contribute to 44% of the total electricity production in Germany, from sources such as wind, solar, hydro, biomass and geothermal energy; while the rest is produced from conventional sources including coal, natural gas, and now diminishing nuclear energy. According to the statistics, in 2022, wind-based electricity emerged as the single largest source of electricity in Germany contributing 21.7% to the total supply – surpassing all the conventional sources. As for the installed capacity, according to SMARD platform, in August 2023, the total system capacity stands at 232.8 GW of which 63 GW is solar PV, 57.6 GW is onshore wind and 8.2 GW is characterized by offshore wind [39].

Due to the already established demand, existing capacity of RE is not made available in the analysis, rather future expansion plans are taken as available capacity to be used for the production of various aviation related fuels and co-products. Various sources provide various estimates for the expansion of the German renewable electricity supply from 2025 onward. However, for the sake of trackable targets, the capacity expansion is limited to the forecasts provided in the “Easter Package” by the German Federal Ministry for Economic

Affairs and Climate Action and the co-revised pertinent acts to achieve 600 TWh of renewable electricity by 2030. The key targets till 2050 provided in the Easter Package and future expansion plans are tabulated in Table 2 and are graphically presented in the Figure 7.

As for the assumption made for the capacity expansion, these are categorized as "conservative" estimates, given the urgency and ambitions to reach climate neutrality. This point can be bolstered by the calculations provided by the Fraunhofer ISE [40], in which the technical potential of various solar technologies are discussed. As an example, for Agri-PV[2] alone a 1000 GW plus potential is concluded by the report. Similar estimates in the range of 800-1200 GW for onshore wind installations are provided by Amme et al. [41] and Lütkehus et al. [42], provided that the acceptance of wind turbines increases and land is appropriately used [43, 44].

Table 2: Germany renewable energy expansion targets and assumptions, 2025-2050

Source: Based on the 'Easter Package' [37] and author's assumptions

Technology	Targets	Assumptions
Solar PV	Now-2025: additional 50 GW 2025-2035: 22 GW additional per annum	2036-2050: 10 GW installed each year
Onshore Wind	Now-2025: additional 26 GW 2025-2035: 10 GW additional per annum	2036-2050: 5 GW installed each year
Offshore Wind	Now-2025: additional 15 GW 2025-2030: further 15 GW expansion 2031-2035: additional 10 GW to be added 2036-2045: 3 GW per annum expansion	No assumption

2.4. Biofuels Production in Germany

Despite the infancy of the SAF sector, the production of other biofuels is relatively substantial in Germany; primarily used for the blending with gasoline and diesel fuels. According to the latest statistics by the German bureau of statistic [45], biodiesel production through methyl esters stood at 3.2 million tons per annum in 2017, while 640 kilotons of bioethanol was produced in the same period - for which, wheat, rye, sugar beet and rapeseed is

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[2] Agri-PV are Solar PV installations deployed on land co-used for agricultural purposes, either on-ground, elevated structures, buildings, or some other available space

cultivated locally. The breakdown of various important crops used for the production of biofuels, i.e., biodiesel and bioethanol, is illustrated in Figure 8.

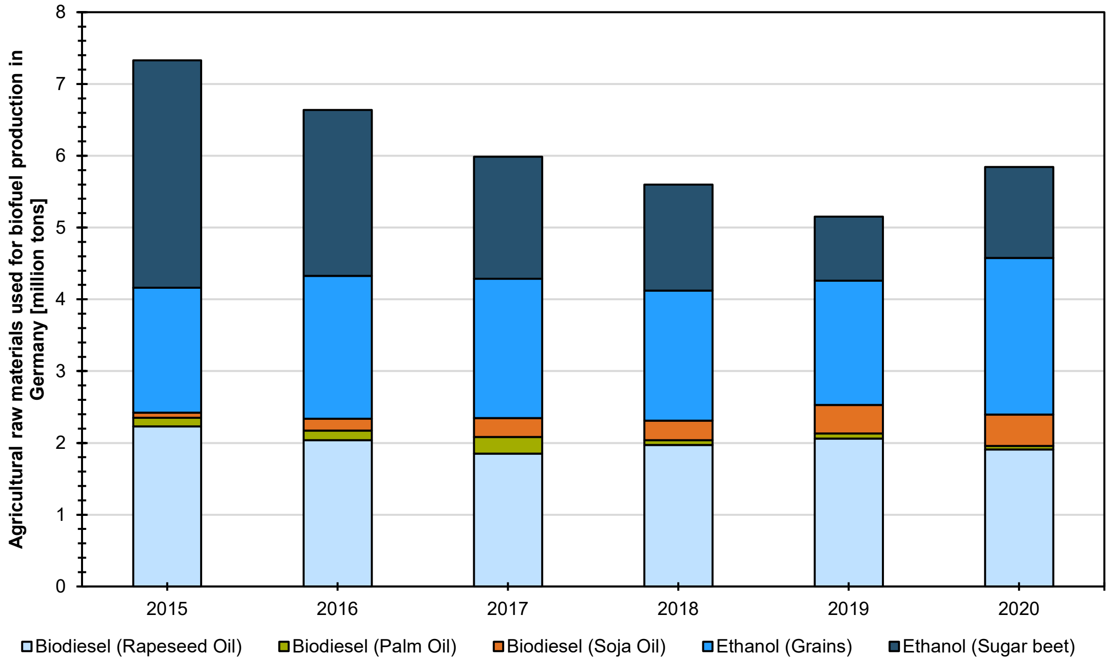

Figure 8: Amounts of agricultural raw materials used for biofuel production in Germany, in tons (2015-2020)

Source: Published by Fachagentur Nachwachsende Rohstoffe e.V. (FNR) [46]

2.5. Energy Crops Cultivation – Land Usage and Potential

As of 2021, 180,590 sq. kilometers (18,059,000 hectares) of area is under cultivation for agricultural-use, accounting for 50.5% of the total land coverage of Germany [47]. In addition to that, it is observed that the proportion of this usage has remained stable over last decades as well (1960-2021), hovering around 50% [48]. As Germany has one of the highest land-usage in the world, and with strict regulations for redesignation of pre-specified land-use; this makes it difficult to expand existing land for additional cultivations, be it for energy- or food crops. As of 2021, only 3,731 sq. kilometers of fallow land is available in the country, which may be used for additional cultivations without affecting the existing crops [49].

Data published by FNR in Figure 9 illustrates the breakdown of land usage of crops for industrial and energy purposes. It is clear that biogas accounts for the highest land area usage, followed by biodiesel and bioethanol respectively; adding up to 2.3 million hectares out of the total 18 million hectares used for agriculture. FNR further provides additional data on the specific yield of various feedstocks used in Germany, which are pivotal in establishing the area and biomass requirements for various feedstock-based pathways – these are appended as Appendix B-4 for easier reference.

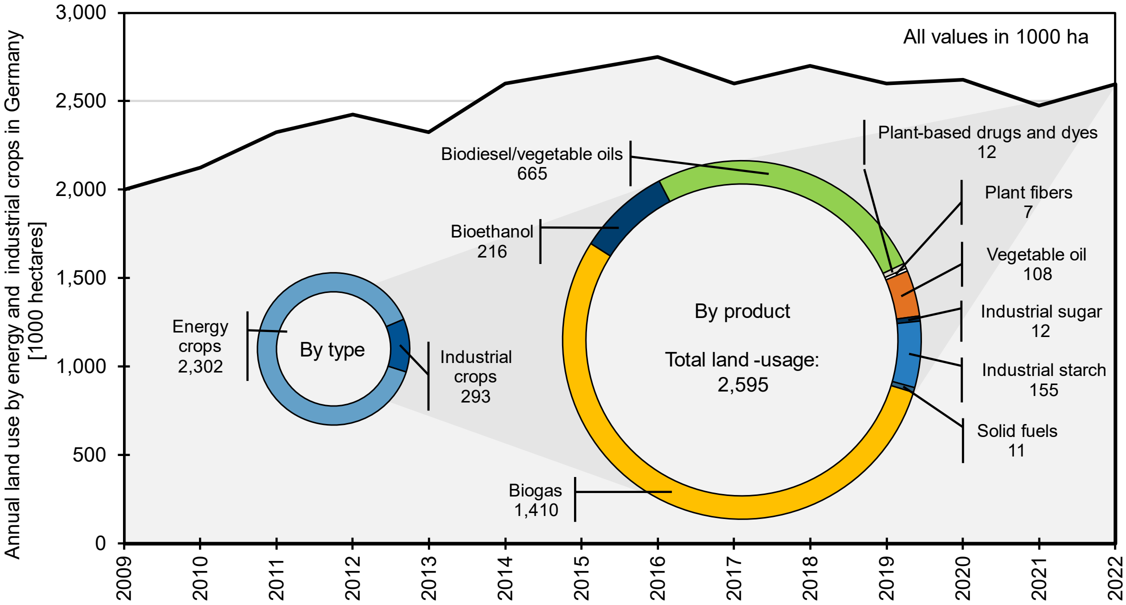

Figure 9: Land-usage of sustainable crops by sector of usage in 1000 hectares [1000 ha]

Source: Published by Fachagentur Nachwachsende Rohstoffe e.V. (FNR) [46]

For bioethanol production, sugar beet crop offers the highest specific yield and is the most land efficient crop for the indigenous production of bioethanol in Germany. As SAF can be synthesized from alcohols, this pathway would yield the most effective land usage for bioethanol pathways. Additionally, for the biodiesel production palm oil offers the most efficient land use scenario. Despite this, the palm oil cannot be used further for biofuel production due to legislative reasons stemming from environmental concerns. In addition to that, there is no major cultivation of palm oil in Germany and the feedstock needs to be imported.

The analysis is extended for various crops listed above, with total production and harvest on an annual basis, along with specific yields listed as Appendix B-1. It is observed that the specific yield of these crops may vary from year-to-year, however, the annual production has maintained a similar level. Moreover, overwhelming majority of the rapeseed production is accounted for by the winter rape harvest.

The other major non-agricultural land use comprises of forest, urban, or water, as well as permanent grasslands. From Asam et al. [50], for the year 2018, it is observed that the arable land in the northern Germany appears to be the hotspot for the cultivation of sugar beet and rapeseed crops, while in the south only rapeseed cultivation in a scattered manner is observable; with hops being the dominant crop in the state of Bavaria with a hot spot of sugar beet cultivation in the east of Munich.

2.6. Availability of Feedstocks

2.6.1. 1st Generation Feedstocks

1st generation feedstocks are primarily derived agricultural products i.e., energy crops or crops cultivated specifically for the production of fuels. From the crops, which are readily cultivated in Germany and having an already established acceptance among farmers, supply chain, and expertise are the prime candidates for pathways based on 1st gen. feedstocks. Hence, already cultivated crops provide the most optimum selection under these conditions. Moreover, these crops should also have relatively high crop yield to ensure optimum use of the land; for bioethanol production sugar beet is the clear choice as it has the highest yield in comparison to its peers. Meanwhile for biodiesel, even though palm oil offers a better yield, however, it is not endogenously cultivated and currently facing a ban; resultantly, rapeseed is short-listed.

Other cultivated crops do not offer any specific advantages over the selected crops and in conjunction with the above-mentioned reasons, rapeseed and sugar beet are selected as 1st gen. feedstocks for this analysis. In terms of land to cultivate these crops, only fallow land is made available in this analysis, i.e., 3,731 sq. kilometers or 373,000 hectares. As these crops are seasonally overlapping, the land cannot be used back-to-back and only mutually-exclusive land-usage is possible. In order to improve the availability of feedstocks, more stringent methods such as export ban on biodiesel from rapeseed can be considered.

It is paramount to highlight that the selected crops compete with food and feed crops and are not in compliance with the Article 2 Point 34 of REDII directive [3] and thus does not comply with the SAF requirements under the ReFuelEU Aviation directive [28]. That being said, they are explored further as possible feedstocks due to commercial-scale facilities already operational in Germany and the rest of the world, and may offer a frictionless transition path to more advanced feedstocks.

Yield improvements and population change impact on crop production are not considered in the model. That being said, in the analysis by Majer et al. [51], it is estimated that steady population and decreasing livestock number in tandem with steadily increasing agricultural yields would reduce the area demand for food and feed production; this would in turn appropriate this land for potential energy crop cultivation. Following a simplistic analysis, this potential gain is not accounted in the calculations.

2.6.2. 2nd Generation/Advance Feedstocks

The meta-studies for Germany conducted by Thrän et al. and Majer et al. in 2011 and 2013 respectively [51, 52] serve as the foundation of the technical potential[3] discussed further for various advance feedstocks. The findings of the short-listed feedstocks from the studies are summarized below. It is further assumed that the land use does not change, thus the distribution of these resources remains constant throughout the analysis. However, climate change, among other influencing factors, may have significant impact on the potential of these feedstocks.

2.6.2.1. Forestry Biomass

The overall technical potential for forestry biomass in Germany lies in the range 511 PJ/annum, accounting for logging residues, fuel wood, unutilized logs and barks, and unharvested annual growth. The fuel wood is already utilized for energy purposes and thus cannot be considered for the production of aviation fuels. Thereby excluding the fuel wood from the calculations, theoretically, only 13.7 million $\text{tons}_{\text{air-dry}}$ (265 PJ/annum) of biomass is available for energy purposes per annum, majority of this potential is located in the regions of Bavaria, Baden-Württemberg and Hessen [51, 52].

2.6.2.2. Straw

The studies [51, 52] estimate the straw from cereal and rapeseed production for the year 2020 to be 184 PJ/annum. The production of the straw is directly related to the cultivation area of cereal and rapeseed crops and grain-straw ratio. Despite this, due to the lack of data actual correlation factor cannot be developed and the estimation is assumed to be the technical potential for further analysis. Furthermore, it is stated that the sustainable potential lies at 20% of the maximum due to the considerations for humus formation and sustainable soil functions. This limits the technical potential to 36.8 PJ/annum. The regional distribution is correlated with the cereal and rapeseed production areas – mostly in northern Germany [50].

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[3] [52] defines the technical fuel potential as the total energy content of the biomass to be used for energy purposes, expressed in terms of lower heating value (LHV).

2.6.2.3. Biodegradable and green waste

Generation of biodegradable and green waste feedstock is correlated with the population density. The overall potential stands at 23 PJ/annum – discounting for contaminants, loss during collection, and water content [51, 52].

2.6.2.4. Waste and industrial wood

Studies [51, 52] claim that approx. 7 million $\text{tons}_{\text{air-dry}}$ of waste wood could be utilized for energy production. However, due to significant downstream uses, majority of this resource is utilized for additional production. Afterwards, only 58 PJ/annum remains available for energy uses.

2.6.2.5. Total Advance Feedstock Available

Summing up all the short-listed feedstocks in Germany yield an overall technical potential of approx. 328 PJ/annum. Despite this, the usable potential is significantly lower due to the existing utilization of these feedstocks in various energy and non-energy processes. According to Brosowski et al. [53], 26.9-46.9 million $\text{ton}_{\text{dry-mass}}$ of usable technical potential exists [53], corelating this range with the mentioned maximum potential of 92.7-122.1 million $\text{ton}_{\text{dry-mass}}$ results in an available potential of 22% to 51% this is then used to adjust the above listed feedstocks. Thereby, the available technical potential for future energy usage lies in the range of 84.3-193.7 PJ p.a. (23.43-53.84 TWh). Appendix B-5 provides further information as graphs for feedstocks discussed above to established this potential.

It is worth noting that, there is no consideration made for the use of these feedstocks in other applications such as for diesel or biogas production. Although, diesel is generally produced as a co-product in most conversion pathways. Therefore, while developing the economic-model, considerations can be made to sell these by-products for improving the economics and faster returns of such projects.

Under the European law, advanced biofuels are classified as fuels produced from feedstocks listed in Part A of Annex IX of REDII such as algae, municipal waste, straw, animal manure, bagasse etc. [3] – these are in contrast to conventional crop-based biofuels enjoy certain regulatory benefits in terms of taxation, carbon emissions etc. That being considered, 3rd generation and 4th generation feedstocks i.e., algae and hybrid feedstocks are not discussed due to the lack of any commercial, large-scale deployment which is required for a comprehensive decarbonization of the sector. However, these may provide support in the future, once the technology is deployed at-scale.

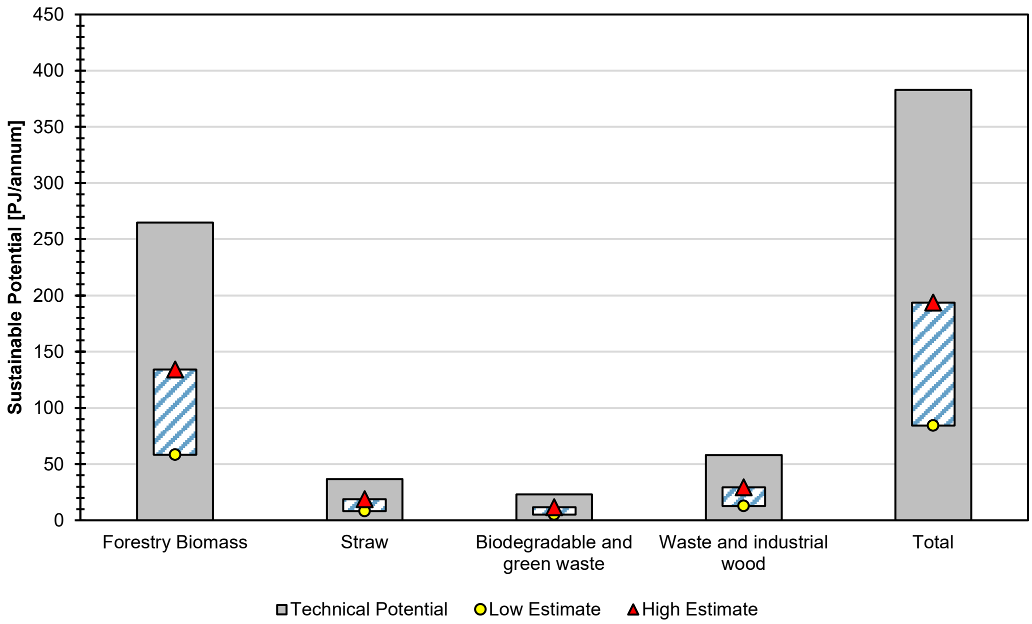


Figure 10: Second generation feedstocks sustainable technical and unused potential in Germany

Source: Author’s own graphic, synthesized data from [51–53]

2.6.3. Competing Sectors

Apart from the availability there is a pressing concern about the diversion of potential feedstocks for other activities such as food and feed production, energy generation and/or heating. Due to the limited scope of the thesis these are not fully explored and are not included in the analysis. However, preliminary research indicates that due to the highly flexible nature of biomass plant there is an ever-increasing interest in expanding the installed capacities through auctions, and plans are being put forward to scale-up the biomethane production by 600 MW per year from 2023 onwards [37]. This will further limit the supply of these feedstocks for aviation specific needs.

In addition to this, a psychological argument can also be made here, as the refueling operation for international flights is the major demand vector, as established earlier, most of the produced fuel will be used for these purposes. As these emissions would occur outside the German border and may not directly impact the local population, while other competing sectors and their emissions, like heating, energy-intensive industries, or transport, which would directly and immediately affect the German population. This could lead to a widespread reluctance, or in worst case, resistance, to the allocation of these feedstocks for aviation related activities.

3. Potential Sustainable Aviation Pathways

“A complex system that works is invariably found to have evolved from a simple system that works.”

- *John Gall, Systemantics: How Systems Really Work and How They Fail (1977)*

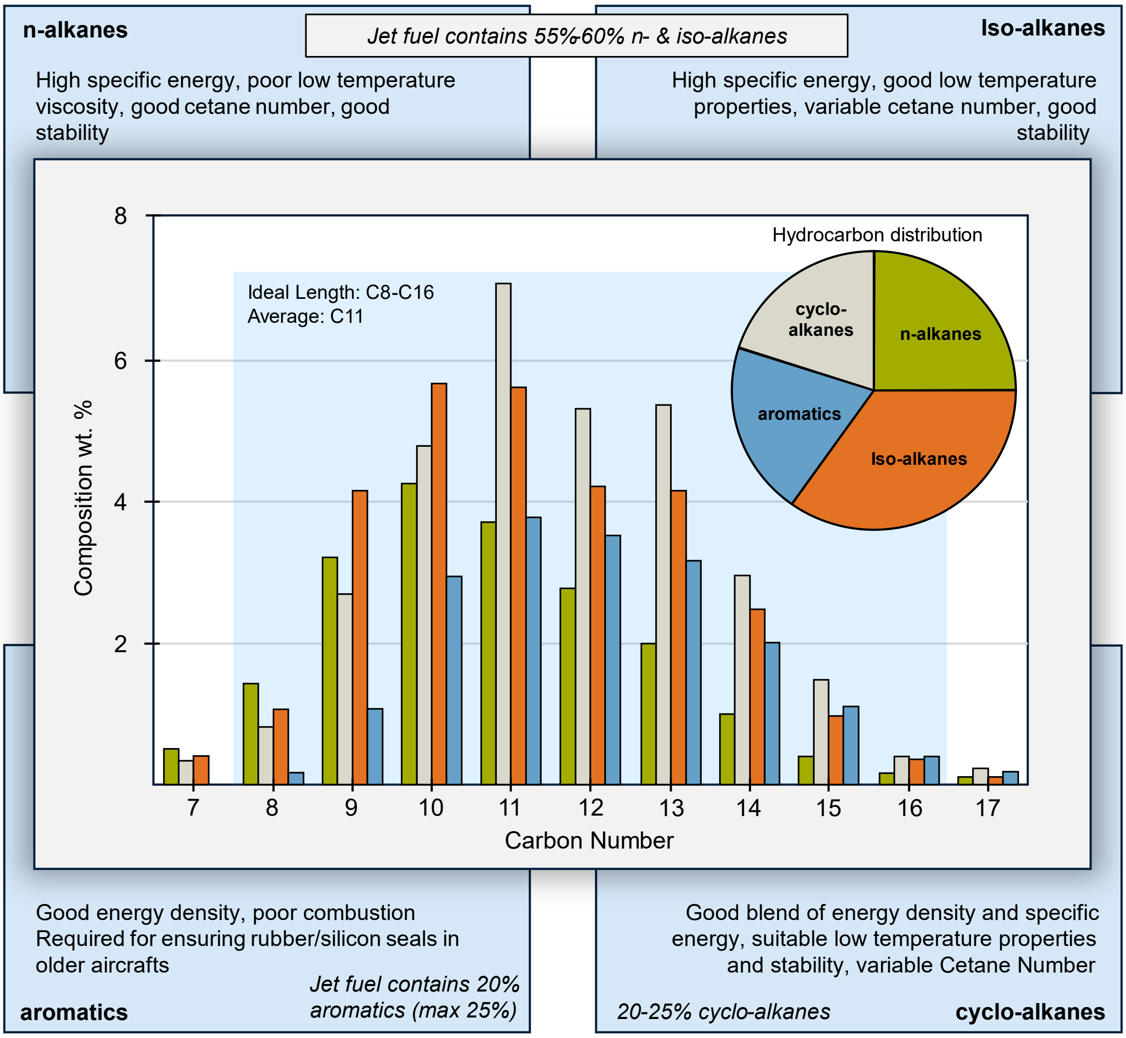
3.1. Conventional Jet Fuel

Woortman [54] defines jet fuel as “*a bulk product requiring substantial amounts of functional additives*”. For aviation purposes, currently, jet fuel is the primary energy source and almost all of it is currently derived from fossil fuel and is similar to kerosene in composition. Thereby, during the course of the discussion jet fuel and kerosene may be interchangeably used. “Functional Additives” are added to base kerosene to improve it operational characteristics and performance. There is no specific formula for jet fuel composition as it is derived from middle distillates during the refining process - between gasoline and diesel [55]. According to the findings from Holladay et al., the composition of jet fuel (carbon length) lies in the range of C7-C17 (see Figure 11), with ideal length being C8-16 [56]. Hydrocarbon structures, namely, n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics are normally distributed over this ranges, with the average carbon length being C11.

These hydrocarbons and their relative quantities define the thermo-physical properties of the jet fuel and standard-defined quantities are functionally necessary for the safety and longevity of the aircraft. For example, large quantities of aromatics are considered detrimental from the air quality and emissions perspective, however they cannot be completely eliminated for the airworthiness of older aircrafts, as the seals in the fuel handling system may degrade at an accelerated pace in their absence [57].

3.2. Certification of Aviation Fuels

Although there is a need for aviation gasoline (Avgas) for small aircraft, and jet fuel (Jet B) for military-related purposes, most of the aviation jet fuel (Jet A/A1) is used in civilian activities, and thus remains the focus of this analysis. Due to global nature of the supply and demand, and concerns regarding operational and storage safety; the production, supply, and storage of jet fuel is highly regulated and controlled by airline operators, aircraft manufactures and government regulators – this is achieved through standardization. The most recognized standard for regulating jet fuel production is ASTM D1655-21a (A/A1) along with inter-compatible Def Stan 91-091 (UK), while jet fuel derived from alternate processes relevant for sustainable aviation fuels (SAF) are standardized under **ASTM D7566-21** [58]. Any new fuel, therefore, must meet ASTM specifications and be approved through the ASTM D4054 process [56]. As the focus has shifted towards developing SAFs due to environmental concerns and the fact that compliance under ASTM D7655 is relatively harder to achieve, thereby every batch of jet fuel proceed under ASTM D7655 specifications is by default fully compatible with existing facilities and can be used alternatively without any limitations in the aviation fuel supply chain [59].



High specific energy, poor low temperature viscosity, good cetane number, good stability

High specific energy, good low temperature properties, variable cetane number, good stability

Good energy density, poor combustion Required for ensuring rubber/silicon seals in older aircrafts

Good blend of energy density and specific energy, suitable low temperature properties and stability, variable Cetane Number

Figure 11: Jet fuel composition by weight fraction and hydrocarbon distribution, with important properties and functions

Source: Derived from the graphs in Holladay et al. [56] and additional information from [60]

The standards stated above clearly outline the required thermal, physical, and chemical properties of the fuel blends as minimum or maximum threshold for various parameters; the energetic content of the fuel and density are the most important property for this analysis - these are referred from the ASTM D7566 standards. For the energetic content the value of 42.8 MJ/kg or 11.89 MWh/ton and for density 0.8 kg/liter are taken as reference values [61]. The energetic content is fixed as a minimum limit and any ‘compatible’ fuel must produce the minimum amount of energy for the fuel burn, otherwise reduction of power may negatively impact flight safety and operations [62, 63].

3.3. Drop-in and Non-Drop-in Alternatives

As the fuels produced under these specifications are fully compatible with the existing turbines, fuel handling and storage systems, and meet the technical requirements set under the standards, they are considered as “**drop-in**” fuels. However, the numbers approved are significantly limited by the conversion technologies, allowable feedstocks, and blending rates, thus limiting the options that can be used to decarbonize the aviation fuel supply.

As for the **“non-drop-in”** alternatives, they require either fundamental changes to the aircraft design and combustion technology to adapt for different kerosene-based jet fuels, or alter the complete architecture of the aircraft as in the case of hydrogen or electric airplanes. The latter is the least desirable option from the economic perspective, but both of these options are not ideal from the operators and airports perspective as they necessitate significant upfront investment to upgrade or replace the older aircrafts, overhaul the complete air-side fuel handling facilities, and develop newer systems and training protocols to handle the switch [64]. Notwithstanding, the alternate technologies are being developed and modern kerosene-based aircrafts are being tested/developed to be compatible with non-drop-in fuels [57, 65–68].

3.4. Sustainable Aviation Fuels

For the analysis, sustainable aviation fuels (SAFs) are defined as a drop-in or a non-drop-in alternatives to conventional aviation fuels, which are produced from sustainable and renewable feedstocks, either from biogenic or non-biogenic sources [69]. The conversion of these feedstocks into usable fuel may involve biological, biochemical, chemical, thermal, and/or thermochemical processes [60, 70–74]. A more robust definition may also include the classification of feedstocks under certain sustainability criterion – these are presented in Section 3.5. Based on the broadness of these definitions, it is imperative that a classification framework is implemented; for this purpose the classifications in Bullerdiek et al. is used, and the SAFs are classified as, namely [69]:

1. Biomass based SAF (b-SAF) - biogenic
2. Electricity based SAF (e-SAF) – non-biogenic
3. Hybrid SAF (h-SAF)

3.4.1. Biomass-based SAF

In essence, the categorization is based on the primary source of energy for the production of these fuels. In the b-SAF production, biogenic feedstocks are used, such as 1st gen., 2nd gen. or even advanced feedstocks – the biochemical energy stored in the feedstock is converted to chemical energy through various processes. In the broader definition of biogenic fuels, b-SAF is a sub-class of biofuels with a specific application in the aviation industry. The production of b-SAF is standardized under the ASTM D7566 and its annexures. All of the pathways approved in the aforementioned standard requires blending of conventional jet fuel to meet specifications, thereby reducing the effectiveness of decarbonization potential [75]. Table 3 provides a descriptive summary of all the production pathways approved in ASTM D7566.

Apart from the below-mentioned production pathways, there exists two additional pathways approved under D1655 Annex A1 for co-hydroprocessing of easter and fatty acids, and Fischer-Tropsch hydrocarbons in a conventional petroleum refinery. The maximum allowable blending of these fuel with conventional jet fuel is highly restrictive – only allowing 5%. That being said, it is reported that relaxations on the blending limits for co-processing are under consideration and higher blends will be allowed to maximize existing refineries utilization [34]. Moreover, it is also evident that the FT-SPK with aromatics (FT-SPK/A) and CHJ can potentially be used as standalone pathways (see Table 3) i.e., without the need for any blending, as these contains approximately 20% aromatic compounds which are currently required by ASTM certification [76].

Even though these processes are certified to meet the ASTM standards, it is worth noting that all the potential feedstocks may not be valid for Germany – due to concerns relating to agricultural, land- & water-use, and competition with food & fodder crops. For example, according to media sources [77], in 2023 Germany has banned the use of palm oil for biofuel production, citing concerns to global food shortages and deforestation. In addition to that, there is a proposal by the German Environment Minister, Steffi Lemke, to completely abolish the production of biofuels by 2030 from other crop-based feedstocks, such as wheat, rapeseed, corn, and soybeans [78]. This raises significant concerns regarding the long-term availability, and indigenous production of biofuels in Germany, be it for aviation or other sectors.

Table 3: ASTM D7566 approved drop-in SAF technologies with common feedstocks and maximum allowable blending

Source: [26, 55, 56, 59, 60, 64, 69, 70], with addition referenced in the table, author's inputs

Technology and Production Pathways	Maximum Blending (%vol/vol)	Feedstock Example[4] [5]	TRL[6]	FRL[7]	Comments	Approval	Global commercial Examples
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) & Fischer-Tropsch Paraffinic Kerosene with Aromatics (FT-SPK/A)	FT-SPK: 50% FT-SPK/A: 50-100% [76]	Waste (Municipal Solid Waste, coal, gas, saw dust)	FT-SPK: 7-8 FT-SPK/A: 6-7	FT-SPK: 7-9 FT-SPK/A: 7-9	FT-SPK/A is a variation of the FT process in which fully synthetic aviation fuel is produced Gasification is generally used to convert biomass to syngas	FT-SPK: 2009 FT-SPK/A: 2015	FT: Fulcrum Bioenergy (1 and 2), Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum FT-SPK/A: Sasol
Hydroprocessed fatty acid esters and fatty acids (HEFA)	50%	Vegetable oils: palm, camelina, jatropha, used cooking oils, Rapeseed oil. Any lipid source: fats, oil, or greases (FOGs)	8-9	9	Palm oil banned from 2023 onwards [77]	2011	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC, Total, skyNRG, Philips 66, Preem
Hydroprocessed Hydrocarbons-synthesized isoparaffinic kerosene (HH-SPK or HC-HEFA)	10%	Oils from specific algae (botryococcus braunii)	5	7		2020	IHI Corporation

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[4] Feedstock according to the ASTM D7566 Certification, however there can be other feedstocks.
[5] Could be limited by other regulations (e.g., ReFuelEU Aviation)
[6] TRL: Technology Readiness Level classification based on [79]
[7] FRL: Fuel Readiness Level based classification based on [80]

Technology and Production Pathways	Maximum Blending (%vol/vol)	Feedstock Example[4] [5]	TRL[6]	FRL[7]	Comments	Approval	Global commercial Examples
Synthesized Iso-paraffin (SIP)	10%	Sugar cane and Sugar beet	7-8	5-7		2014	Amyris, Total
Alcohol-to-Jet (ATJ)	50%	Sugar cane, Sugar beet, Saw dust, lignocellulosic residues (Straw)	7-8	7	Only isobutanol and ethanol pathways are applicable. Some ATJ pathways contain aromatic[8] compound which may enable 100% SAF certification [26].	2016 2018 (Ethanol)	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy, Lanzajet
Catalytic Hydrothermolysis Jet Fuel (CHJ)	50%-100% [76]	Waste oils or energy oils	6-7 [76]	7		2020	Applied Research Associates (ARA), Readifuels

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[8] Aromatic compounds, even though considered bad from the emissions and air quality perspective, are still required for the rubber seals in aircraft engines, and a fuel blend lacking these aromatic compounds may affect the airworthiness of the aircraft.

Table 4: Various Power-to-Liquid pathways with their respective technology readiness level, ASTM approval and limiting factors

Source: Based on the analysis by Schmidt et al. [81] and Batteiger et al. [82], author's own inputs

Technology and Production Pathways	Maximum Blending (Target) (%vol/vol)	TRL	FRL	Approval Status under ASTM D7566 and compatibility	Comments
Fischer-Tropsch synthesis (low temp.)	100%	7	6-8	- Not approved - Fully compatible	- Due to similarity with biogenic FT-SPK pathway, expected to be approved in the future as a stand-alone process - Scaling issue with reverse water gas shift process
Fischer-Tropsch synthesis (high temp.)	100%	5-6	3-5	- Not approved - Fully compatible	- Dependent on development of high temperature electrolysis
Methanol synthesis (low temp.)	50-100%	8	6-8	- Not approved - Potentially 100% compatible	- Due to similarity with biogenic ATJ pathway, expected to be approved in the future as a stand-alone pathway
Methanol synthesis (high temp.)	50-100%	7-8	3-5	- Not approved - Potentially 100% compatible	- Development of high temperature electrolysis and ASTM approval are lagging behind

3.4.2. Electricity-based SAF

For e-SAF production, non-biogenic, electricity-derived feedstocks are used, such as hydrogen from electrolysis and CO_2 from carbon capture (CC). The primary energy in e-SAF production comes from the electrical energy – preferably renewable electricity (RE), which is converted to chemical energy in the form of kerosene through various processes. This approach is known as 'sector coupling' and is enabled by various 'Power-to-X' (PtX) technologies – mostly focusing on fuel generation and substitution [83]. Consequently, in a broader definition, e-SAF is often referred to as Power-to-Liquid or PtL in literature, and as renewable fuels of non-biological origin (RFNBO) in legislations.

Hydrogen produced by electricity is used as a primary feedstock for the production of syngas, methane, and liquidized petroleum gas (LPG). The generated gases can be incorporated into existing supply chains and storages - providing additional flexibility and opportunity for renewable energy consumption. Syngas produced by Power-to-Gas (PtG) technology can be used to produce liquid fuels by means of Fischer-Tropsch (FT) synthesis or Methanol (MeOH) synthesis [84]. Liquid fuels, due to their innate higher energy densities and simpler (in most cases faster) refueling systems have considerable advantages in transportation sector, especially in the long-haul and bulk transport sectors such as shipping and aviation [85]. Thus, PtL can enable decarbonization in the aviation sector along with the promise of less disruptive changes to the existing infrastructure. There is developing consensus that in order to achieve deep decarbonization, the use e-SAF or PtL in the aviation industry is paramount – especially for resource limited countries like Germany [31].

While these technologies have been characterized as 'technologically competent' in numerous scientific literatures, it is contended that the primary challenge for achieving large-scale commercial deployment lies in the realms of economics, efficiency, and, notably, technology readiness, intricately tied to ASTM approval. Table 4 provides an overview of the status quo to e-SAF production pathways. The low and high temperature distinction lies in the coupling of these technologies with low or high temperature electrolysers.

In theory, these technologies presuppose an excess of renewable electricity within the grid, which can be harnessed to generate and store diverse energy products during periods of low electricity cost. Subsequently, these stored energy products can be utilized to meet later demands. Theoretically, this surplus of renewable electricity should compensate for the relatively low conversion efficiencies inherent in these technologies. However, this scenario does not align with the current reality, as the grid continues to heavily rely on fossil-based electricity. The process of conversion and reconversion, therefore, lacks both technical and economic feasibility. This underscores the relevant connection between indigenous e-SAF production in Germany and the widespread deployment of renewable energy sources [86].

For this analysis, the b-SAF would be interchangeably referred to as biogenic SAF or pathways, and similarly e-SAF as non-biogenic SAF or PtL pathways.

3.4.3. Hybrid SAF

In addition to these single-sourced SAFs, h-SAFs are derived from complementing b-SAF and e-SAF feedstocks. For example, to enhance the process yield of biogenic conversion processes, they may be supplemented with electrolytically produced hydrogen. The resultant fuel would contain the calorific content of both feedstocks [69]. Despite this, due to the broadness of their configuration, h-SAFs are not discussed further.

3.5. SAF Assessment Framework

3.5.1. Availability Dimension

The availability dimension focuses on the accessibility of feedstocks and potential competing demands that might divert feedstocks away from SAF production. These parameters have been defined and quantified in preceding chapters, and ongoing assessments will delve deeper into this aspect. For context, Germany already has an established agriculture industry along with a robust biomass and biofuels industry – this greatly mitigates the concerns regarding availability. That being said, there are only a limited number of feedstocks that can be produced indigenously and efficiently, given the land area constraints. For electricity-derived fuels this constraint is translated to the availability of renewable electricity.

Another factor that can affect the availability lies on the demand side. With increasing aviation demand, the previously available resources may not be sufficient enough to fully satisfy the fuel demand, thus limiting the ability to expand and ultimately increase the reliance on fuel or feedstock imports. In this pursuit, an aviation demand forecast is carried out in Chapter 4.

3.5.2. Viability Dimension

Within the viability dimension, both the economic and technical feasibilities of various SAF production pathways are scrutinized. While some pathways may already demonstrate technical feasibility, the inquiry into their economic and commercial viability remains open and will be subject to further investigation. Apart from low conversion efficiencies of existing pathways and technology costs – which are expected to improve. The economic viability is further directly affected by geographical factors, such as cost of feedstock and energy to produce SAF are one of the biggest cost-drivers. Due to the limited scope of this thesis, the viability would only be assessed for German aviation demand with limited number of technologies and available feedstocks.

3.5.3. Sustainability Dimension

The sustainability dimension stands as a pivotal factor in the SAF assessment framework. The overarching goal of SAF development in Germany is the reduction of direct and indirect GHG emissions from the aviation sector. This dimension encompasses an evaluation of environmental sustainability. The sustainability assessment can be evaluated with standardized frameworks and tools; the most widespread being the Lifecycle Assessment (LCA) framework.

Given the complexity of assessing SAF options, particularly when considering various pathways, feedstocks, regions, and use-cases, a pragmatic approach becomes imperative. Rather than evaluating each individual combination in isolation, a regulatory framework emerges as a practical solution. Such a framework can establish emissions thresholds for each pathway and feedstock combination, alongside additional sustainability benchmarks encompassing factors such as water use, land use, and the potential impact on food and fodder production. The default values provided under the legislative framework are generally derived from LCA analysis using average values for the region under consideration. However, this pragmatism offsets the higher resolution offered by individualized analysis and evaluation, on the other hand enables a level-playing field for various developers to deploy their pathways in a time efficient manner.

It is opined that this approach not only streamlines the assessment process but also offers a standardized and comprehensive mechanism for ensuring the sustainability of SAFs in the context of GHG emissions reduction from the aviation activities. It is deemed extremely important that uniformity and clear decision-making tools are established to accelerate the decarbonization of various sectors, including aviation.

3.5.3.1. SAF Sustainability Criterion

Two regulatory frameworks are identified over the course of the analysis, i.e., CORSIA Sustainability Criteria and EU REDII Directive with direct applicability for the aviation sector. The key criteria are summarized in Table 5.

Table 5: SAF sustainability eligibility criteria under EU REDII and ICAO CORSIA

Source: Compiled from [3, 26, 87, 88]

Criteria	EU REDII	CORSIA
Scope	- Criteria for biofuels, including SAF - ReFuelEU Aviation further narrows the allowable feedstocks to REDII Annex IX	- Criteria for alternative aviation fuels, including SAF
GHG emissions threshold	- Significant GHG emission reduction envisaged on a lifecycle basis over the fossil baseline of 94 gCO$_2$eq/MJ - Biogenic fuels: 65% minimum Non-biogenic fuels: 70% minimum	- Eligible fuels must demonstrate an emission reduction of at least 10% against fossil baseline of 89 gCO$_2$eq/MJ on a lifecycle basis
Land Use and Carbon Stock	- Biomass from primary, protected forests, peatlands, wetlands, grasslands, areas with high biological diversity are banned, as this can cause degradation of high carbon stock areas and adversely affect flora and fauna	
Indirect Land Use Change (ILUC)[9]	- Not included in the criteria	- ILUC emissions based on lifecycle analysis - Max of ILUC and default emission value is considered
Competition with food and feed crops	- Not eligible	- No explicit mention
Default values	- Defaults values provided for various feedstocks and pathways - For CORSIA, regional defaults are available but do not cover all the possible feedstock for each pathway	
Applicability	- Geographical: EU-27, mandatory - Temporal: Currently applicable	- Geographical: Global, voluntary - Temporal: First pilot phase

From the findings above, it is evaluated that, currently, the REDII criteria is more applicable for the German case, due to its apropos mandatory compliance and stringent GHG emission targets; any pathway meeting REDII standards would surpass the threshold set under CORSIA framework. Moreover, certain advantages for emission factors are allocated under REDII, based on land-use change, second generation feedstocks etc. This can positively impact the emission rating of the end fuel, making it viable to compete with emission

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[9] REDII defines ILUC as the adverse effect caused by the cultivation of crops for biofuels, bioliquids and biomass fuels as it displaces traditional production of crops for food and feed purposes putting pressure on existing land which may extend agricultural activities on land with high carbon stock and biodiversity.

savings limits set under the regulation. However, these are ignored in the analysis and the assessment is independent of any corrections over the calculated emissions.

3.6. Short-listed Pathways

As of writing this thesis, the biogenic pathways are the most technologically established and commercially-ready pathways for SAF production, and enjoy pre-existing certification under global normative frameworks. As Dyk and Saddler exclaims [55], there is no clearly winning technology. Thereby, efforts are necessitated to appropriately select a pathway based on geographical location, feedstock availability, upstream-, midstream-, downstream infrastructure, and fuel demand, among other reasons.

In this pursuit, the available biogenic feedstocks in Germany are mapped along with their potential and accompanying infrastructure as described in chapter 2, supported by the information regarding biogenic pathways in section 3.4 and graphically presented in Figure 12. It is observed that not all pathways are eligible for the German market, at scale, due to limitations imposed by land-use, regulations, low conversion efficiency of the processes, technology readiness, and/or low blending limits. These impress a “barrier to entry” encountered by various probable pathways. The findings from this exercise are presented in Table 6.

Furthering the analysis for non-biogenic pathways, the options are rather limited, as evident from the options listed in Table 4. Only 2 technologies based on low temperature electrolysis are observed to have reached commercial maturity; these are methanol synthesis and Fischer-Tropsch synthesis. In addition to this, a steady source of CO_2 is required by the synthesis process, for which high concentration sources of CO_2 are selected for further analysis, as direct air capture is extremely expensive and no breakthrough in terms of technological development is known to the author. Amine washing of concentrated CO_2 sources is an industrial-scale process, which has reached at-scale deployment and has been operational globally for decades. These two non-biogenic pathways are also appended in the Table 6 to provide a complete overview of the analysis, along with key observations.

The short-listed scenarios are further refined based on their techno-commercial limitations and merits, and further optimized for an efficient decarbonization model for the German aviation sector. Due to the broadness of the scope of techno-commercial study, the short-listed pathways are discussed in-detail in Chapter 5 and 6 with more concrete justifications for the selection of these routes. In addition to these pathways, it is expected that alternate aviation technologies, namely, hydrogen and direct electrification, would play a significant role in the future, and any comprehensive decarbonization would be incomplete without addressing these pathways. Thereby, more light is shed on the generation of hydrogen and electricity for aviation in Chapter 6 in order to put forward a holistic strategy for decarbonization and study the macro-economic implications that may occur in pursuance of such a strategy.

Table 6: Short-listed pathways for Germany selected for further modelling

Source: Author's own analysis, additional references cited in the table

Pathways	Potential Feedstock(s)	Observations/Comments	Further Analysis
HEFA	Biogenic: Rapeseed, Used cooking oil, Algae	- High TRL and FRL - Established supply chain - Limited potential for used cooking oil [89] - No existing potential could be identified [76], however can be a potential pathway in the future [54] - ASTM approved - >=50% blending allowed - Rapeseed not allowed under REDII	- Yes - Only rapeseed oil from fallow land and export ban
ATJ (Ethanol)	Biogenic: Forest residue, Agricultural residue, Sugar beet	- High TRL and FRL - Established industry for bioethanol production - Low recovery for biomass feedstocks [76] - ASTM approved - >=50% blending allowed - Sugar beet not allowed under REDII	- Yes - Only sugar beet
ATJ (Isobutanol)	Biogenic: Forest residue, Agricultural residue, Sugar beet	- High TRL and FRL - Low recovery for biomass feedstocks [76] - Higher estimated cost of production [90] and already existing supply chain for bioethanol - ASTM approved - >=50% blending allowed - Sugar beet not allowed under REDII	- Not selected

Pathways	Potential Feedstock(s)	Observations/Comments	Further Analysis
Gasification + FT	Biogenic: Forest residue, Agricultural residue, Municipal waste	- Technology with high TRL and FRL - Ability to handle varied feedstocks with various origins and calorific values - ASTM approved - >=50% blending allowed - All feedstocks allowed under REDII	- Yes
SIP	Biogenic: Sugar beet	- Technology with high TRL but relatively lower FRL - Extremely low blending limits (10%) - Single potential feedstock - Sugar beet can be used more efficiently in other processes - ASTM approved - Sugar beet not allowed under REDII	- Not included
FT synthesis	Non-biogenic: Concentrated CO_2 source and fresh water	- Coupled with low temperature electrolysers both technologies exhibit high TRL and FRL - Blending in the range 50%-100% is expected with even 100% fully compatible status for newer aircrafts, however, both are not currently approved under ASTM standards - If coupled with RE sources, both technologies are considered ‘zero emission’ under regulations (REDII) - Only limited by RE supply and can be scaled up to meet the demand, i.e., the ceiling is substantially higher than biogenic sources - Can be deployed locally close to load centers and large airports or in a co-located setting with carbon-intensive industries such as steel and cement	- Yes, for e-kerosene production
Methanol synthesis	Non-biogenic: Concentrated CO_2 source and fresh water		- Yes, for e-kerosene production

Pathways	Potential Feedstock(s)	Observations/Comments	Further Analysis
		- For FT, Reverse Water Gas Shift (RWGS) reaction is selected due to currently commercially operational production plants. Direct FT is still under development and no large scale deployment is observed [36] - Methanol synthesis is fundamentally an ATJ process with synthesis of alcohol from CO_2 and H_2 generated by electricity.	

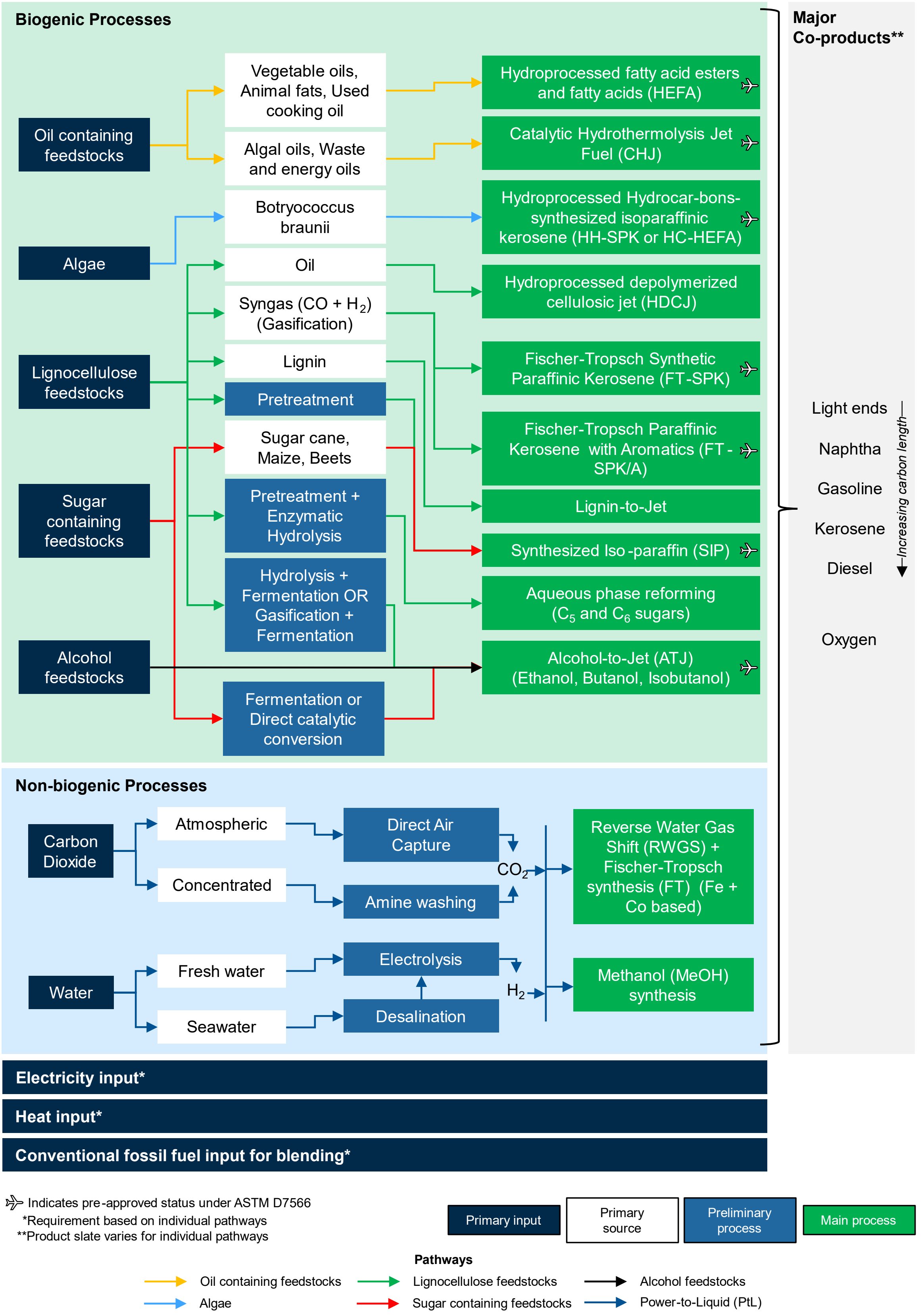

Figure 12: Overview of possible fuel conversion pathways by feedstocks' primary input type, preliminary processing, and main conversion processes, along with ASTM approval status

Source: Based on the findings of OR adapted from [55, 60, 70–75, 91–95]

4. Aviation Energy Demand Modelling

"Begin at the beginning, "the King said, very gravely", "and go on
till you come to the end: then stop."
Lewis Carroll, Alice in Wonderland (1865)

4.1. Preamble

During the literature review, various estimates for the future development of aviation demand in the German market have come to light, including from various government- and non-government bodies, technical reports, and scientific papers. Instead of using these estimates verbatim, it is decided to pursue an exercise to develop a deeper understanding of the dynamics and the factors at play, which may drive the energy demand of aviation in the region. To develop this understanding, historical trends are analyzed for various macro-economic and technical aspects, and by employing statistical methods, correlations and dependencies among these factors are established, which are then used to forecast the energy demand for the period from 2025 till 2050.

Building upon the discussion in section 2.1.1 on the German aviation sector growth, within the period of 2004 to 2019, the aviation fuel consumption in Germany, including aviation fuel, jet fuel and aviation gasoline has increased with a CAGR of 2.15% per annum, with 2019 consumption standing at almost 10.2 million tons of fuel per year. Although, the pace of growth has tempered off due to the devastating impact of COVID-19 pandemic on aviation activities; the sector has shown remarkable resilience and has returned to 86% of the pre-pandemic level in 2023 in EU [96]. Thereby, it is expected that the historical trend would remain valid for the foreseeable future. Subsequently, the timeline for the historical data is terminated at 2019 to reduce the variance introduced by the pandemic and a common 20-year timeseries is selected for all the considered factors, except for Aviation Consumer Price Index (CPI) as it was only published from 2004-onwards in the selected database. The next sections provide a more detailed discussion on the key factors considered and the underlying relationships.

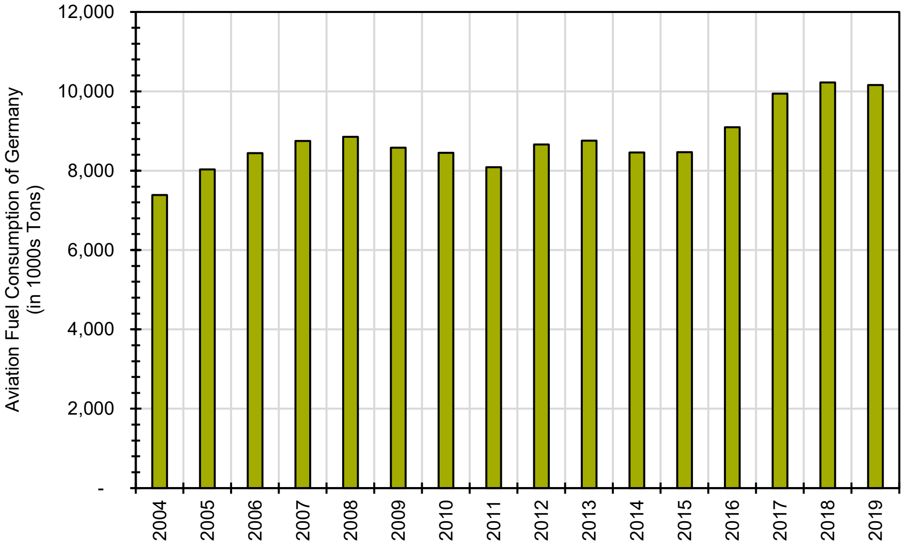

Figure 13: Aviation Fuel Consumption in Germany - in 1000s tons; including Aviation Fuel, Jet Fuel and Petroleum, without lubricating Oils and Greases

Source: Original data from [19], graphics by the author

CORSIA targets are global in-nature and does not necessarily apply to regional emissions. Hence, a local methodology should be developed taking into consideration the regionally significant variables. Thereby, the demand modelling step, undertaken during the course of the thesis provides valuable insights into the development of the German aviation market and offers a certain level of flexibility in creating additional scenarios and assessing their sensitivity on the pathways considered.

4.2. Forecast Model and Key Variables

4.2.1. Description

As illustrated in Figure 14, the aviation energy demand forecast is founded on various technical and macro-economic variables. Fuel demand is considered as a primary variable and used as a proxy for aviation demand, because of the status quo all aviation demand comes from fuel combustion technologies. The correlations between fuel demand and other variables are established, namely, population change, GDP per capita, cost of travel derived from aviation CPI, and fuel efficiency improvements. The correlations are based on 20-year historical datasets (where possible) and forecast is carried out for 30 years from 2020 till 2050, out of which 2025-2050 period is selected for further modelling. Additionally, the aviation market structure in Germany is assumed to be fully liberalized and competitive, and no asymmetry of information is assumed in the model.

The datasets are filtered and processed to eliminate data corruption issues and subsequently indexed to 2010-levels, i.e., 2010-value for each dataset is considered as 100 and succeeding and preceding values are scaled accordingly. Indexing based on 2010-levels is done to save effort, as most of the datasets were already indexed with this benchmark. However, this is completely arbitrary and any reference point would result in identical results. The indexed datasets are analyzed with Microsoft Excel and a Multivariate Regression Analysis (MRA) is executed using built-in tools. The results are automatically evaluated using the ANOVA functionality in Excel, and consequently short-listed based on R-Square (R^2) and p-value (Significance-F) values[10].

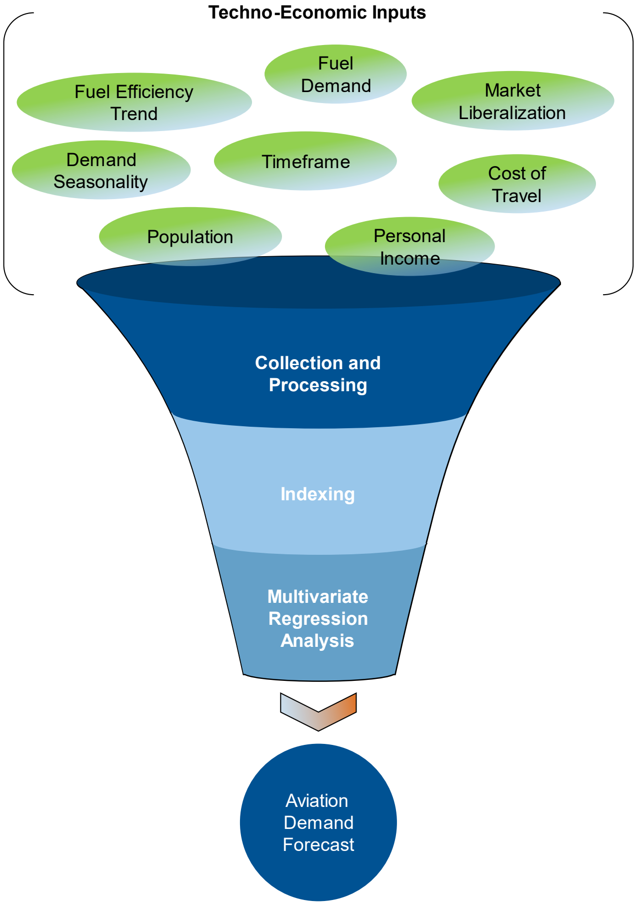

Figure 14: Aviation energy demand forecast model with key variable and steps

By using the coefficients obtained from the MRA for the considered variables and the energy demand for 2019, the long-term demand forecast is established. The resultant annual demand values are adjusted for seasonal demand variations by means of an annual

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[10] Pripp [97] and Dahiru [98] provide a clear and concise description of significance tests for regression analysis and the associated benchmark p-values

distribution, resulting in monthly values for aviation fuel consumption which are divided by the number of hours of the respective month to obtain hourly values required for the energy model. The selection of influencing variables is largely based on the long-term forecast modelling conducted by ICAO [99], in the immediate case the model is adapted for the German market due to the limited scope of the thesis.

4.2.2. GDP Growth vis-à-vis Aviation Demand

The relationship between aviation demand and economic activity is clearly established in the scientific literature, however the magnitude is still under debate and is considered highly dependent on various regional and global factors [100–103]. In this analysis, economic activity is represented by GDP and its forecasted changed over the modelling period. It can be argued that personal disposable income (PDI) can be a better representative of economic activity for the aviation sector, as the individuals with more income may intend to travel more. Moreover, it has been identified that the PDI is not directly linked with GDP per capita and is often outpaced across multiple regions around the world [104]. However, it is concluded that it is extremely hard to predict as PDI is dependent on numerous other factors, including, average family size, number of bread earners etc. Due to overarching time-constraints, for this analysis, the relationship between GDP per capita and aviation demand were relied upon.

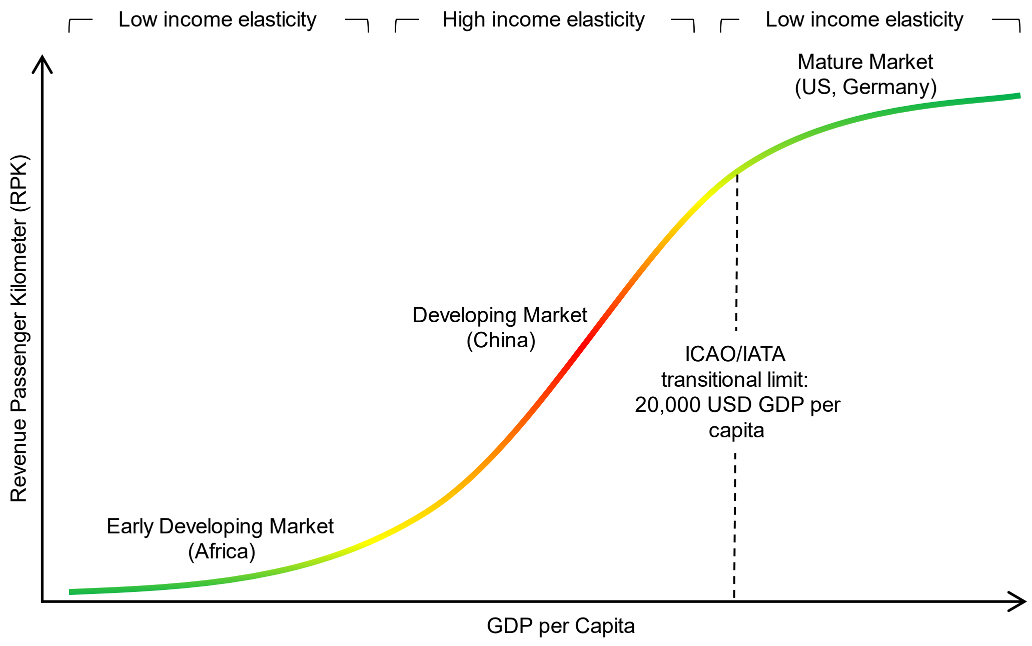

Figure 15: Simplified relationship between aviation demand (in terms of RPK) and GDP per capita of a country

Source: Author's own illustration, with inspiration from ICAO [99]

Furthermore, this simplification is not unrealistic, as reported by Hanson et al. [100], there is abundance of evidence available regarding the correlation between GDP/GDP per capita and aviation demand. As the overall economy develops the aviation market is poised to develop with it. The observed trend appears to follow an S-curve, initially the demand behaves inelastically to the economic growth and reacts slowly to the GDP growth, but tends to accelerate as the economies develop at a higher pace, before settling down to moderate values (see Figure 15). Aviation demand is represented as RPK (Revenue Passenger Kilometer) which is the total of revenue paying passengers and the distance travelled in kilometers. IATA/ICAO claims that the transition point where the demand elasticity settles down lies at 20,000 USD per capita [99]. As Germany's GDP per capita of approx. 52,000 USD is much higher than this benchmark, the reaction of the German aviation demand to GDP per capita change is expected to be 'moderate' in nature.

For Germany the aviation energy demand and GDP has risen steadily over the last 20 years, with aviation demand observing a slightly steeper rise, as observable in Figure 16. Despite this the correlation between the two datasets remain extremely high - 0.906 for the 20-year timeline and reducing to 0.885 if only the last 10 years are considered. This result further strengthens the assumptions and makes GDP per capita an appropriate yardstick to gauge the forecast the growth in the aviation sector.

Historically, the GDP per capita in Germany has risen at an average rate of approx. 3% per annum. A study conducted by German Federal Ministry of Digital and Transport (BMDV) forecasts a growth rate of 1.35% real per annum in GDP per capita until 2040 and afterwards slowing down to 1.26% real per annum until 2051 [105]. For this analysis, 3% p.a. growth is assumed for the base case, for low- and high demand growth cases, GDP growth of 1.5% and 4% are assumed respectively.

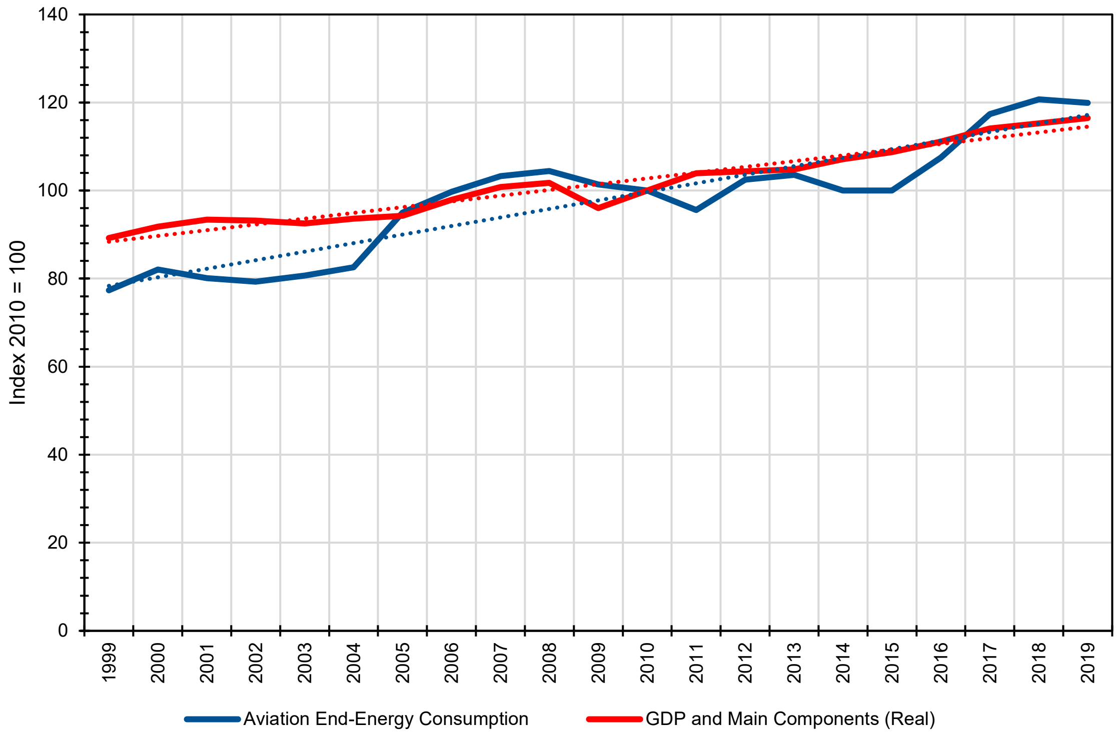

Figure 16: 20-year historical data for aviation energy demand and GDP per capita in Germany, linear trend plotted as dotted-line

Source: Author's own analysis, with original data from [19, 106]

4.2.3. Fuel Efficiency Improvements vis-à-vis Aviation Demand

Fuel efficiency improvements are associated with fuel burn rates of an airplane, thus directly corelated to the cost of operating a flight. Labor cost and fuel cost account for up to 60% of the total operational cost of a flight [107], it is therefore expected that the fuel efficiency improvements can significantly reduce the overall cost of flying thus making flying affordable for lower income groups; in return increasing the overall aviation demand and vice versa. It is observed that the overall fuel combustion rate in the airline industry is experiencing a downward trend since 1960s [108] – with estimates based on ICAO metric value a CAGR of -1.05% is observed for the period 1960-2014. This is conservative than the -1.24% CAGR observed when calculation are done based on fuel requirement per passenger-km. Nonetheless, there is a clear downward development of fuel consumption in the airline industry across all airplane types [108].

This fuel efficiency gain is observed to be offset by the average fleet age of an airline. Most modern airlines tend to maintain a fleet age of around 10-12 years, subject to regional development [109]. Afterwards, depending on the remaining life of the aircraft, they are either used for cargo transport or a completely retired – average retirement age of aircraft is predicted to be 25 years on average [109]. In the study by Kharina & Rutherford in 2015

[108], it is observed that, there exists a time-lag of 12 years between fuel burn improvement by the industry and time required to reach ICAO`s goals. The study also explored the drivers of the slowdown in fuel efficiency after 1990, citing to the introduction of less efficient regional jets into the fleet, against newer, and more efficient aircraft types. Between 1999 and 2014, the fuel efficiency has increased by 0.57% CAGR.

In 2010, ICAO conducted a study [7] to determine various medium- and long-term fuel burn technology goals for achieving ICAO ’s long-term goal of improving annual fuel efficiency by 2% and stabilizing global CO_2 emissions at 2020 levels. However, in the same report the independent experts have concluded only 1.4% per annum improvement by 2030, associating it with the aircraft design and technology improvement. Meanwhile, the ICAO study aims at a holistic system efficiency. For this instance, as other operational peripheries are not considered, the improvement claimed by the independent experts is much more relevant. This fuel efficiency improvement is also corroborated by the analysis done Kozuba and Ojciec [110].

As there is a clear lack of consensus, for the forecast model, it is assumed that the long-term historical trends will remain valid in the future and are also considered valid for the German market. For this reason, curve fitting technique is used to develop a numerical equation using long-term data and extrapolate the existing trends till 2050. Power curves are observed to provide the ‘best fit’ based on R-square (R^2) values, with selected trendline based on ICAO metric value achieving 0.95 determination (see Figure 17). The following equation is used to calculate the relative increase or decrease in fuel consumption during the forecast period for all demand cases (base, low and high).

$$FE_{ICAO} = (2 \times 10^{79}) * x^{-23.47} \tag{1}$$

For equation (1), x is the year in the range of 1960 to 2050, and FE_{ICAO} is the value for fuel efficiency based in ICAO Metric Value – indexed to 1968 = 100. The extrapolated trend is then re-indexed to 2010 = 100 for an easier assessment in relation to aviation energy demand in Germany. It is observed that there exists a clear negative correlation between fuel efficiency improvement and fuel demand in Germany and is characterized by a correlation factor -0.910 (see Figure 18).

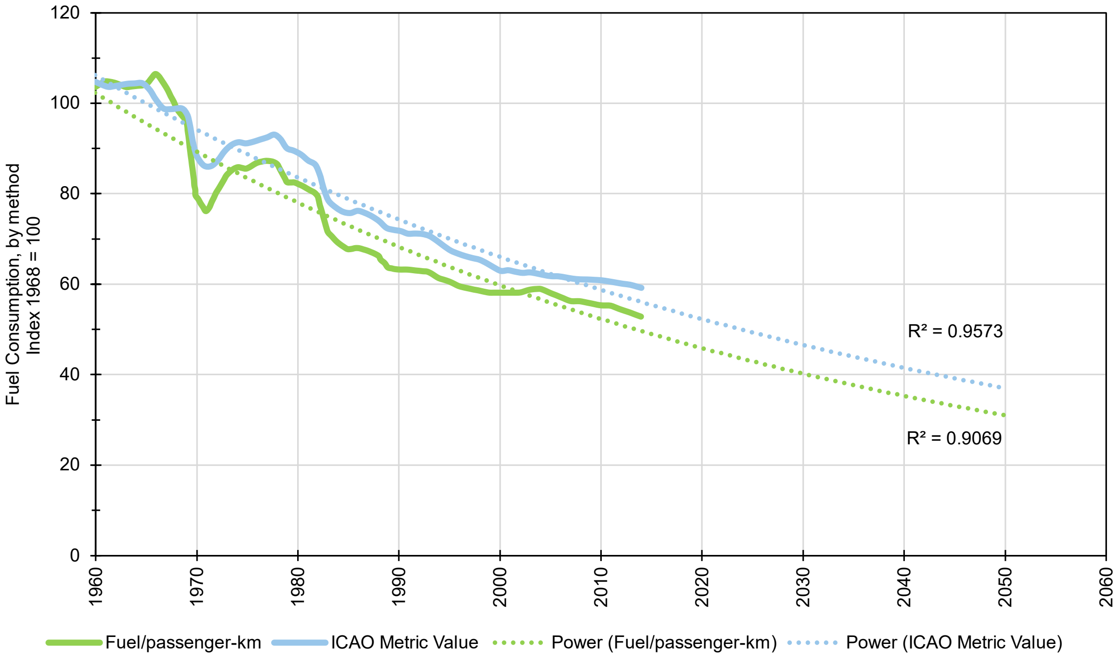

Figure 17: Curve-fitting results of long-term fuel efficiency improvement in the global aviation sector

Source: Original data from [108], trendline and projections established by the author

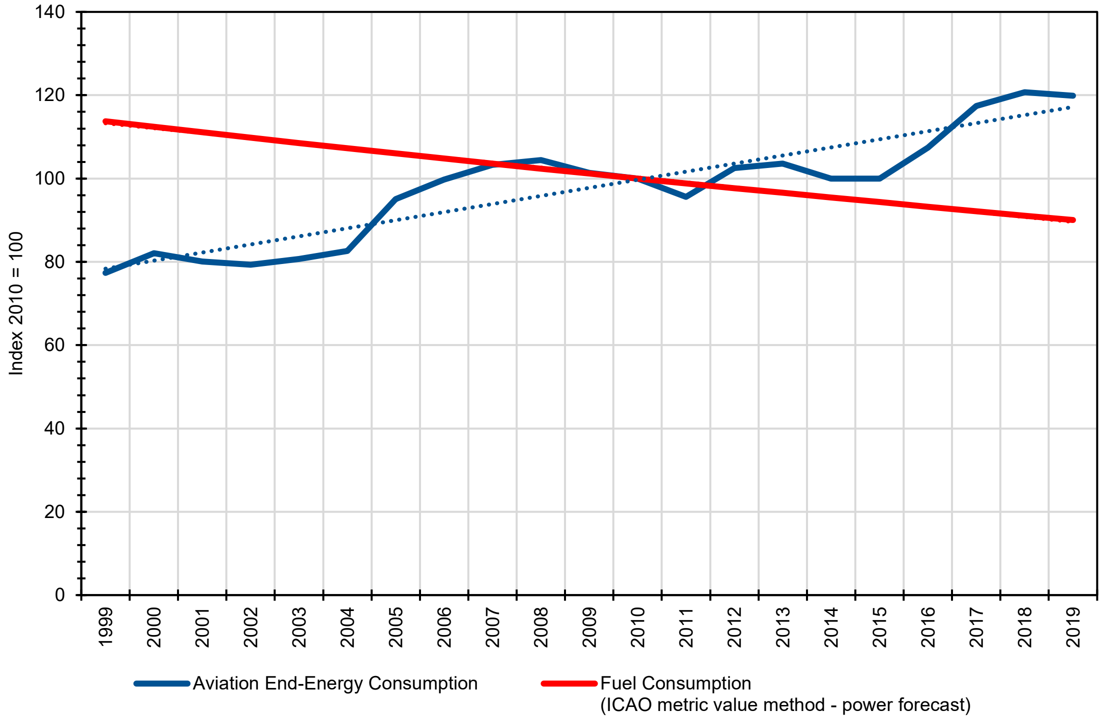

Figure 18: 20-year historical data for aviation energy demand and extrapolated fuel efficiency improvements in Germany, linear trend plotted as a dotted-line

Source: Aviation energy demand from [19], analysis conducted by the author

4.2.4. Population Growth in Germany

The population of a region is directly associated with aviation demand, as a higher number of people equates to more potential flyers and higher economic activities. In the case of Germany, the population and the age demographics is not expected to change [105]. Even with stagnant population growth, German aviation demand has consistently risen over the considered time period, highlighting a decoupling between aviation demand and population in German market. Thereby, population change is not considered in the aviation forecast modelling. However, in a region with evolving population and demographics, this factor would play a significant role in forecasting the long-term aviation demand.

4.2.5. Cost of Flying impact on Aviation Demand

Aviation Consumer Price Index (AvCPI) is a sub category of the general Consumer Price Index published by the Federal Statistical Office of Germany (DESTATIS). The AvCPI tracks the cost of air travel over years, accounting for fuel costs, salaries, taxes, and duties among other factors affecting the costs. For the purpose of reasonable simplification, AvCPI for intercontinental travel is used as metric of aviation costs. It is assumed that the intercontinental travel generally reflects higher direct variable costs such as fuel, salaries, and maintenance, while the landing and airport fees are minimized as they plane spends comparatively more time in-flight. That being said, the trend between domestic, within Europe and intercontinental CPI is comparable and generally follows similar ebbs and flows [19].

As it is clearly evident from the graph (see Figure 19), despite both of them having a positive slope, there is a clear contrasting behavior, highlighted by point 1 and 2 in the figure – as the AvCPI (cost of flying) increases, the aviation energy demand (aviation demand) drops and vice versa. From the statistical evaluation, the calculated correlation factor between the two datasets is 0.561. Despite the low correlation factor, AvCPI is considered in the model as it helps to evaluate the aviation demand from a consumer's perspective.

For the period from 2004-2019, a 2.5% CAGR is observed and is used as an input for the base demand scenario. However, it is observed that, there is a correlation between General CPI and GDP of a country, as both are a measure of inflation in an economy but from different perspectives [111]. As aviation sector is part of the larger economy, AvCPI is expected to follow a similar relationship with GDP. But, in order to have a growing aviation sector, the GDP must grow faster than the AvCPI, otherwise the effects from these factors are cancelled-out and demand would remain at similar levels. For this reason, for a high demand scenario, AvCPI is assumed to be 2.2% per annum, and for the low demand scenario it is assumed to be 1.8% per annum as the GDP growth slows down as well.

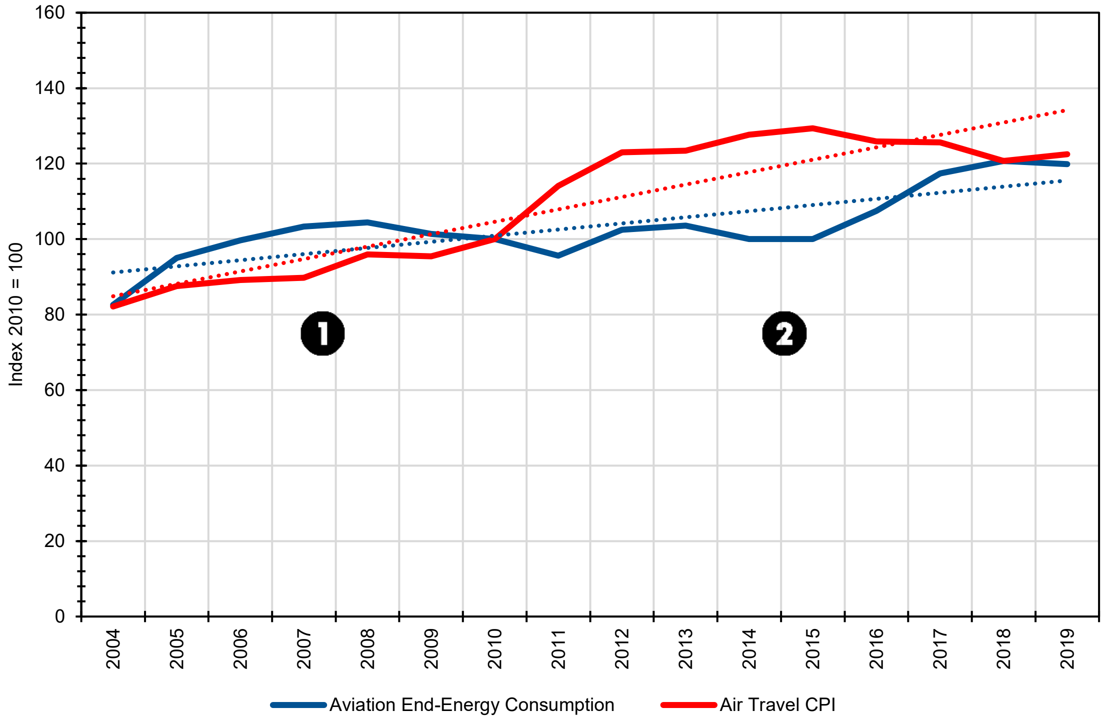

Figure 19: 20-year historical data for aviation energy demand and cost of air travel, linear trend plotted as a dotted-line

Source: Original data from [19, 112], analysis conducted by the author

4.2.6. Seasonality in German Aviation Sector

The German aviation sector experiences seasonal variations over the course of a year. The number of controlled flights increases during warmer months and quenches during colder months. This month-on-month variation between months with the highest and lowest values is 2.73% of the annual total flights. Similar behavior is also observed on datasets with longer timespans [96]. This distribution is assumed to be proportional to the aviation energy demand, due to the lack of any direct dataset addressing this need known to the author. It is acknowledged that, this does not necessarily mean that aviation energy demand behaves in a similar manner, as demand may be met by smaller or larger aircrafts, or longer or shorter routes, among various other factors that can have a completely different energy demand profile. Nonetheless, due to the lack of more specific datasets it is assumed that energy demand follows a similar monthly trend.

The distribution illustrated in Figure 20 is used as a scaling factor to transform the annual energy forecast to monthly forecast, and subsequently using number of hours of the respective month to transform to hourly values for energy modelling purposes.

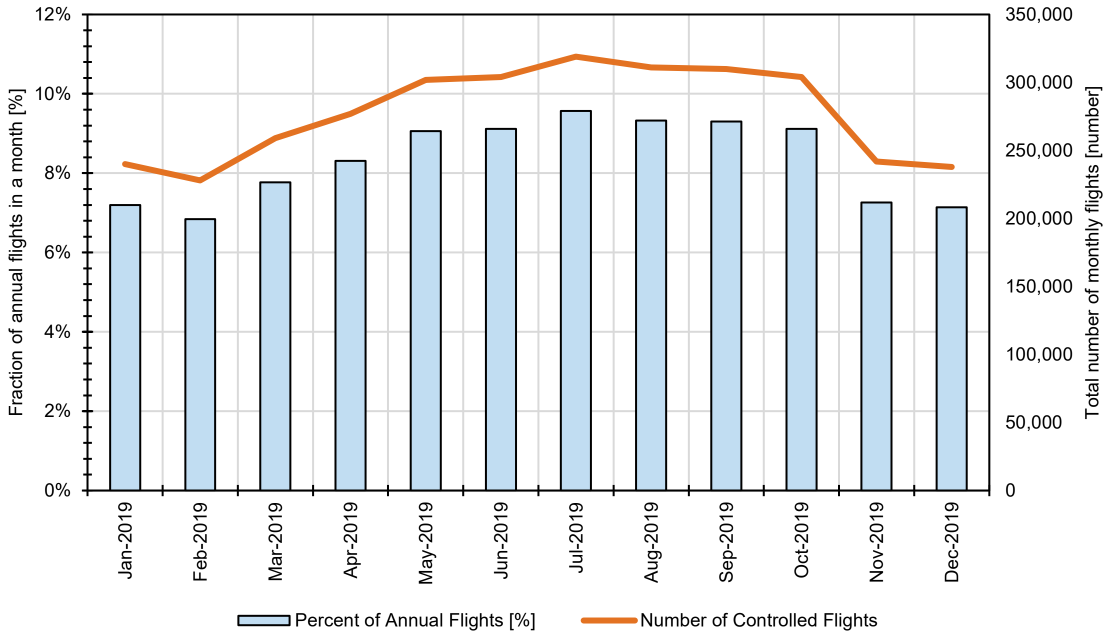

Figure 20: Monthly distribution of controlled flights in Germany, 2019

Source: Author's own analysis based on the data from DFS [113]

4.3. Multivariate Regression Analysis and Modelled Demand

Based on the key variables discussed above, 6 models are assessed to provide the best approximation of the observed historical data using Multivariate Regression Analysis (MRA), with various configurations of GDP, AvCPI, and fuel efficiency estimations. The results of the MRA are tabulated in Table 7. It is clearly evident that MRA 3 offers the best approximation of the underlying variables based on R^2 and p-values. It can be seen that, p-values for all the models are extremely low and are considered 'statistically significant' ($p\text{-value} < 0.05$), however the correlation factor (R^2) varies significantly across various models. MRA 3 offers the best parameters among the modelled scenarios and is, therefore, selected as the reference model for forecasting future aviation demand in Germany.

Figure 21 provides a graphical representation of the relationship between the aviation energy demand and the resultant time-series from various MRA models. This also leads to similar observations and conclusion that, MRA 3 offers the best fit among the modelled scenarios as both timeseries can be visually observed to follow each other closely. Only the period of 2004-2019 is plotted on the graph, as it is the common time period among all the considered variables.

Table 7: Multivariate Regression Analysis modelled scenarios and summary of results

Model	Key Variables			Regression Statistics			
	GDP	AvCPI	Fuel Efficiency	R^2	St. Error	F-value	p-value
MRA 1	Yes	Yes	Fuel/RPK method	0.828	4.483	9.267	6.99E-05
MRA 2	Yes	Yes	ICAO metric value method – linear forecast	0.828	4.483	19.267	6.99E-05
MRA 3	Yes	Yes	ICAO metric value method - power forecast	0.924	2.984	48.513	5.54E-07
MRA 4	Yes	No	Fuel/RPK method	0.712	5.576	16.059	3.07E-04
MRA 5	Yes	No	ICAO metric value method – linear forecast	0.712	5.576	16.059	3.07E-04
MRA 6	Yes	No	ICAO metric value method - power forecast	0.712	5.572	16.089	3.05E-04

Based on the short-listed MRA 3 model, the demand forecast for the future years is calculated using the following equation.

$$\begin{aligned} Demand_n = \big[210.9498 + (0.9392 * GDP_n) - (0.6908 * AvCPI_n) \\ - \left(1.4871 * FE_{icao,n}\right)\big]_{Index\ 2010\ =\ 100} \end{aligned} \tag{2}$$

Where, $Demand_n$ is the annual aviation energy demand for the nth year, GDP_n is the GDP of the nth year, $AvCPI_n$ is the Aviation CPI for the nth year and $FE_{icao,n}$ is the fuel efficiency for the nth year derived from the ICAO metric method using power curve fitting. It must be noted that all these parameters are Indexed to 2010 = 100 and resultant demand can be converted to absolute values using the 2010-reference energy consumption of 362 PJ or 100.55 TWh.

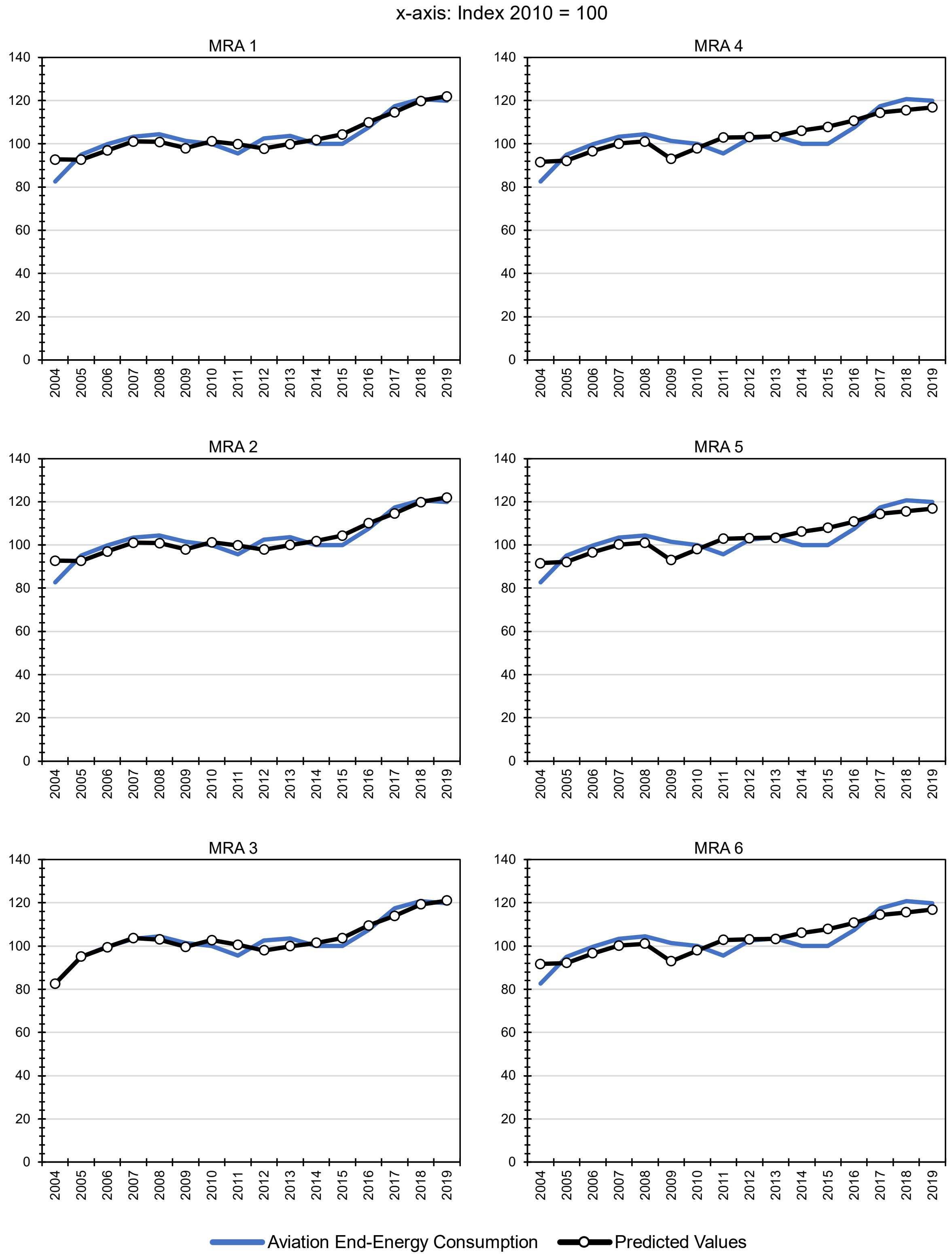

Figure 21: Relationship between aviation energy demand observed and modelled values from Multivariate Regression Analysis

4.4. Aviation Demand Forecast

4.4.1. Demand Curves

Using equation (2) and the parameters defined in Table 8, the aviation energy demand for Germany is forecasted for the years 2020 till 2050. This energy demand is considered as a proxy for overall aviation demand. Based on the model, it is expected that German aviation sector will grow, albeit at various rates based on underlying economic conditions. The long-term forecast for these economic parameters is extremely difficult and often does not materialize, however, effort is expended to transparently define the assumption and present the most accurate possible outcome within the constraint of time and scope of this thesis.

Table 8: Summary of various aviation demand forecast cases

	Demand Growth		
	Low	Base	High
GDP Growth	1.5%	3.0%	4.0%
AvCPI Growth	1.8%	2.5%	2.2%
Fuel Efficiency Improvement		Historical values	
Expected CAGR	0.6%	1.8%	3.2%
Total Change$_{2019}$	19.9%	74.2%	167.0%

According to the prognosis, the aviation demand in Germany will grow by 1.8% CAGR and would be approx. 175% of the current values by 2050, provided that the historical trends remain valid in future. Under a suppressed demand growth, the sector would experience a sluggish 0.6% CAGR and would only be approx. 20% larger than it is currently. If permitted by favorable conditions and higher economic growth, the sector may expand 3.2% on average till 2050 and would be 2.7 times the current size. It is reiterated that these estimates are based on extremely simplistic assumptions and may not fully capture the underlying dynamics of the aviation sector in Germany. Despite this, these estimates are used to understand the constraints that may be imposed on the supply-side, if the forecasted demand is to be met in a sustainable manner within the framework of global, regional, and national legislations. Figure 22 provides a trendline for base, low, high demand scenarios.

It may be noted that, this demand forecast is only based on kerosene-based aviation and do not include the influence of alternate aviation technologies on the overall energy demand of the sector. In order to gauge the accuracy of the model, the obtained forecast is evaluated under the light of existing forecast by national and international bodies. The results of which are discussed in subsequent section.

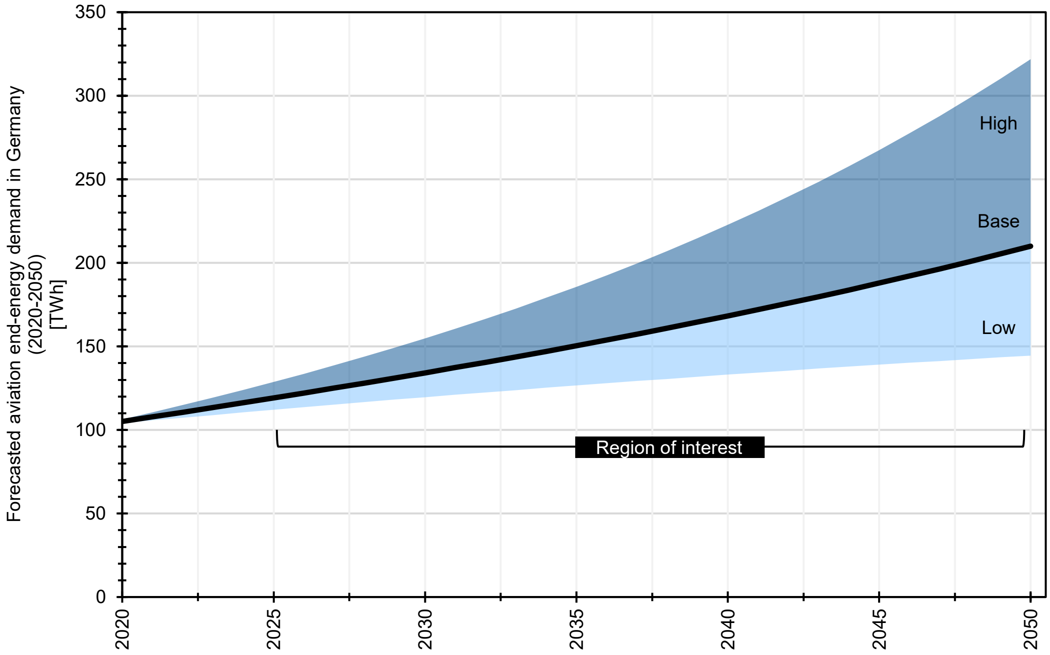

Figure 22: German aviation energy demand forecast, 2020-2050

4.4.2. Comparative Analysis

In 2012, ICAO developed a 30-year forecast model for passenger and cargo air traffic demand; comprising of datasets from 1995 through to 2012, including considerations for disposable income, population growth (in conjunction with income growth), economic & business activities, global trade, airline networks, deregulation and the cost of air travel [99]. Through which ICAO expects an increase in RPK by 2.5% CAGR for 10, 20, and even 30 years for the European market, while the domestic demand is expected to remain relatively low [99]. Within the context of reference report, RPK values are used as an indicator of aviation demand, which is different from the immediate case as the forecast is based on energy requirement. Despite this, a correlation between these two measures can be established as more revenue generation would necessitate more flying customers, resulting in higher energy demand. In a different study conducted by the German Energy Agency (DENA) for e-kerosene use in aviation fuel [31], which forecasts long-term growth trends in aviation demand for global, European, and US markets. The forecast is at higher resolution compared to the ICAO study with demand values for each 5-yr period till 2050. Additionally, as the DENA study is published in 2022, the adversarial impacts of COVID-19 pandemic is accounted for in the long-term growth; a slower growth in 2020s and acceleration beyond 2030 in both scenarios developed by the agency. Regardless of that, for both of the studies, it is clear that the expected demand from 2019 till 2050 increases with a CAGR of approx. 2.4% in Europe, which is comparatively slower than the global aviation industry.

This estimate is more optimistic than the calculated estimate and falls in-between the base- and high-demand scenarios.

As both of the reports focus on the European market, which, understandably, can be different from the German market - due to inclusion of less mature economies, thus, the results of the developed demand forecast are compared with the forecast published by the German Ministry of Digital and Transport (BMDV) [105]. In this report, a detailed prognosis is developed catering to the dynamics of the German market and within the broader context of the whole transportation system in Germany. The report forecasts an increase of 68% within the period of 2019-2051, representing a CAGR of 1.63%; this estimate is extremely similar to the forecasted base case growth of 1.8% per annum.

Based on the above reasoning, it is deemed that the forecast carried out sufficiently address the dynamics of the German market and establishes a benchmark to evaluate the energy requirements to meet these demands.

4.5. Alternate Propulsion Technologies' Impact on Forecasted Demand

4.5.1. Technical Parameters

Due to the technical disparity between kerosene-based planes and alternate technologies, namely, hydrogen- and electric planes, it is expected that there will be a significant change in the holistic energy requirements of the sector as these technologies are introduced. The report published by DENA provides a comparison of these technologies and the energy requirement per passenger-km [31] - the values provided by DENA are also corroborated by other scientific literature [114–116]. As the DENA study also provides projected improvements in the fuel conversion efficiencies till 2050, for this analysis, these projections are taken as the reference values. From the data (see Figure 23), it is clearly evident that the alternate propulsion technologies offer much more efficient use of energy to serve a similar demand. Over the entire timeline, it is estimated that, hydrogen planes will be approx. 20%-30% more efficient than kerosene planes and electric planes would offer an energy efficiency of 60%-70% over the kerosene-propelled airplanes. This will in turn drastically alter the energy requirements, subject to how much diffusion the alternate technologies can be achieved.

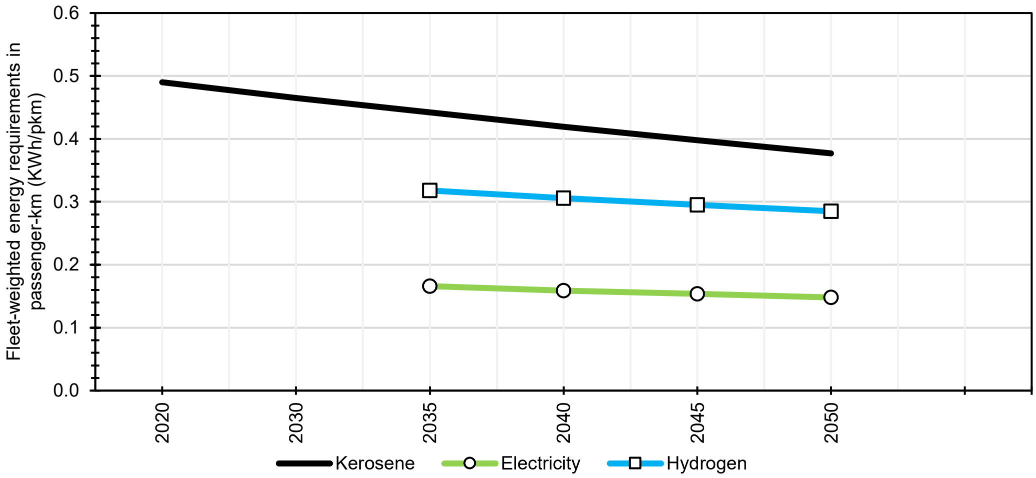

Figure 23: Fleet-weighted energy requirement per passenger-km, in KWh/pkm, 2030-2050

Source: Original data from [31]

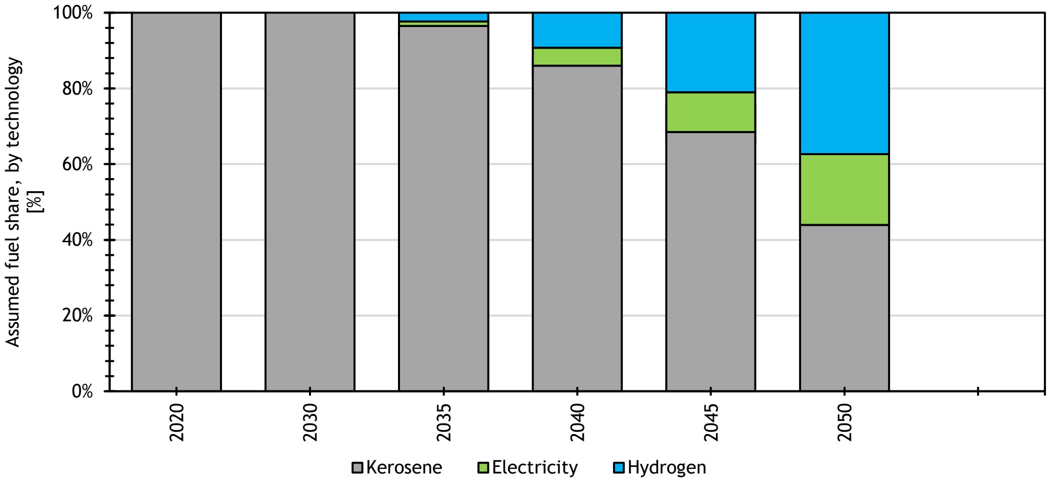

Figure 24: Assumed fuel share by plane propulsion technology, 2020-2050

Source: Original data from [31]

The diffusion of alternate technologies is extremely hard to predict, as most of the design are in early stages of development and a specific release date is not yet publicized. Based on various estimates from airplane manufacturers, national regulators and scientific papers, it is forecasted that these technologies would be put into service around the middle of 2030s, approximately 2035 [31, 65, 117–121]. For this analysis, the study conducted by DENA [31] is used as the reference, as it is done by a German institution and would provide a more realistic estimate for the German market. The assumed shares of alternate propulsion technologies at a 5-year interval are presented in Figure 24 and is used to adjust the previously forecasted demand for all demand cases.

$$\begin{aligned} Demand_{n,adjusted} &= \left(Demand_n * x_{kerosene,n}\right) \\ &+ \left(Demand_n * x_{hydrogen,n} * \eta_{hydrogen,rel,n}\right) \\ &+ \left(Demand_n * x_{electric,n} * \eta_{electric,rel,n}\right) \end{aligned} \tag{3}$$

For the adjustment pertinent to alternate technologies based on energy efficiency and fuel share, equation (3) is used. In which $Demand_{n,adjusted}$ is the adjusted aviation demand ($Demand_n$) for nth year; $x_{kerosene,n}$, $x_{hydrogen,n}$, $x_{electric,n}$ are the share of kerosene-, hydrogen- and electric aviation respectively; $\eta_{hydrogen,rel,n}$ and $\eta_{electric,rel,n}$ are the relatively fuel efficiency w.r.t kerosene-based fleet for hydrogen and electric planes respectively.

4.5.2. Adjusted Demand Curves

With the adjustments formulated above, the forecasted demand is adjusted for base, low and high demand growth scenario using equation (3) along with the factors illustrated in Figure 23 and Figure 24. The adjusted final demand is plotted in Figure 25. From the figure it is clearly evident that, the alternative propulsion technologies would drastically alter the energy demand of the sector. As the hydrogen and electric planes are introduced in 2035, the demand for kerosene starts to drop and settles at levels well below of the 2020-levels by 2050. Based on the calculations, alternative technologies are forecasted to offer 20-30% reduction in annual energy consumption. It is worth emphasizing that, these values are based on projected trends, the actual deployment of these technologies is subjected to, including but not limited to, the development of these technologies at an accelerated pace, the range and capabilities of the aircrafts, regulatory policies, safety and air worthiness concerns, cost of transition and inherent cost of these technologies, and competition with railways due to shorter range.

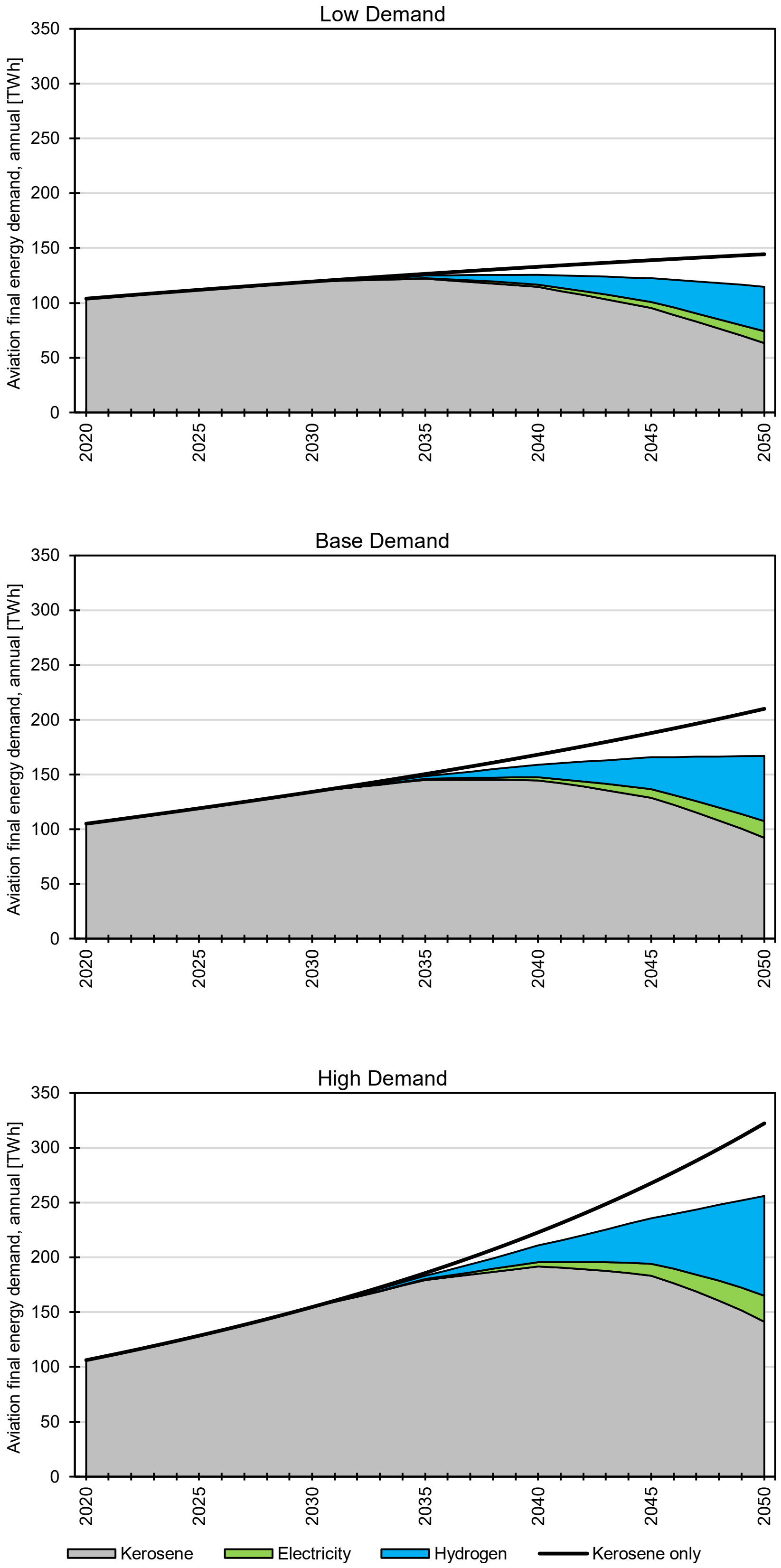

Figure 25: Adjusted aviation demand forecast with kerosene, electric and hydrogen propulsion technologies along with non-adjusted demand forecast

5. Assessment of Biogenic Pathways in the Light of Foreseeable Aviation Demand

> *” There are many paths to the top of the mountain, but the view is always the same.”*
>
> \- *Chinese Proverb*

5.1. Preamble

In this chapter, the short-listed biogenic pathways are analyzed for their potential to sufficiently meet the demand under various growth scenarios. As previously established, biogenic pathways are already approved under the ASTM D7566 and have an already established global and local production capacity. Therefore, it is only sensible to assess the indigenous potential of the German market, under the constraints highlighted in previous chapters to meet or exceed the fuel needs of the aviation sector. In pursuit of which, firstly, a general overview is provided regarding the technical aspects considered when converting available feedstocks with their coupled conversion pathways. Secondly, the maximum substitution potential of HEFA, ATJ and GFT pathways are established. Thirdly, associated emissions are calculated for each pathway and finally a ranking criterion is formulated to rate the potential of each pathway under the technical and environmental constraints. The chapter also summarizes the techno-physical aspects of each pathway, that may be used to develop an energy optimization model later on. It is clarified that, the calculations instead of focusing on the individual steps of conversion processes, try to deal with the complexity of the analysis at a macro-level. It is acknowledged that simplifications are made that would come into play when a high-resolution analysis is carried out, however, justifications and clarifications for the simplifications are provided to the best of the knowledge of the author.

5.2. Biogenic Pathways

As previously discussed in section 3.6, the biogenic pathways listed below are already approved under the ASTM D7566 standard and have a diverse, well-established supply-chain for feedstocks in Germany. Even though, as previously highlighted, the feedstocks selected for these pathways may not fully comply with the REDII directive, despite this they are selected as they offer the best land-use potential for cultivation and highest fuel yield per hectare. Over the course of the thesis, it is observed that land availability is one of the most constraining factors for Germany and in order to develop a “best case” scenario for biogenic pathways, feedstocks with most efficient must be selected. As it will be presented later, even under these favorable conditions the individual biogenic pathways fail to meet the aviation demand in any substantial manner. In order to further the discussion, the following pathways are discussed further and more light is shed on the information relevant to the analysis at hand, namely:

1. Hydroprocessed Esters and Fatty Acids (HEFA)
2. Alcohol-to-Jet (ATJ)
3. Gasification plus Fischer-Tropsch (GFT)

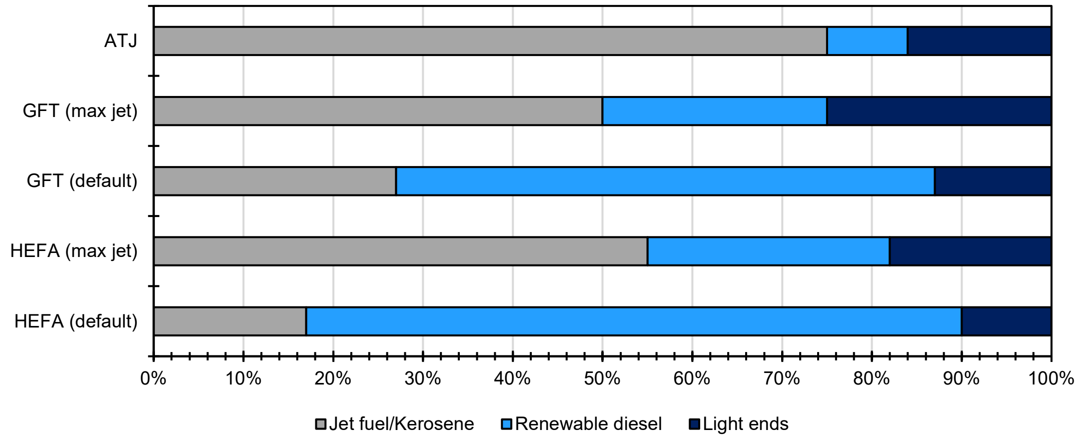

Figure 26: Product-slate (by mass) of selected biogenic pathways and their configurations

Source: [93, 122]

5.2.1. Hydroprocessed Esters and Fatty Acid (HEFA) Pathways

Hydroprocessed Esters and Fatty Acid (HEFA) is also referred to as Hydrotreated Vegetable Oil (HVO) in particularly older literature. It is a thermochemical process in which oil-based feedstocks, such as vegetable oils and fats, are converted into straight chain paraffinic hydrocarbons by means of hydroprocessing. This process is considered as an alternative process to esterification. According to Tao et al., even with a 20% higher system cost than esterification, the HEFA conversion process can offer a better economic proposition due to its product slate, with high quality and clean burning combustion products [60, 123]. In a simplistic form, in the HEFA process the oils are reacted with hydrogen in the presence of a catalyst under high pressure and temperature, and in a step-by-step manner are converted to various alkanes, isomers and cracking products [72, 124].

These converted products are subsequently separated into various hydrocarbon products; in the **default** configuration the product slate of HEFA consists of 17% kerosene, 73% diesel and the light ends make around 10% [122, 124]. However, HEFA can be optimized for jet fuel production, in which the kerosene fraction is increased to 55% while diesel and light ends make up 27% and 18% respectively [122, 124]. For this analysis, the higher jet fuel configuration is referred to as **max jet** (see Figure 26). These products are then blended with conventional jet fuel to be compatible with existing standards, currently only 10% blend-in is allowed under ASTM D7566, but up to 50% blend-in is expected to be allowed soon [69] and this limit is also considered for this analysis.

From the feedstock perspective, plant-based as well as agal oils are compatible with the HEFA process. As discussed in 2.6.2, the supply of algal oils is extremely limited and projects only exist in pilot or demonstration phases, therefore, only plant-based feedstocks remain the focus of this process. Out of which, rapeseed oil produced from indigenously cultivated rapeseed in Germany is selected to provide the input for this process. That being said, if the algal oils become readily available in the future, the land can be better utilized through algae cultivations and can improve the energetic yield from the same land by 3-8 times [81].

As already elaborated, there are 373,100 hectares of fallow land available in Germany [49], with the specific yield estimates of 1.54 tons of rapeseed oil per ha provided by Majer et. al [51], it is calculated that 574 kilotons of rapeseed oil can be produced in Germany, without affecting the land use; this oil using the HEFA process with a conversion factor of 0.9 $\text{tons}_{\text{fuel oil}}/\text{ton}_{\text{rapeseed oil}}$ can be converted to hydrocarbons [122]. Afterwards, consideration for product slate and blending ratio is observed to have a significant impact on the overall potential of the pathway along with its specific carbon emissions.

In order to provide a clear understanding of the processes considered, Figure 27 provides key parameters along with mass and energy values of converted products at each step for the HEFA pathway with max jet fuel recovery and 50% blending with conventional jet fuel (HEFA_8) – various pathway configurations are discussed later. For the same pathway configuration key parameters used for the development of the energy optimization model are appended in Table 9. The final rapeseed oil demand for the production of 1MWh of jet fuel is dependent on the blend-in ratios and product slate.

Table 9: HEFA process land and rapeseed requirements for jet fuel production

Parameter	Value [Unit]
Land required for 1MW of jet fuel output	9,863,041 [$m^2/MW_{Jet\ Fuel}$][11]
Rapeseed oil requirement of 1 MWh of jet fuel (mass)	0.1734 [$t_{Rapeseed\ Oil}/MWh_{Jet\ Fuel}$]
Rapeseed oil requirement of 1 MWh of jet fuel (energy)	1.8110 [$MWh_{Rapeseed\ Oil}/MWh_{Jet\ Fuel}$]
Rapeseed oil requirement of 1 MWh of jet fuel including 50% blending (energy)	0.9055 [$MWh_{Rapeseed\ Oil}/MWh_{Aviation}$]

With the aim to improve the production to rapeseed oil, without affecting the land use is deemed paramount and effort is expended to identify opportunities to increase the output. It is observed that Germany currently exports 1.29 Mt of biodiesel per annum [49]. In a scenario, where this export is banned, it is calculated that additional 868,000 hectares of rapeseed production would be made available for jet fuel production – this fundamentally would triple the indigenous potential without affecting the land use and disrupting the established supply chain, as this land is already under cultivation for rapeseed and would result in a frictionless transition for the farmers of this crop. Figure 28 provides the potential that may be exploited if a ban on the export of biodiesel is practiced along with the potential to produce additional jet fuel from the redirected supply of rapeseed oil.

It is again reiterated that, the feedstock selection for this pathway does not comply with the REDII sustainability criteria, but due to lack of alternatives in Germany it is selected to provide a gauge to assess the maximum potential of biogenic pathways. Assessing the pathway emissions and maximum demand substitution is discussed in-detail in section 5.4.

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[11] 1 hectare (ha) = 10000 square meter (m^2)

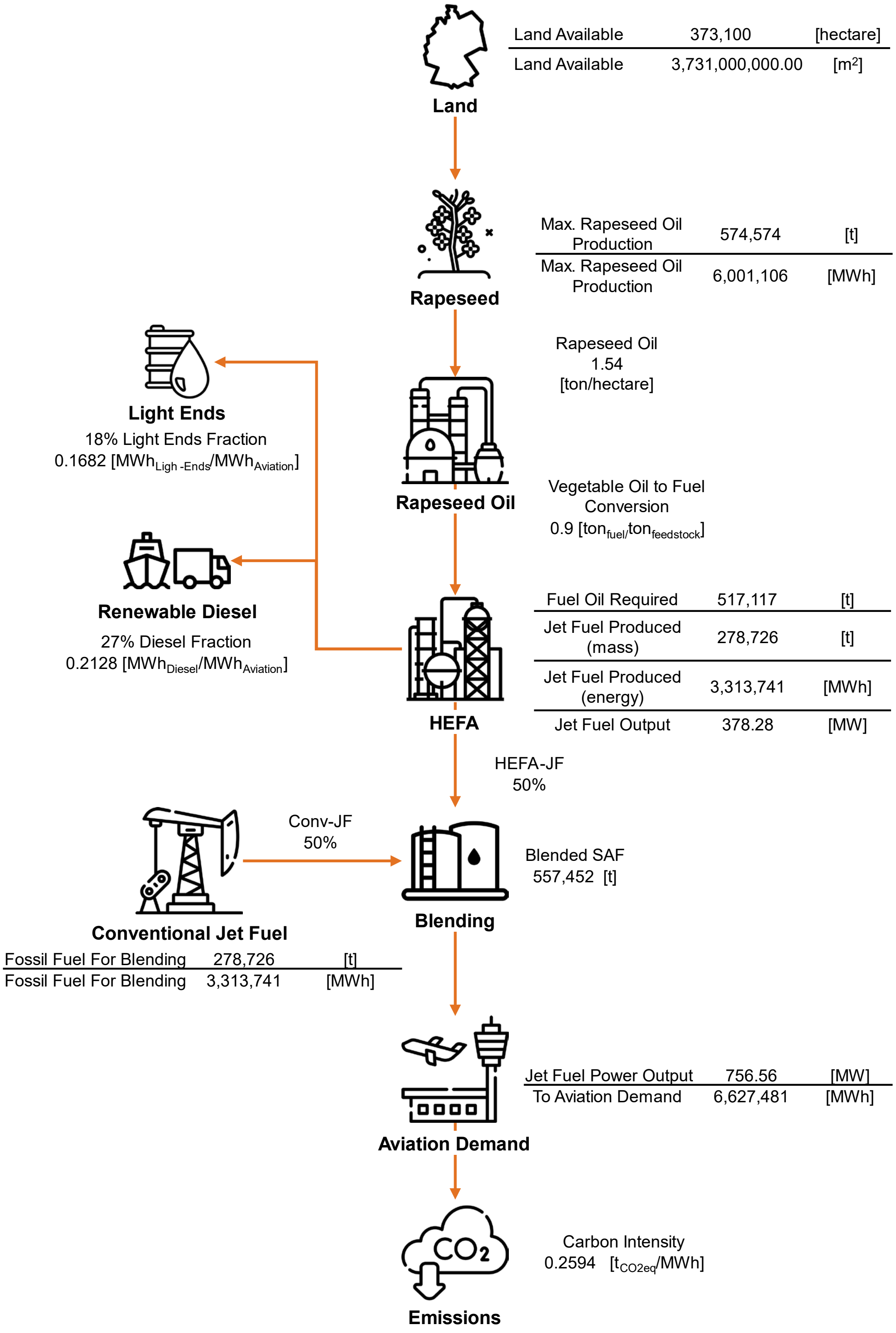


Figure 27: The process flow for HEFA conversion pathway with fallow land cultivation, max jet recovery, and 50% blending (HEFA_8) along with key parameters

Source: Author's own calculations based on own assumptions and various publications [3, 49, 125, 51, 61, 69, 124, 122, 126, 127]

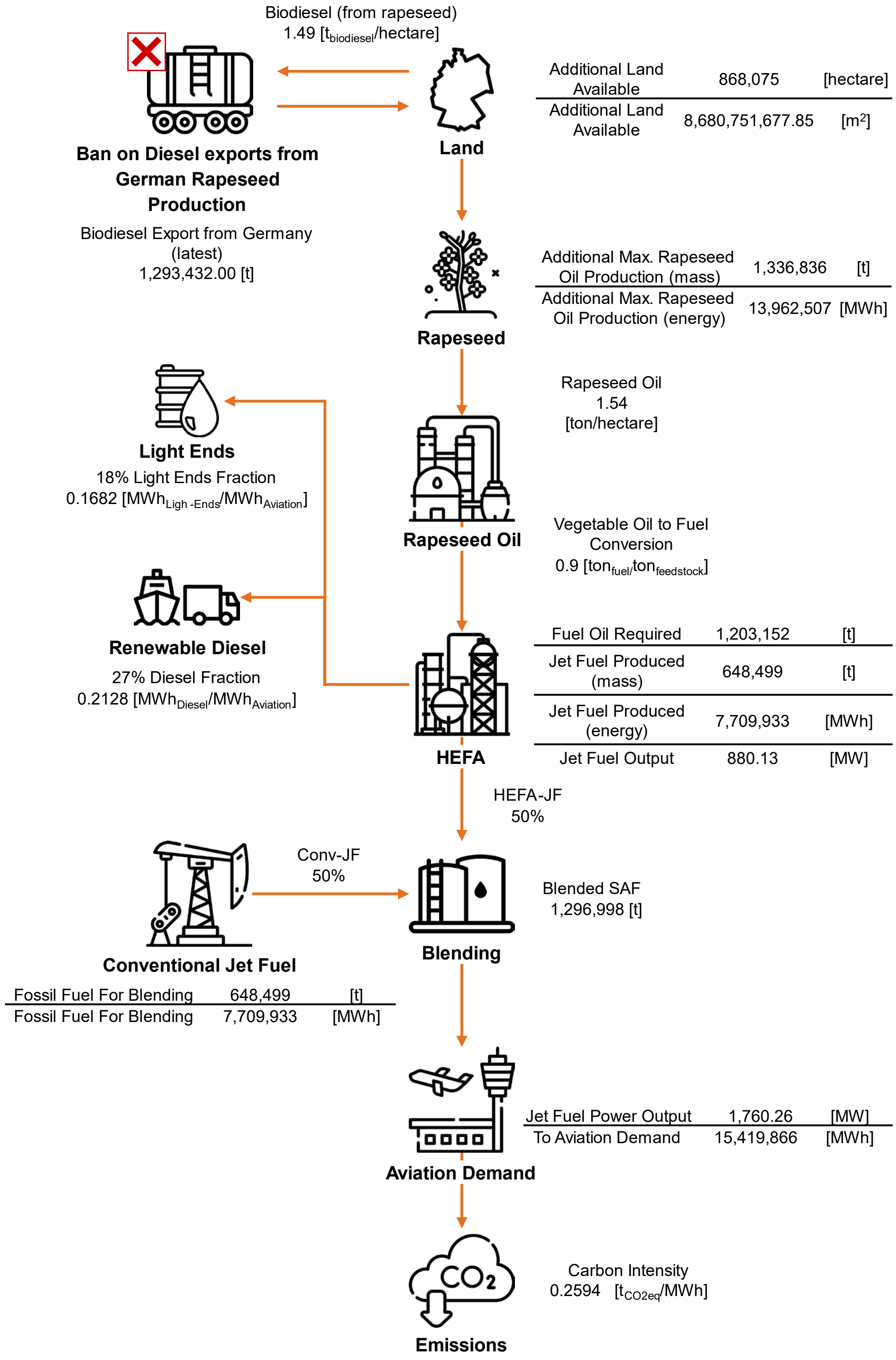


Figure 28: The process flow for HEFA conversion pathway with biodiesel export ban, max jet recovery, and 50% blending (HEFA_8) along with key parameters

Source: Author’s own calculations based on own assumptions and various publications [3, 49, 51, 61, 69, 122, 124–127]

5.2.2. Alcohol-to-Jet (ATJ) Pathway

Alcohol-to-Jet (ATJ) is a thermochemical process in which various alcohol feedstocks can be converted into hydrocarbons including jet fuel, these feedstocks may include methanol, ethanol, (iso) butanol, and even long-chain (C5+) alcohols. ATJ is also known as alcohol oligomerization [75], in which alcohol molecules are processed to olefins, paraffins, and ultimately hydrocarbons in various succeeding steps such dehydration, oligomerization, hydrogenation, and distillation [55, 60, 75, 81, 128]. The ATJ conversions take place in the presence of zeolite and metal oxide catalysts and hydrogen gas is required during hydrogenation [93].

The above-mentioned alcohol feedstocks are generally produced from fermentation of high sugar- and starch-containing cultivations such as corn, sugar cane, switch grass, and sugar beet [128]. In the case of Germany, there already exists an extensive supply chain of sugar beet, which is used for the production of refined sugar and bioethanol. Bioethanol is primarily used in the petrochemical industry for blending with gasoline to produce E10 grade petrol. In fact, the indigenous production for bioethanol in Germany exceeded 635 kt p.a. [49], primarily produced from local cultivations of sugar beet.

Table 10: ATJ process land and bioethanol requirements for jet fuel production

Parameter	Value [Unit]
Land required for 1 MW of jet fuel output	2,746,670 [$m^2/MW_{Jet\ Fuel}$]
Bioethanol requirement of 1 MWh of jet fuel (mass)	0.095 [$t_{Bioethanol}/MWh_{Jet\ Fuel}$]
Bioethanol requirement of 1 MWh of jet fuel (energy)	0.7069 [$MWh_{Bioethanol}/MWh_{Jet\ Fuel}$]
Bioethanol requirement of 1 MWh of jet fuel including 50% blending (energy)	0.7073 [$MWh_{Bioethanol}/MWh_{Aviation}$]

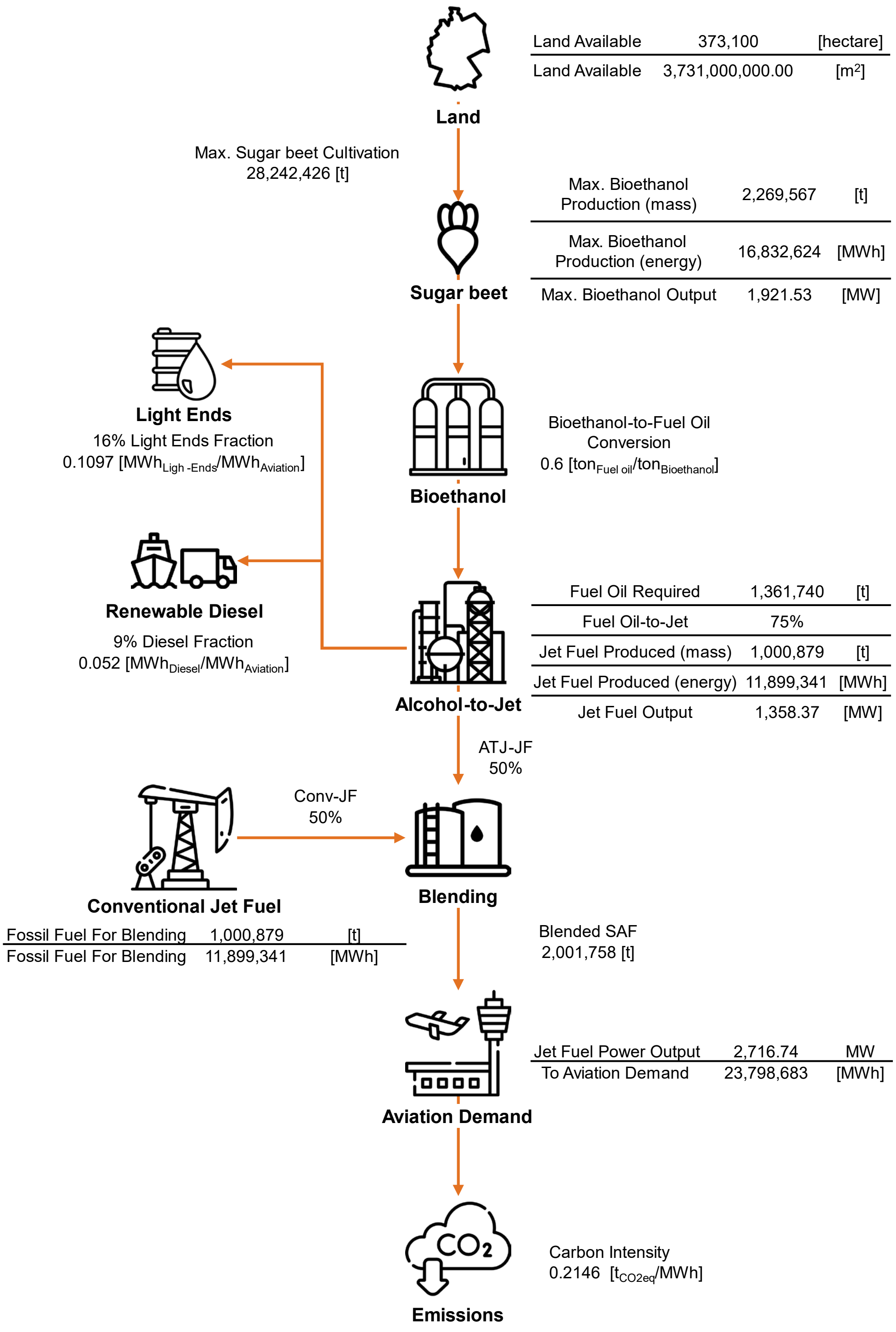
Based on FNR estimates, included as Appendix B-4, it is clearly evident that sugar beet offers the most efficient use of non-cultivated land for this pathway in Germany, producing 7,700 liter of bioethanol per hectare [125]. When calculated with available fallow land, Germany exhibits a potential of approx. 2.2 Mt p.a. of additional bioethanol production which, when processed through ATJ pathway, can produce 1 Mt p.a. of jet fuel, among renewable diesel and other lighter products. Numerous scientific articles highlight a relatively high jet fuel production from ATJ pathway, as high as 75% (mass) of the fuel oil production (see Figure 26) [93, 122, 123]. Due to an ASTM-mandated blending limit of 50%, through ATJ pathway approx. 2 Mt p.a. of SAF can be produced in Germany (see Figure 29). The Table

10 above and Figure 29 provide the key parameters used in the development of ATJ pathway potential for Germany.

Due to the dependency on the cultivation, the emission profile of the ATJ pathway is directly corelated with the emissions of the feedstock used. Even though 1st generation biogenic feedstocks remain the focus of this thesis, which require wide-ranging agricultural activities emitting non-trivial amounts of emissions, over the course of the analysis it is discovered that ATJ feedstock can potentially be produced from steel mill exhaust gases [129] – this has the potential to offer significant reduction in the emissions associated with this pathway. That being said, this potential feedstock is not commercially ready, citing technical and economic concerns, and is not further examined. For 2nd generation feedstocks, due to the spectrum of feedstocks considered, the GFT process is deemed more practical due to its flexibility, however, some 2nd generation feedstock can also be processed through ATJ pathway through fermentation and catalytic conversion [60].

It is acknowledged that the potential calculated above can only be materialized with complete use of the fallow land, however, due to the overlap between sugar beet and rapeseed crops, there exists a competition in exclusive land use. Therefore, a multi-criteria assessment needs to developed. For this reason, apart from total production potential, economic factors are also considered and an optimized approach to deployment of both pathways is exercised, which will be discussed in the next sections and chapter.

It is again reiterated that, the feedstock selection for this pathway does not comply with the REDII sustainability criteria, but due to the lack of alternatives in Germany it is selected to provide a gauge to assess the maximum potential of biogenic pathways. The assessment for the pathway emissions and maximum demand substitution are discussed in-detail in section 5.4.



Land Available	373,100	[hectare]
Land Available	3,731,000,000.00	[m^2]

Max. Bioethanol Production (mass)	2,269,567	[t]
Max. Bioethanol Production (energy)	16,832,624	[MWh]
Max. Bioethanol Output	1,921.53	[MW]

Fuel Oil Required	1,361,740	[t]
Fuel Oil-to-Jet	75%	
Jet Fuel Produced (mass)	1,000,879	[t]
Jet Fuel Produced (energy)	11,899,341	[MWh]
Jet Fuel Output	1,358.37	[MW]

Fossil Fuel For Blending	1,000,879	[t]
Fossil Fuel For Blending	11,899,341	[MWh]

Jet Fuel Power Output	2,716.74	MW
To Aviation Demand	23,798,683	[MWh]

Figure 29: The process flow for ATJ conversion pathway with fallow land cultivation of bioethanol and 50% blending (ATJ_1) along with key parameters

Source: Author's own calculations based on own assumptions and various publications [3, 49, 61, 93, 122, 123, 125]

5.2.3. Gasification and Fischer-Tropsch (GFT) Pathways

The third biogenic pathway considered in this study is different from the first two due to the selection of feedstocks. Instead of 1st generation feedstocks discussed for HEFA and ATJ pathways – which do not comply with the REDII sustainability criteria; Gasification coupled with Fischer-Tropsch synthesis (GFT) offers an extremely flexible approach to convert 2nd generation feedstocks to hydrocarbon products, as it is compatible with any carbon-based feedstock [60]. The Fischer-Tropsch (FT) process is the primary process in which thermochemical conversion of syngas (H_2 + CO) takes place, the FT process is preceded by gasification of the biomass feedstock, which is used to produce syngas. For this analysis, a co-located approach is considered.

The technology for GFT is extremely mature, however, the challenge lies in the assessment and sourcing of the feedstock. As established in section 2.6.2 on page 19, the available technical potential in Germany lies in the range of 84.3-193.7 PJ per annum and is geographically diverse, barring the competition from other sectors which would reduce the estimates even further. Even with the higher potential considered, the conversion efficiency of the GFT process is a limiting factor; based on LHV of the feedstock and converted fuel oil, only 40-50% of the energy is recovered [130–132]. For this analysis the conservative estimate is taken as the reference value. Similar to the HEFA pathway, according to Pavlenko et al. [122], the product slate of the GFT pathway can be adjusted to produce default or maximum jet output, which range from 27-50% (see Figure 26).

In addition to this, considerations regarding blending with conventional jet fuel must also be taken into account, from Table 3 it is evident that, based on the pathway configuration 50-100% blending can be carried out. Although, only 50% blend-in is currently approved by ASTM for FT-SPK and FT-SPK/A pathways. Nonetheless, it is expected that 100% blending is possible, especially for modern aircrafts. The blend-in limit is observed to directly impact the emission profile of the pathway, with higher blending offering the lowest well-to-wake emissions.

Based on above-mentioned points, multiple approaches for the GFT pathways can be configured resulting in various estimates for fuel production and resultant CO_2 emissions – these are discussed in the next section. The Figure 30 provides an overview of the conversion pathway considered for GFT processes. Even with highest potential, maximum recovery and highest blending limit considered, it is calculated that, approx. only 887 kt p.a. of SAF can be produced in Germany from second generation feedstocks – requiring 5.1 MWh of biomass feedstock input per MWh of jet fuel produced.

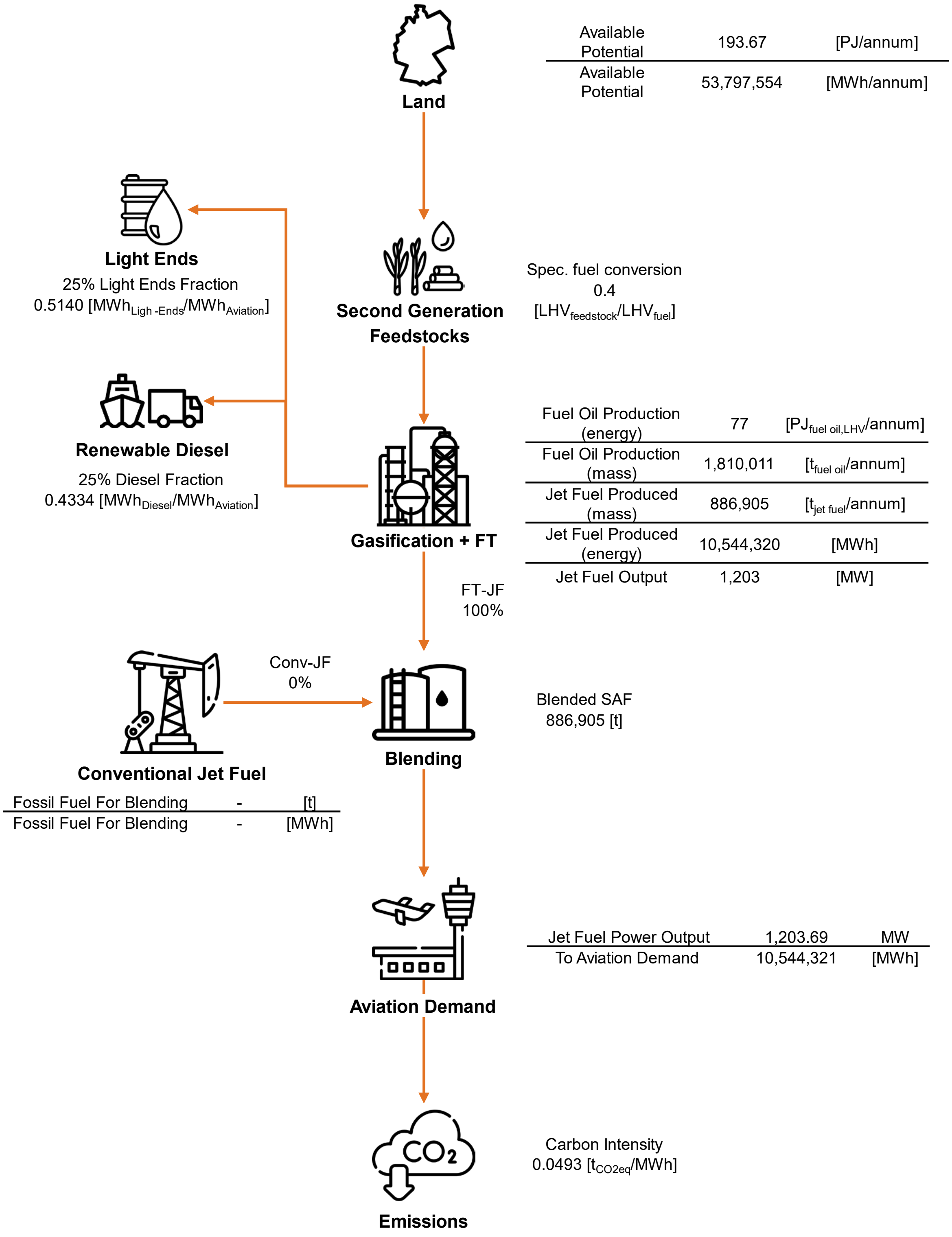


Figure 30: The process flow for GFT conversion pathway with second generation feedstocks, 100% blending and maximum jet fuel recovery (GFT_8) along with key parameters

Source: Author's own calculations based on own assumptions and various publications [3, 61, 122, 130–132]

5.3. Configurations of Biogenic Pathway Scenarios

Taking into consideration the variability introduced by conversion processes, jet fuel recovery potentials, ASTM-approved and pragmatic blending limits, and ultimately feedstock source, in total 17 distinct scenarios of the biogenic pathways are studied. The table below provides a detailed list of scenarios that are assessed for the determination of maximum energy substitution potential and their respective GHG emissions. Based on the product slate provided by Pavlenko et. al [122], the end-hydrocarbon stream can contain lower or higher concentration of carbon length that fall in the jet fuel (kerosene) range. In total 2 distinct strategies are considered, i.e., default and max jet recovery – the breakdown of each respective pathway is already provided in Figure 26.

In addition to this, ASTM approved blending limits also introduce a degree of variability into the scenarios, as it directly affects the carbon intensity and produced volumes of the jet fuel from each pathway. Wherever possible, higher limits are incorporated to develop the most favorable scenario for each pathway; these limits are referenced from scientific sources and are already discussed in the previous sections. Perhaps, most importantly, feedstock selection is the source of largest variability among various scenarios, as it defines the conversion process which encompasses the major distinction factors. For first-generation feedstocks, fallow land and export ban scenarios are taken into account, where possible. Meanwhile, for the second-generation feedstocks, only lower and higher limits are considered – these correspond to 84.3 PJ (23.43 TWh) and 193.7 PJ (53.84 TWh) per annum respectively. All three discussed pathways are considered for the analysis, to assess the overall potential and their GHG footprint.

Table 11: Biogenic pathways' scenarios for environmental and substitution potential assessment

	Scenario Name	Conversion Process	Jet Fuel Recovery	Blending [% of SAF]	Use of Fallow Land	Export Ban	Feedstock Gen. (Crop)
1.	HEFA_1	HEFA	Default	10%	Yes	No	First – Rapeseed
2.	HEFA_2	HEFA	Max	10%	Yes	No	First – Rapeseed
3.	HEFA_3	HEFA	Default	10%	Yes	Yes	First – Rapeseed
4.	HEFA_4	HEFA	Max	10%	Yes	Yes	First – Rapeseed
5.	HEFA_5	HEFA	Default	50%	Yes	No	First – Rapeseed
6.	HEFA_6	HEFA	Max	50%	Yes	No	First – Rapeseed
7.	HEFA_7	HEFA	Default	50%	Yes	Yes	First – Rapeseed
8.	HEFA_8	HEFA	Max	50%	Yes	Yes	First – Rapeseed

	Scenario Name	Conversion Process	Jet Fuel Recovery	Blending [% of SAF]	Use of Fallow Land	Export Ban	Feedstock Gen. (Crop)
9.	ATJ_1	ATJ	Default	50%	Yes	No	First – Sugar beet
10.	GFT_1	GFT	Default	50%	No	No	Second (lower potential)
11.	GFT_2	GFT	Max	50%	No	No	Second (lower potential)
12.	GFT_3	GFT	Default	100%	No	No	Second (lower potential)
13.	GFT_4	GFT	Max	100%	No	No	Second (lower potential)
14.	GFT_5	GFT	Default	50%	No	No	Second (higher potential)
15.	GFT_6	GFT	Max	50%	No	No	Second (higher potential)
16.	GFT_7	GFT	Default	100%	No	No	Second (higher potential)
17.	GFT_8	GFT	Max	100%	No	No	Second (higher potential)

5.4. Limits to Growth for Biogenic Pathways in Germany

Due to the concerns regarding land usage for 1st generation feedstocks and a higher technical limit on the 2nd generation feedstocks, it is paramount to assess the limits of what biogenic pathways can offer to ameliorate the aviation emissions in Germany. A simplistic approach is devised to asses these limits, namely, the maximum substitution potential and specific emission for each pathway scenario.

5.4.1. Maximum Substitution Potentials

Maximum substitution potential refers to the ability of the pathway configuration to offset a certain energetic component of the final aviation demand. As the calorific value and density of the aviation fuels are standardized with a low threshold limit, this can also be translated into mass or volume substitution potential. For the assessment, the potential of each pathway is calculated based on the resource availability in relation to feedstock cultivation or export ban, along with the limitations imposed by the specific pathways in terms conversion efficiencies, fuel production and product slate, and finally adjusted for imposed blending limits.

The calculated potential is then compared with the total forecasted demand (2025-2050) i.e., with the sum of low, base, and high aviation energy demands for the entire modelling period individually. Due to various demand forecasts, there exists a range of energy substitution potentials that can be met by a single conversion pathway – this is represented as the error bars in Figure 31. The higher limit represents the ability of the respective scenario to meet the energy needs of the low aviation demand scenario, meanwhile the lower bound represent the potential under high demand scenario. This is due to the fact that, under low demand amidst production capacity limitations, a larger fraction of the demand can be substituted by the respective pathway and vice versa.

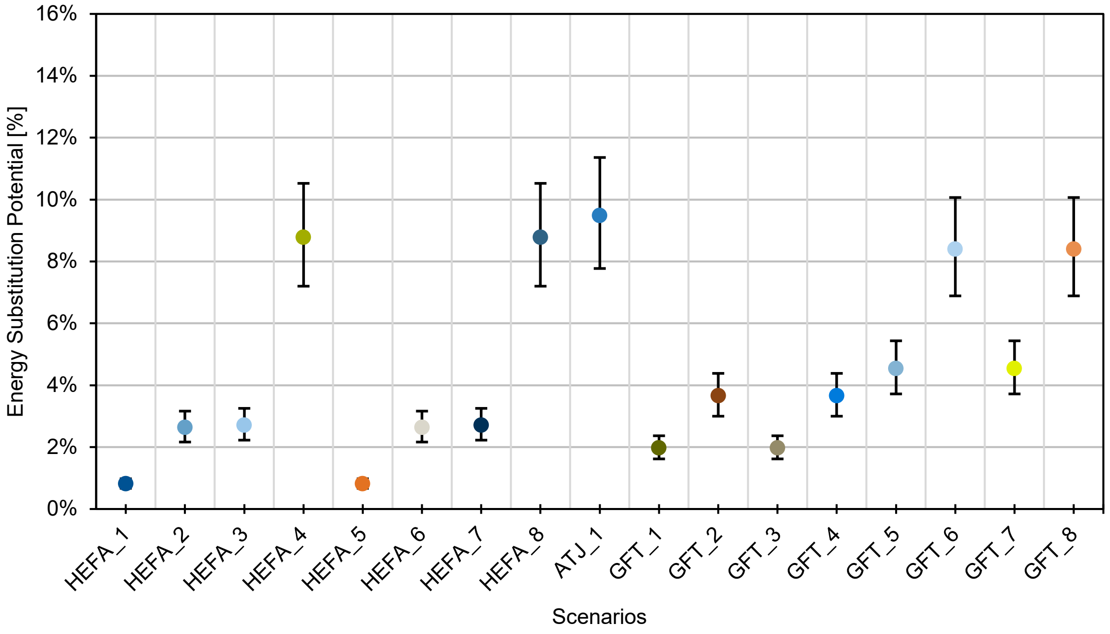


Figure 31: Total energy substitution potential of biogenic scenarios for low, base, and high aviation demand forecasts

Evidently from Figure 31, all the modelled scenarios fail to a provide substitution potential above 12% of the total demand. This is due to the fact that all the feedstocks are supply constrained – imposing an upper limit of how much energy can be indigenously produced in Germany without importing feedstocks or changing the land use. Despite this, the substitution potentials, as depicted in Figure 31, are misleading. This is due to the fact that most scenarios rely on almost 50% blending of conventional jet fuel to be able meet the requirements set under various normative. This implies that the actual amount of sustainable fuel produced is significantly lower than the depicted values. This dependency on fossil fuels not only impacts the total volume of fuel produced but also reflected on the specific GHG emissions of each pathway.

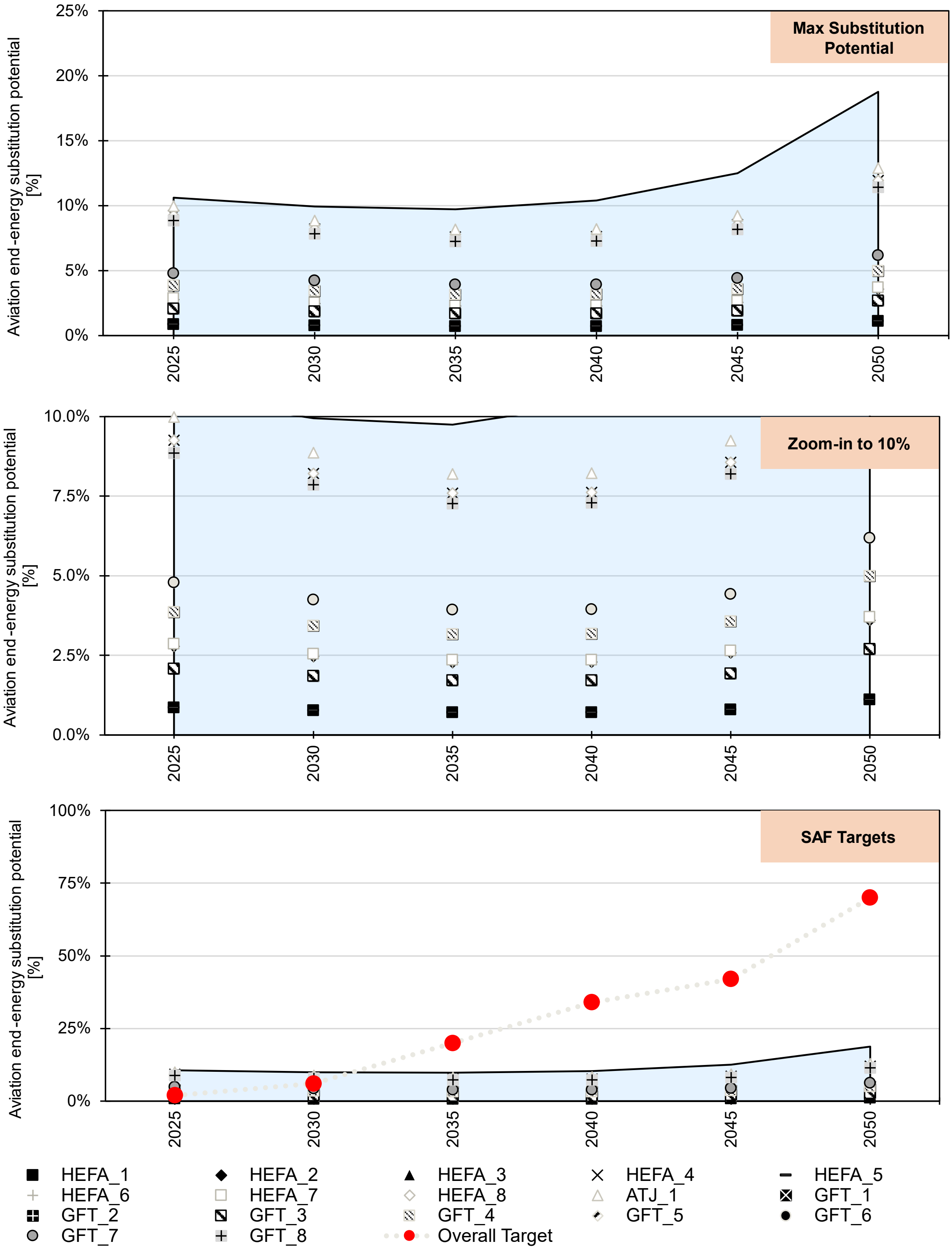


Figure 32: 5-yr energy substitution potential of biogenic scenarios in comparison with REDII/ReFuelEU Aviation Targets

Due to the availability of demand forecast on an annual basis, the estimation of substitution potentials can also be carried out at a higher resolution than the one presented in Figure 31. In this pursuit, potential for each biogenic pathway is calculated on an annual basis and the resultant values at every 5-yr interval are selected starting from 2025 till 2050, as illustrated in Figure 32. The shaded area (light blue) represents the range of the aviation demand that can be potentially covered by individual scenarios. Furthermore, due to similar overall potentials, various pathways are observed to overlap one another and cannot be clearly depicted in the figure above. These are:

1. HEFA_1 and HEFA_5
2. HEFA_2, HEFA_3, HEFA_6, and HEFA_7
3. HEFA_4 and HEFA_8
4. GFT_1 and GFT_3
5. GFT_2 and GFT_4
6. GFT_5 and GFT_7
7. GFT_6 and GFT_8

It is notable that, the maximum demand potential gradually falls till 2035 and then slowly rises to around 18%. This is attributed to the development of kerosene demand as alternate aviation technologies are introduced in to the aviation market – as the fraction of kerosene-based aviation fades, the max potential of respective can cover larger fraction of the remaining demand. However, even with this change, the overall potential to meet the forecasted aviation demand by biogenic pathways remains low, and even under most enabling conditions, biofuels are unable to fully cover the SAF demand targets. Therefore, need for non-biogenic (e-SAF) pathways and/or imports still exists in Germany.

Detailed values regarding SAF produced and energy substitution potential are appended in Appendix C.

5.4.2. Specific Emissions

In addition to potentials, specific emission of various scenarios plays a decisive role in understanding the constraints. These constraints are imposed by regulatory and environmental concerns and are affected by cultivation and processing of various feedstocks. As this analysis is geared towards developing a macro-economic and sector-wide understanding of SAFs, the granularity regarding GHG emission calculations is reduced and do not strictly comply with standardized LCA protocols.

To calculate the emission intensity of HEFA conversion pathways, the reference values provided in REDII Annex V for biodiesel production from rapeseed feedstock are being adopted. The cultivation, processing and transportation emissions are included in the reference value and it is assumed that the total process emissions are proportionally divided over the product slate of the HEFA process and is reflected in the functional unit. For the SAF produced from HEFA process, an overall specific emission of 50.1 g_{CO2eq}/MJ (0.1803 t_{CO2eq}/MWh)[12] is used as the base value [3]. Based on the blending limit, the base value is proportionally adjusted for the fossil fuel inclusion for each scenario, due to the fact the calorific values (LHV) for both streams are same, mandated by ASTM D7566. The fossil fuel specific emission of 94 g_{CO2eq}/MJ or 0.3384 t_{CO2eq}/MWh is also provided in REDII Annex V [3].

A similar approach is taken for the GFT pathways, and an equivalent diesel value is taken as the reference value for this analysis. The base value of 13.7 g_{CO2eq}/MJ (0.049 t_{CO2eq}/MWh) is inclusive of cultivation, transportation, and processing emissions [3]. Similar to the HEFA approach, the base value is then proportionally adjusted to include the effects of blending with fossil jet fuel.

The determination of ATJ specific emission is not so straightforward, as there is no directly provided estimates for SAF produced from ATJ pathway in REDII Annex V. However, reference values for bioethanol production from sugar beet is provided in the legislation, thus necessitating an indirect approach. According to REDII Annex V, the cultivation, processing, and transportation of bioethanol from sugar beet emits 19.5 g_{CO2eq}/MJ (0.0702 t_{CO2eq}/MWh) of GHG emissions. To process the bioethanol to jet fuel through ATJ process requires an additional 3.2-6.7 g_{CO2eq}/MJ of GHG emissions, pursuant to the nature of the feedstock [133, 134]. For this analysis, a conservative estimate of 5.7 g_{CO2eq}/MJ is selected based on the estimates by Hannon et al. [134]. Hence, the base value for SAF produced from ATJ pathway is taken as 25.2 g_{CO2eq}/MJ or 0.0907 t_{CO2eq}/MWh. The calculated specific emissions of conversion pathways falls in the same range as the estimates put forward by numerous scientific papers and reports, such as [60, 69, 81, 82, 88, 94, 133, 135–138].

Due to the disparity in terms of carbon emissions between conventional jet fuel and fuel produced from biogenic pathways, the specific emissions are adversely affected in the cases where large quantity of conventional jet fuel is mixed with biogenic SAF. GFT pathways clearly exhibit the lowest specific emissions out of all the modelled scenarios, meanwhile HEFA pathways predominantly exist on the opposite end of the spectrum due to higher fossil component. Detailed tables regarding GHG emissions as a function of aviation

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[12] 1 g_{CO2eq}/MJ = 0.0036 t_{CO2eq}/MWh

demand and potential avoided emissions for each scenario are appended in Appendix C: Pathways Assessment.

Table 12: Specific emission of biogenic scenarios inclusive of blending with fossil jet fuel

Scenario Name	Blending Limit [% of SAF]	Specific Emission [g_{CO2eq}/MJ]	Specific Emission [t_{CO2eq}/MWh]
HEFA_1	10%	89.61	0.3226
HEFA_2	10%	89.61	0.3226
HEFA_3	10%	89.61	0.3226
HEFA_4	10%	86.55	0.3116
HEFA_5	50%	72.05	0.2594
HEFA_6	50%	72.05	0.2594
HEFA_7	50%	72.05	0.2594
HEFA_8	50%	72.05	0.2594
ATJ_1	50%	59.60	0.2146
GFT_1	50%	53.85	0.1939
GFT_2	50%	53.85	0.1939
GFT_3	100%	13.70	0.0493
GFT_4	100%	13.70	0.0493
GFT_5	50%	53.85	0.1939
GFT_6	50%	53.85	0.1939
GFT_7	100%	13.70	0.0493
GFT_8	100%	13.70	0.0493

5.5. Ranking Criteria and Short-listed Pathways

Due to the numerosity of the studied scenario and the interdependency between maximum substitution potential and specific emissions, it is still unclear which biogenic scenarios offer a balanced approach between supply- and environmental constraints. Therefore, a ranking criterion is necessary where the scenarios can be compared with one another taking into consideration both of the above-mentioned factors. For this pursuit, a scoring system is formulated for **substitution potential score (SPS)** and **carbon intensity score (CIS)**. In order to calculate these scores following equations (4) and (5) are used.

$$SPS_{scenario\_x} = \left\lfloor \frac{SP_{scenario\_x}}{\max\left(SP_{scenario\_1} \dots SP_{scenario\_n}\right)} \right\rceil \tag{4}$$

$$CIS_{scenario\_x} = \left\lfloor \frac{SE_{scenario\_x}}{\min\left(SE_{scenario\_1} \dots SE_{scenario\_n}\right)} \right\rceil \tag{5}$$

$$Overall\ Score_{scenario\_x} = SPS_{scenario\_x} + CIS_{scenario\_x} \tag{6}$$

For the calculation SPS of any scenario, a rounding function is used where the average substitution potential (SP) of the scenario is divided by the maximum of the average substitution potential among all biogenic scenarios. Similarly, for CIS, a rounding function is employed in which the specific emission (SE) of the respective scenario is compared against the least emitting scenario. The overall score is simply calculated using an arithmetic sum of both score by using equation (6). By employing this approach, scenarios with the highest potential and least emission are identified. Figure 33 illustrate the overall score and the rank order of all of the 17 biogenic scenarios modelled in this study.

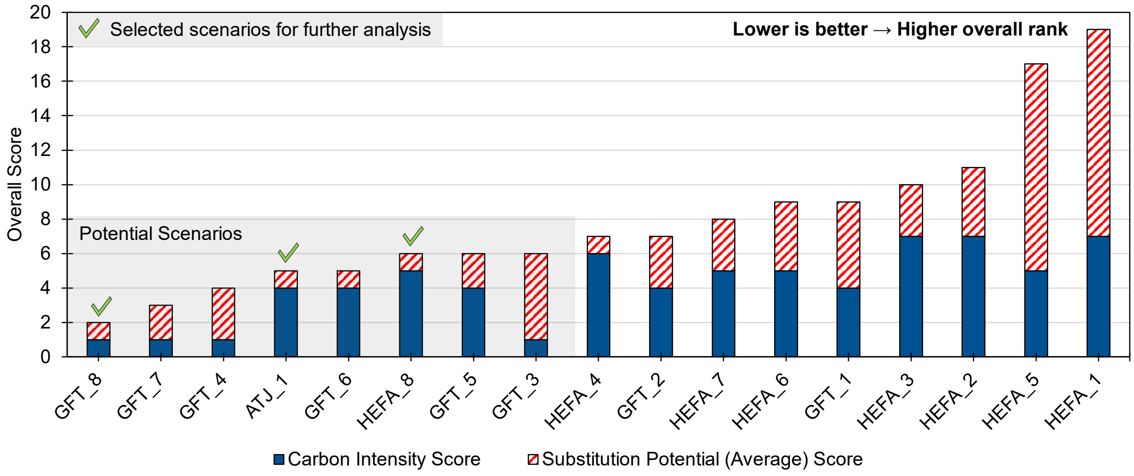

Figure 33: Overall score for biogenic scenarios and short-listed scenarios for energy modelling

As it is evident from Figure 33, various scenarios can potentially have a similar score. That being said, due to mutually dependent nature of the scenario development, scenarios stemming from a single pathway cannot be simultaneously considered. Therefore, only highest-ranking scenarios from each biogenic pathway are selected for energy modelling and economic assessment. These are: **GFT_8**, **ATJ_1**, and **HEFA_8** pathways.

The energy modelling approach is deemed necessary as the economic influences are thus far not included in this analysis. Moreover, due to variation in feedstock costs, technology costs and product slate, it is expected that the economic parameters would greatly impact the outcome of the analysis and define which scenarios can be developed. This is extremely important as the biogenic scenarios due to their limited ability to meet German aviation demand have to compete with non-biogenic sources, and parallelly, among themselves due to scarce land resource.

6. Non-Biogenic Pathways and Development of Energy Model

"Essentially, all models are wrong, but some are useful."
- *George E.P. Box (1987)*

6.1. Preface

As it is clearly established in the preceding chapter; the inability of the biogenic pathways to fully meet the foreseeable aviation fuel demand by 2050 in Germany. It is therefore paramount that alternate fuel production pathways and propulsion options are studied in the context to fully meet the forecasted demand within the bounds of indigenous resources. In this pursuit, the current chapter develops an understanding regarding the production of SAF through non-biogenic pathways i.e., PtL or e-fuels. In addition to this, energy requirement of alternative propulsion technologies, namely, hydrogen and electric aviation are also given due consideration in this chapter. And finally, techno-economical parameters for the development of an energy model are compiled, such as, capital expenses (CAPEX), operational expenses (OPEX), storage costs, feedstock costs, carbon price, etc.

6.2. Non-Biogenic Pathways

Based on the TRL and FRL of various Power-to-Liquid and currently operational SAF projects in Germany summarized in section 3.4.2 and 2.2.3 respectively, two potential pathways are identified, namely:

1. Methanol Synthesis
2. Fischer-Tropsch (FT) Synthesis

6.2.1. Methanol Synthesis

According to Dieterich et al. [36], the industrial methanol synthesis (MeOH) process is extremely well-developed with over a century on industrial experience. Germany is a pioneer in this fuel production technology, as one of the biggest and oldest industrial plant i.e., BASF Ludwigshafen is located in Germany [36]. Moreover, almost 90% of the European methanol production capacity is contributed by Germany [139]. Similar to previously described processes, methanol synthesis is also a thermochemical process, but rather carried out in the presence of CuO/ZnO catalyst and is supplemented by low temperatures and pressures [36].

Apart from the biogenic feedstocks used in the fermentation of alcohols and production of fuels, the methanol (CH_3OH) can also be synthesized from H_2 and CO_2 [75, 91, 139]. The synthesized methanol can be simply processed in a similar manner used in the production of jet fuel through ATJ pathway. This is achieved by distinct intermediate processes, namely, DME (Dimethyl Ether) synthesis, olefin synthesis, oligomerization, and finally hydrotreating [91]. Due to this reason, the methanol synthesis pathway is similar to the ATJ pathway [140] and a similar product slate is assumed for the end products, including jet fuel/kerosene, renewable diesel, and light ends (see Figure 26). Based on this, a product slate split of 75%-9%-16% between jet fuel, diesel and light ends is assumed.

Despite having a similar process to ATJ pathway, under the ASTM normative there does not exist any direct approval regarding methanol synthesis pathway. Rather, it is envisaged that a separate certification for this pathway will soon be established [141]. Thereby, it is assumed that newer aircraft complying with this certification will be fully compatible with the jet fuel produced from methanol synthesis and no jet fuel blending would be necessary.

As of writing this analysis, practically all the methanol production in Germany relies on steam methane reforming (SMR) of natural gas to obtain their primary feedstocks, i.e., H_2 and CO_2 [139, 142]. However, in order to make the process comply with the sustainability criteria established previously, production of H_2 and CO_2 feedstocks should be derived from renewable and sustainable sources.

For hydrogen gas, direct production through electrolysis using renewable electricity is deemed practical and with a developing hydrogen economy in Germany and the neighboring countries, a large regional supply chain is expected in the coming years. Use of renewable electricity eliminates any direct emissions originating from the electrolysis process, thereby making it complaint with REDII directive.

For CO_2 production, plethora of biogenic and non-biogenic options exists, for this analysis carbon capture using amine washing from concentrated sources is used as a primary source – justifications for which a provided in the later section. Therefore, using green hydrogen and CO_2 capture, the methanol synthesis does not release any direct GHG emissions.

Using stoichiometric relations in accordance with equation (7) for an average carbon length of C11[13], alongside estimates and procedures provided in various sources [36, 71, 73, 81, 82, 95, 122, 141, 143–146] technical parameters of the process including input and output streams are established. For the conversion process, an integrated plant approach is assumed and 10% of the light ends production is redirected for process heating to avoid additional use of natural gas [85, 141, 147] – this is based on the energetic losses and power input required to run the process [148]. The Figure 34 provides an overview of the process flow used for calculations along with key values.

$$12H_2O + 11CO_2 \rightarrow C_{11}H_{24} + 17O_2 \tag{7}$$

The overall process efficiency lies in the range of 49.4-54% for the year 2025 and 2050 respectively and is directly dependent on the electrolyser efficiency. As the electrolyser technology is further improved, citing to efficiency gains, the renewable energy input is expected to fall from 2.02 MWh to 1.86 MWh.

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[13] Average carbon length of C11 is based on the assumption that the process is optimized for the production of kerosene and justification for which are discussed in section 3.1 based on the work of Holladay et al. [56]

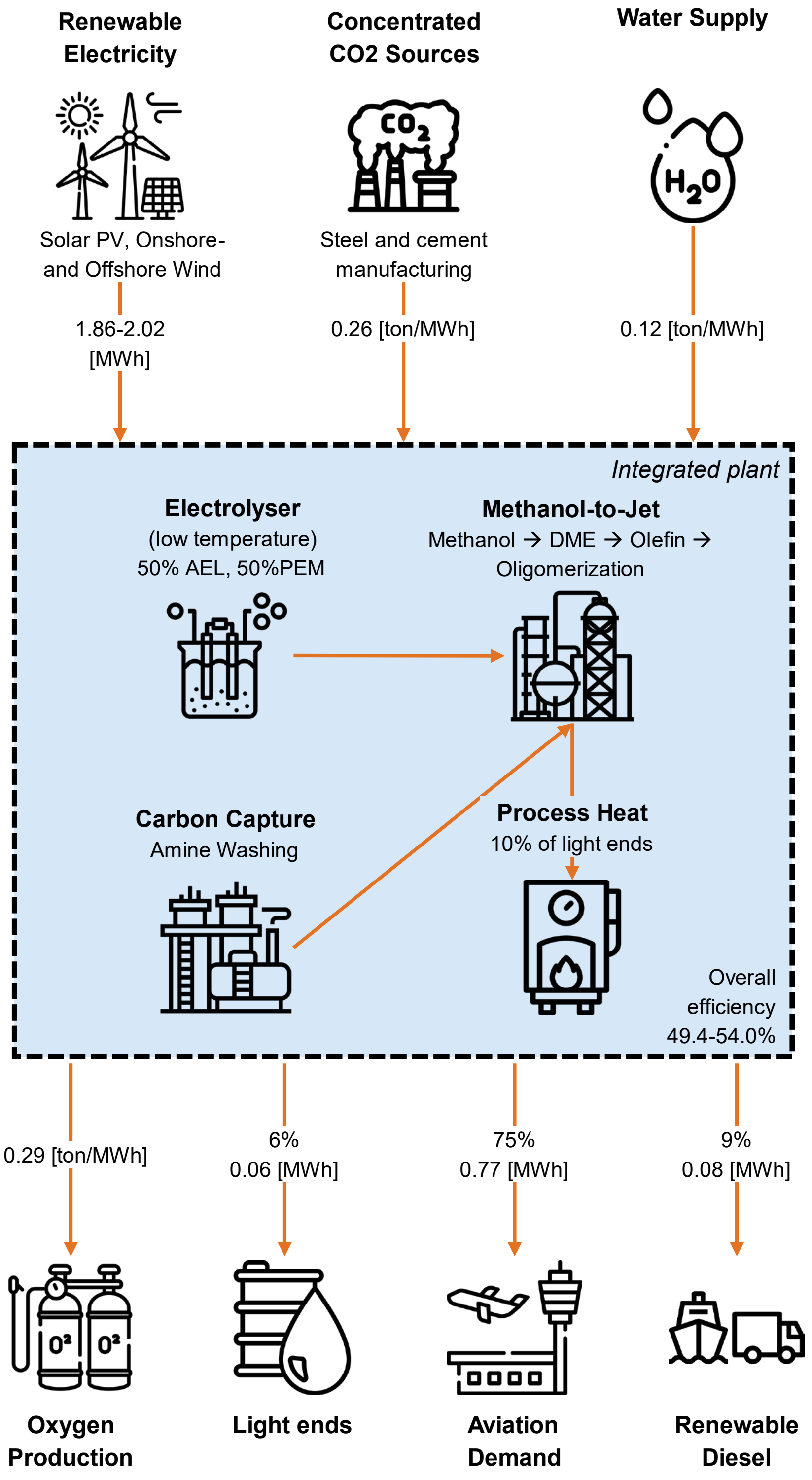

Figure 34: The process flow of methanol synthesis pathway with integrated hydrogen electrolysis and carbon capture along with key parameters

Source: Author-calculated values based on [36, 71, 73, 81, 82, 95, 122, 132, 141, 143–146]

6.2.2. Fischer-Tropsch Synthesis

Similar to GFT pathway defined for biogenic fuels, the Fischer-Tropsch synthesis, is a thermochemical conversion process where syngas (CO + H_2) is converted to hydrocarbons. The key difference being the source of syngas, in the biogenic pathways, the gasification of biomass is used to obtain these feedstocks. However, similar to MeOH synthesis, H_2 gas can be produced through electrolysis. For CO production, CO_2 gas is captured from concentrated sources and by using Reverse Water Gas Shift (RWGS) is converted to CO [71, 91].

Similar to biogenic pathways, the direct FT process, in which CO_2 gas is directly used in the conversion is still in its infancy and is not considered for this analysis [36]. Similar to MeOH synthesis approach, 10% of light ends are recirculated for process heating - this methodology is comparable to the one used by Schmidt et al. [141] and Peters et al. [147].

Through stoichiometry, it is calculated that the flows of reactants and products for the chemical reaction is similar to the MeOH synthesis and is also represented by equation 7. An integrated plant approach with similar assumptions to MeOH synthesis is considered for this pathway as well, and the overall process flow along with key parameters are presented in the Figure 35.

Product-slate of the non-biogenic pathway is assumed to be similar to the product slate of biogenic GFT pathway and is represented by Figure 26 on page 58. To reiterate, a product split between jet fuel, diesel, and light ends production is taken to be 75%, 25% and 25% respectively. However, Peters et al. [147] makes a distinction between high-temperature and low-temperature FT synthesis, the latter having a better yield of longer chain hydrocarbons such as jet fuel. This idea is also put forward by [95, 149] in which jet fuel yield is categorically improved by means of temperature and catalyst selection. That being exclaimed, the distinction in process temperatures is ignored for this simplistic analysis and similar distribution to the GFT (max jet) pathway, as iterated above, is assumed to be the product slate of FT synthesis as well.

The overall process efficiency is also highly dependent on the electrolysis efficiency and is calculated to be in the range of 48.4%-53% - with improvements linked to the improvements in the electrolyser efficiency. This is equivalent to the overall process energy requirement of 1.9-2.08 MWh.

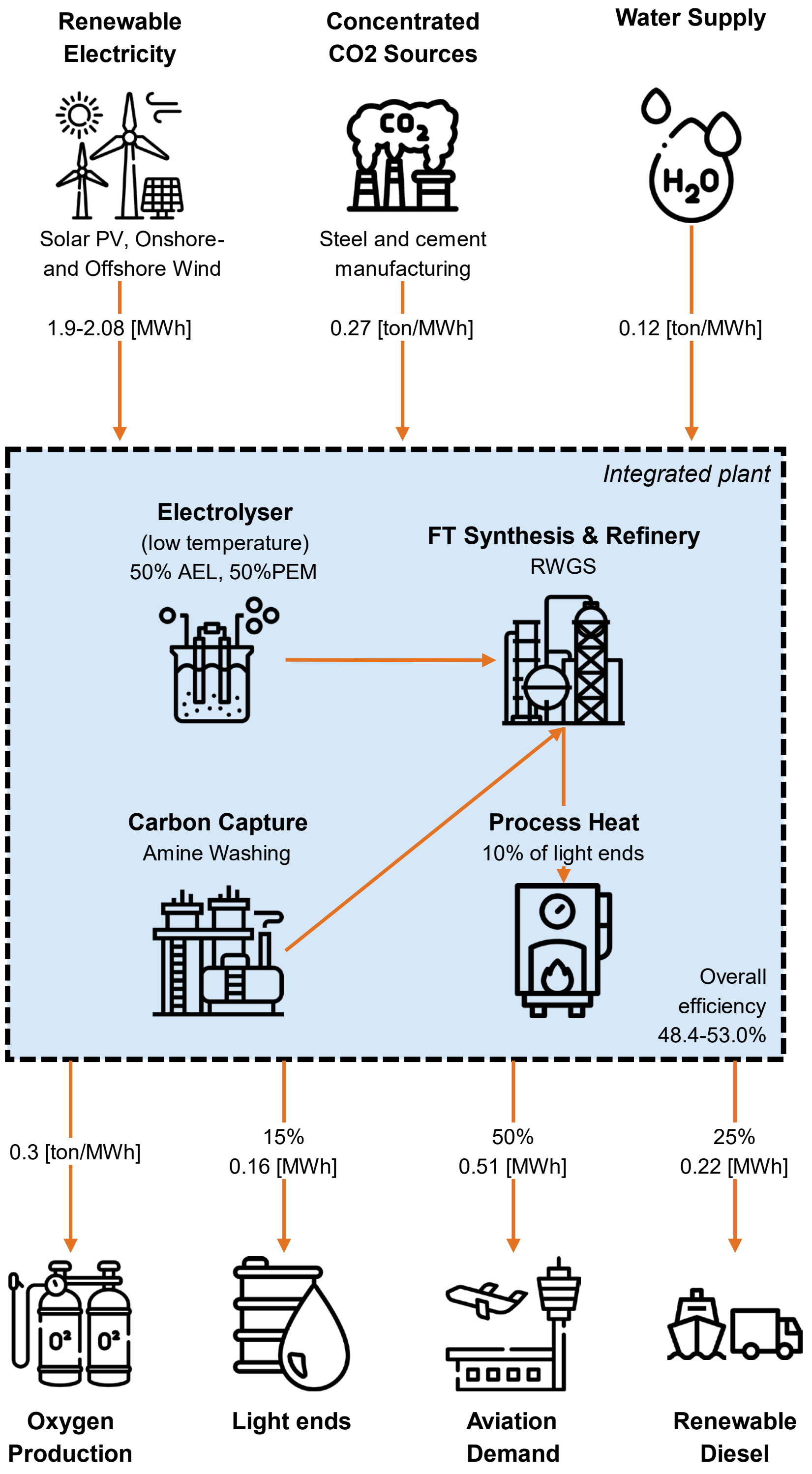

Figure 35: The process flow of Fischer-Tropsch pathway with integrated hydrogen electrolysis and carbon capture along with key parameters

Source: Author-calculated values based on [31, 36, 71, 73, 81, 82, 85, 95, 122, 132, 140, 141, 143, 143–146, 150]

6.2.3. Electrolyser Technology Selection

Hydrogen can be easily produced from clean water and electricity using electrolysers. The hydrogen gas produced from renewable electricity is referred to as ‘green hydrogen’. The green hydrogen can be directly used in multiple applications, such as: electricity production, seasonal storages, heating, transport and can also serve as a feedstock for liquid and gaseous fuels production. Given the properties of hydrogen, combustion in a turbine or engine as well as electricity generation in a fuel-cell are technically feasible. Conveniently, the hydrogen generated can also substitute natural gas in the existing gas networks or could be transported by Liquid Organic Hydrogen Carriers (LOHC) such as dibenzyltoluene (H0-DBT) and perhydrodibenzyltoulene (H18-DBT), or through cryogenic liquid hydrogen (LH_2) at -253 degree Celsius [85]. For this analysis, the production of hydrogen is used either as a feedstock for SAF production or used directly in hydrogen aviation.

Due to the reliance of e-SAF pathways and hydrogen-based aviation on hydrogen supply, the electrolyser technology is deemed as a key variable for cost and technical parameters. Three technologies are identified over the course of the study having promising deployments over the modelling period. These are: alkaline electrolyser cell (AEL), proton exchange membrane electrolyser cell (PEM), and solid oxide electrolyser cell (SOEC).

Each of these technologies offer distinctive advantages and suffers from clear disadvantages, therefore, a distinction among these technologies needs to be made and a balance approach regarding the future system expansion is paramount for a cost-effective supply of the future hydrogen demand. In pursuit of this, the table below provides a summary of the considered technical parameters of the key electrolyser technologies developed through the review of multiple scientific sources [85, 139, 140, 145, 150–155].

Table 13: Comparison of Electrolyser Technologies

Source: Summary of findings from [85, 139, 140, 145, 150–155] and author’s own assessment

Parameter	AEL	PEM	SOEC
Operating Temperature	Low (<100 °C)	Low (<100 °C)	High (>800 °C)
Operating Pressure	1-200 bar	1-350 bar	1-5 bar
Electrolyte	20-30% NaOH/KOH	Perfluoro-sulfonic acid	ZrO_2 doped with Y_2O_3
Cell Separator	Diaphragm	Electrolyte membrane	Electrolyte membrane
Efficiency	~70%	~60%	~80%

Parameter	AEL	PEM	SOEC
Availability	Commercially available	Commercially available	Currently in R&D stage
Lifetime	Longer lifetime	Shorter lifetime compared to AEL	Short lifetime due to material degradation
Production Capacity	High	Significantly lower production capacity compared to AEL	Significantly lower production capacity compared to AEL
Startup Time	Long	Short startup time compared to AEL	Relatively longer startup time
Load Flexibility	Low load change flexibility	Suitable for start-stop operation	Due to long startup time, not suitable for start-stop operation
Coupling with Intermittent RE Supply	No	Yes	No
Investment Cost	Lower	Higher CAPEX compared to AEL	Highest system cost
Operation Cost	Relatively higher	Relatively lower due to high direct current	Relatively lower due to higher efficiency
Hydrogen Purity	Lower hydrogen purity due to the presence of alkaline solution	Good hydrogen purity	Good hydrogen purity
TRL	8-9	7-8	5

From Table 13, it is evident that AEL and PEM technology are clearly ahead of the SOEC technology, thereby for the future system design only AEL and PEM electrolyser are considered. Moreover, it is observable that there is no clear winner between AEL and PEM technologies, as both of the technologies offer certain advantages in terms of cost, flexibility, or ease-of-integration. Therefore, a 50%-50% technology split is assumed between AEL and PEM electrolyser installations.

The electrolysers are not modelled as a standalone unit, rather an integrated plant approach with a coupled fuel production facility is assumed. This can be avoided with a robust hydrogen supply network, where the electrolyser capacity can be placed closed to RE sources. Given the lack of certainty regarding hydrogen supply infrastructure, at this stage, an integrated plant approach offers the most pragmatic option.

6.2.4. Carbon Capture Technology Selection

Carbon capture (CC) technology is ranked as the limiting factor for various non-biogenic SAF pathways, as the TRL of the whole pathway is severely impacted with inclusion of low TRL of CC technologies [141, 155]. However, pursuant to the source of CO_2, some CC technologies exhibit extremely high TRLs due to highly matured industrialization. For this study, carbon capture using mono ethanolamine (MEA) amine washing is selected, due to its high maturity, commercial readiness, and deployment at scale [150]. Schmidt et al. also assumes a similar approach due to technological maturity and ranks TRL of amine washing at 9 [141].

It may be noted that, amine washing can only be coupled with high concentration, point CO_2-sources like of which can be found in steel, cement, or petrochemical industry. This is due to the fact that, cost of CC is directly corelated with the CO_2 concentration, and less concentrated source require more energy and consumables which negatively affects their economic performance [147]. Due to which, point sources are in high demand and there is a serious concern regarding their future availability. But given the urgency of decarbonization of the aviation sector and limited options towards decarbonization, a case regarding the priority of the aviation sector for point carbon sources can be made. In Christensen (2017) estimates regarding the future availability of point sources are presented. It is estimated that, in Germany, there will be approx. 295 Mt of CO_2 released from point sources in 2030, reducing to 225 Mt of CO_2 by 2040 [143]. In cases where the fuel production through concentrated sources for the ‘hard-to-abate’ sector is prioritized, the availability of CO_2 should not be a concerning factor.

It is probable that, direct air capture (DAC) may have matured by that time and perhaps be commercially and economically usable at-scale. However, given the current TRL of 6 for DAC [141], this study ignores all the pathways involving DAC and only CC with amine washing of concentrated sources are taken into consideration. The CC plant is integrated and coupled with the fuel production facility as illustrated in Figure 34 and Figure 35.

6.3. Alternate Aviation

In line with the technology distribution of the forecasted aviation demand, it is clear that energy production for hydrogen and electric aviation must be taken into consideration. For this reason, in the modelling period from 2035 onwards, standalone capacity for electrolysers for hydrogen production and airplane charging infrastructure is modelled. For the hydrogen-based aviation, similar aspects regarding the technology selection are taken into consideration, as described in section 6.2.3 and a similar electrolysis technology split of 50-50 between AEL and PEM electrolysers is assumed. The process flows are established using stoichiometric calculations and estimates from Christensen (2017) [143] and Zhou et al. [132] are represented in Figure 36. For electric aviation, direct coupling between electric planes and the RE supply network is envisaged. A charging efficiency of 95% is assumed with electric supply from renewable energy installations.

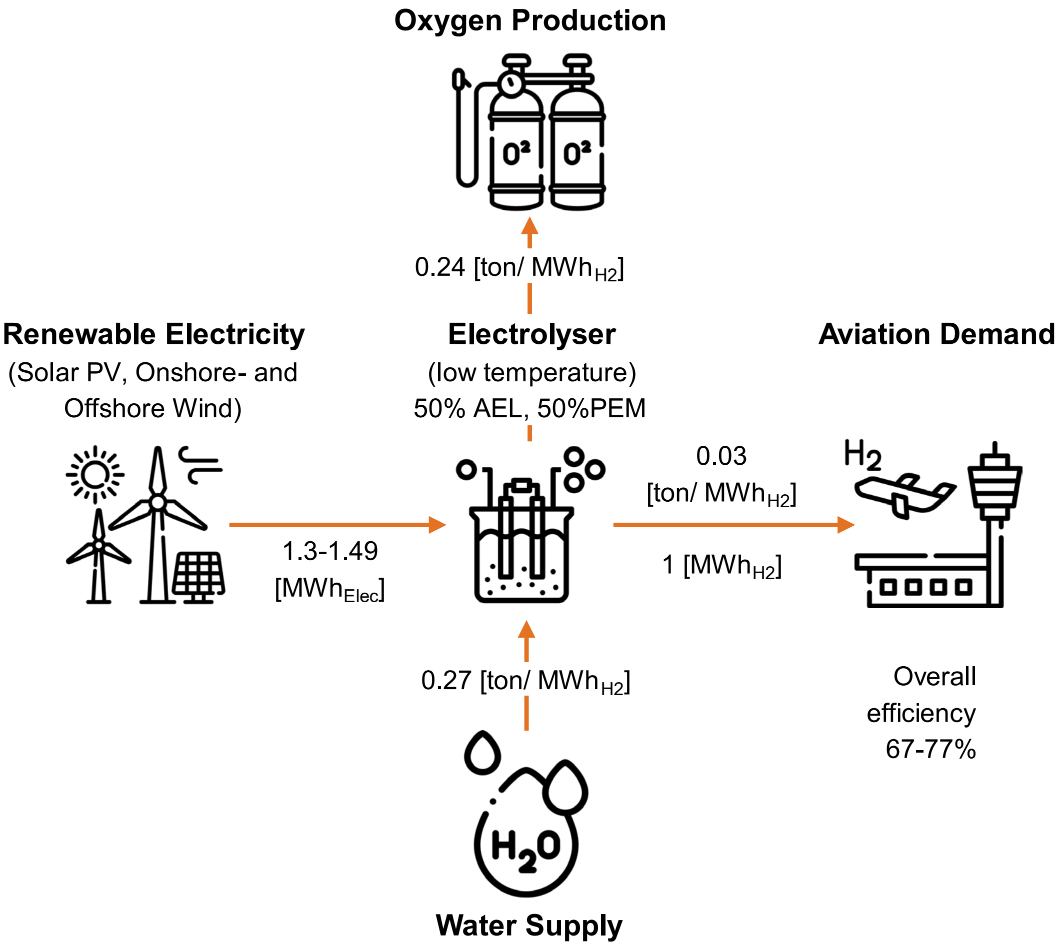

Figure 36: The process flow of hydrogen production along with key parameters

Source: Based on estimates from Christensen [143] and Zhou et al. [132] and stoichiometric calculations

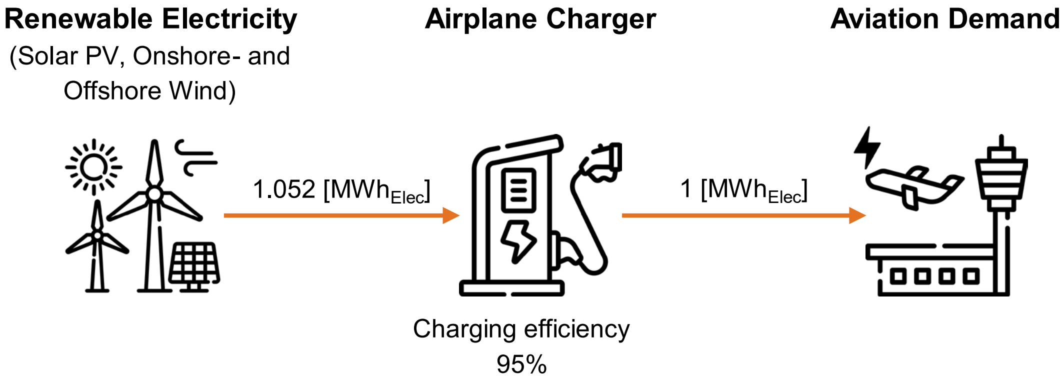

Figure 37: The process flow of electric aviation charging along with key parameters

Source: Assumed values

6.4. Energy Modelling Framework

In contrast to the biogenic approach, a direct approach to calculate the system requirements for e-SAF and alternate aviation is not possible. This is due to the fact that, there exists an interconnection between fuel production and electricity production from RE sources. Due to the inherent intermittencies and complexities associated with the RE supply, an energy model-based approach needs to be followed to optimize the system installations. Moreover, effects from the nature of demand and SAF technologies also play a vital role in the selection of technology for electricity production and are directly affected by the availability of the solar and wind resources in the region. In case these intermittencies are ignored, a suboptimal process design may be put forward – leading to unnecessary costs in the future.

For this analysis, a linear optimization energy model based on the urbs framework is used [18]. In the model, various processes including biogenic, non-biogenic and alternate aviation pathways are modelled and considerations are made regarding cost, technology, economics, resource constraints, time-dependent demand profile, and the interplay between the available feedstocks and energy supply. This integrated approach helps in scheduling the installations and operations of these processes in an optimized manner over the entire modelling period between 2025 and 2050.

In order to develop this model, apart from the already established values additional techno-economic parameters are required and are presented in the next section. Certain key parameters are used as probable ranges to understand the sensitivity of the model to these parameters and provide a clearer understanding of the underlying dynamics of the energy model.

6.5. Major Techno-Economic Modelling Parameters

6.5.1. Conversion Technology Capital and Operation Costs

Capital costs of the technology are a function of the production volumes, and “economy of scale” effects can be observed with increased production volumes. According to Malina et al. [156] for every order of magnitude increase in the production capacity, the cost of production for fuel is reduced by 50%. This is extremely important as large facilities would help relieve the economic pressure for the selected technologies. Hence, wherever possible, cost estimate for a large-scale production facility is assumed. In addition to this, as the costs are provided from various reference time and sources, in order to have a consistent cost estimate, the reference values are adjusted for annual inflation of 1.5% p.a. from their respective years to 2025 (start of modelling period). A 1.5% per year inflation is calculated to be the indicative average inflation over the last 20 years in Germany.

Apart from highly mature biogenic technologies, for e-SAF technologies, hydrogen production and renewable power plants, an annual system cost reduction of 1% p.a. is assumed. The tables below provide the summary of the CAPEX and OPEX for various technologies used for the energy modelling purposes. For the biogenic pathways, as the yield increase and efficient land usage is not accounted for by the model, it is assumed that the prices for the biogenic feedstocks will remain constant – adjusted for the inflation with the respective discounting factor.

Table 14: Summary of CAPEX and OPEX for HEFA process

Source: References provided in the table

Parameter	Value [Unit]	Sources
HEFA: Feedstock Price		
Rapeseed Oil Price	1,200 [€/ton]	[157]
Rapeseed Oil Price	115 [€/MWh]	Calculated based on calorific value from [125, 158]
HEFA: CAPEX and OPEX		
Total CAPEX	137 [Million €]	[122]
Production Capacity	230 [Million Liters per annum]	[122]
Production Capacity	184,000 [ton per annum]	Based on gravimetric calculations
Production Capacity	2,187,556 [MWh per annum]	Based on LHV
Production Capacity	250 [MW]	Calculated
CAPEX	548,612 [€/MW]	[122]
Fixed OPEX	13.69 [Million €/annum]	[159]
Fixed OPEX	54,801 [€/MW/a]	[159]
Variable OPEX	10.72 [€/MWh]	[159]

Table 15: Summary of CAPEX and OPEX for ATJ process

Source: References provided in the tables

Parameter	Value [Unit]	Sources
ATJ: Feedstock Price		
Bioethanol Price	1,327 [€/ton]	[160, 161]
Bioethanol Price	178.87 [€/MWh]	Calculated based on calorific value from [125, 126, 158]
ATJ: CAPEX and OPEX		
Total CAPEX	355 [Million €]	[122]
Production Capacity	230 [Million Liters per annum]	[122]
Production Capacity	184,000 [ton per annum]	Based on gravimetric calculations
Production Capacity	2,187,555 [MWh per annum]	Based on LHV
Production Capacity	249.72 [MW]	Calculated
CAPEX	1,421,586 [€/MW]	[122]
Fixed OPEX	23.46 [Million €/annum]	[159]
Fixed OPEX	93,945 [€/MW/a]	[159]
Variable OPEX	12.51 [€/MWh]	[159]

Table 16: Summary of CAPEX and OPEX for GFT process

Source: References provided in the tables

Parameter	Value [Unit]	Sources
GFT: Feedstock Price		
Biomass Price	40.00 [€/MWh]	[162]
GFT: CAPEX and OPEX		
Total CAPEX	585 [Million €]	[122]
Production Capacity	230 [Million Liters per annum]	[122]
Production Capacity	184,000 [ton per annum]	Based on gravimetric calculations
Production Capacity	2,187,555 [MWh per annum]	Based on LHV
Production Capacity	249.72 [MW]	Calculated
CAPEX	2,342,614 [€/MW]	[122]
Fixed OPEX	50.83 [Million €/annum]	[159]

Parameter	Value [Unit]	Sources
Fixed OPEX	203,547 [€/MW/a]	[159]
Variable OPEX	7.15 [€/MWh]	[159]

Table 16 provides the CAPEX and OPEX for biogenic technologies. As these technologies are already mature, the system cost improvement for these technologies is not considered. Therefore, the costs listed above remain consistent for the entire modelling period and are only adjusted by the discounting factor for later installations. For non-biogenic pathways, due to an integrated plant approach, the CAPEX includes the cost of the SAF production plant as well electrolyser and carbon capture plant. The carbon capture technology is selected to be amine washing due to a concentrated CO_2 source. In addition to this, a small hydrogen storage is also included for operational purposes.

The tables below provide a detailed list of cost assumptions for non-biogenic pathways for the year 2025 and 2050. For the modelling purposes, cost estimations are taken at 5-yr intervals to correspond with the intertemporal range in the energy model. A system cost improvement of 1% per annum is considered as these technologies are still in development and potential for cost reduction still exists, especially for electrolysers. Due to the 50-50 split between AEL and PEM electrolyser, average values of costs and other techno-economic parameters such as efficiency and lifetime are considered. Moreover, a SAF plant output of 200MW of jet fuel is taken as the reference point for the calculation of unitary values; this is equivalent to approx. 132,000 ton of jet fuel per annum [141].

Table 17: Summary of CAPEX of non-biogenic technologies for 2025-2050

Source: Author estimates based on [36, 132, 141, 143, 147]

Parameter	[Unit]	Methanol Pathway	FT Pathway
Technical key data			
Electricity input	[MWh_e/MWh_{Fuel}]	1.94 (2025) 1.69 (2050)	2.04 (2025) 1.78 (2050)
Overall efficiency (Elec→Fuel)	[%]	52% (2025) 59% (2050)	49% (2025) 56% (2050)
CAPEX			
Electrolysis (50% AEL, 50% PEM)	[Million €/MW_{Fuel}]	0.90 (2025) 0.54 (2050)	0.90 (2025) 0.54 (2050)
H2 storage (Process)	[Million €/MW_{Fuel}]	0.09 (2025) 0.01 (2050)	0.94 (2025) 0.11 (2050)

Parameter	[Unit]	Methanol Pathway	FT Pathway
CO_2 supply	[Million €/MW_{Fuel}]	0.27 (2025) 0.16 (2050)	0.28 (2025) 0.16 (2050)
Synthesis & conditioning	[Million €/MW_{Fuel}]	0.64 (2025) 0.35 (2050)	0.63 (2025) 0.34 (2050)
Total	[Million €/MW_{Fuel}]	1.91 (2025) 1.06 (2050)	2.75 (2025) 1.16 (2050)

On the similar lines, the costs for hydrogen production for the year 2025 till 2050 in 5-yr increments are established and are tabulated in Table 18.

Table 18: Summary of CAPEX for electrolyser in 2025-2050

Source: Author estimates based on [36, 132, 141, 143, 147]

Parameter	Value [Unit]
Technical key data	
Electricity input	1.49 (2025) 1.30 (2050) [MWh_e/$MWh_{Hydrogen}$]
Overall efficiency (Elec→H_2)	67% (2025) 77% (2050) [%]
Life	9.78 (2025) 15.85 (2050) [Years]
CAPEX	
Electrolysis (50% AEL, 50% PEM)	0.90 (2025) 0.54 (2050) [Million €/$MW_{Hydrogen}$]
H_2 storage (process, short-term)	0.94 (2025) 0.11 (2050) [Million €/$MW_{Hydrogen}$]
Total	1.84 (2025) 0.65 (2050) [Million €/$MW_{Hydrogen}$]

The variable costs for e-SAF and hydrogen production are calculated based on a 90% capacity factor of the electrolyser which is equivalent to approx. 8000 full-load hours [36, 147]; this is highly infeasible with direct coupling of intermittent RE supply with the plant. Though, with a diverse and robust grid supplied by RE, a grid-connected plant will be able to achieve this capacity factor. That being said, this is a question of operational behavior of the plant, and is dependent on a plethora of factors which cannot be fully included in this analysis due to its limited scope.

Table 19: Key parameters for OPEX calculation for e-SAF pathways and hydrogen electrolysers

Source: Author-calculated values based on the listed references

Parameter	Value [Unit]	Sources
Annual Fixed OPEX	3% [% of CAPEX]	[155]
Electrolyser Replacement	9.78 (2025) 15.85 (2050) [Year]	[132]
Electrolyser Replacement	26.60% [% of Electrolyser CAPEX]	[155]
Catalyst Replacement (MeOH and FT plants)	3 [Year]	[155]
Catalyst Replacement (MeOH and FT plants)	1% [% of CCU CAPEX]	[155]

Based on the values listed in Table 19, the operational costs for MeOH synthesis, FT synthesis and hydrogen production are calculated and tabulated in the following table.

Table 20: Summary of OPEX of non-biogenic technologies for 2025-2050

Source: Author estimates based on [36, 132, 141, 143, 147, 155]

Parameter	[Unit]	Methanol Pathway	FT Pathway
Fixed OPEX	[Million €/MW_{Fuel}/a]	0.06 (2025) 0.03 (2050)	0.08 (2025) 0.03 (2050)
Variable OPEX Components			
Electrolyser Replacement (life dependent)	[Million €/MW_{Fuel}]	0.24 (2025) 0.14 (2050)	0.24 (2025) 0.14 (2050)
Electrolyser Replacement (Amortized)	[Million €/MW_{Fuel}/a]	0.03 (2025) 0.01 (2050)	0.03 (2025) 0.01 (2050)
Electrolyser Replacement (Amortized)	[€/MWh_{Fuel}]	3.99 (2025) 1.70 (2050)	3.99 (2025) 1.70 (2050)
Catalyst Replacement (life dependent)	[Million €/MW_{Fuel}]	0.003 (2025) 0.002 (2050)	0.003 (2025) 0.002 (2050)
Catalyst Replacement (Amortized)	[Million €/MW_{Fuel}/a]	0.001 (2025) 0.001 (2050)	0.001 (2025) 0.001 (2050)
Catalyst Replacement (Amortized)	[€/MWh_{Fuel}]	0.13 (2025) 0.07 (2050)	0.13 (2025) 0.08 (2050)
Water Cost	[€/MWh_{Fuel}]	0.25 (2025) 0.25 (2050)	0.25 (2025) 0.25 (2050)
Total Variable OPEX	[€/MWh_{Fuel}]	4.37 (2025) 2.02 (2050)	4.38 (2025) 2.02 (2050)

6.5.2. Renewable Power Plant CAPEX and OPEX

In order to run the aviation energy supply systems in an environmentally-compliant manner, completely decarbonized electricity supply is indispensable. For this reason, only supply from onshore-, offshore wind parks, and solar PV plants is considered. The current estimates for the system costs are referenced from recent reports published by IRENA [163] and EU [164] and adjusted to 2025-values using an annual inflation of 1.5% p.a. and a subsequent system cost reduction factor of 1% p.a. These values are then extrapolated till 2050 to derive the estimates for each 5-yr interval in the modelling period. The table below summarizes the CAPEX and OPEX estimates for RE power plants used to develop the energy model. The renewable energy installations are based on the targets put forward by the German government and are already discussed in-detail in section 2.3.

Table 21: Summary of OPEX of electrolysers for 2025-2050

Source: Author estimates based on [36, 132, 141, 143, 147, 155]

Parameter	Electrolysers (50% AEL, 50% PEM)	[Unit]
Fixed OPEX	0.06 (2025) 0.02 (2050)	[Million €/$MW_{Hydrogen}$/a]
Variable OPEX Components		
Electrolyser Replacement (life dependent)	0.24 (2025) 0.14 (2050)	[Million €/$MW_{Hydrogen}$]
Electrolyser Replacement (Amortized)	0.03 (2025) 0.01 (2050)	[Million €/$MW_{Hydrogen}$/a]
Electrolyser Replacement (Amortized)	3.99 (2025) 1.70 (2050)	[€/$MWh_{Hydrogen}$]
Water Cost	0.56 (2025) 0.56 (2050)	[€/$MWh_{Hydrogen}$]
Total Variable OPEX	4.55 (2025) 2.26 (2050)	[€/$MWh_{Hydrogen}$]

Table 22: CAPEX and OPEX for solar PV, offshore- and onshore wind power plants, 2025-2050, including system cost improvements

Source: Based on reference values from [163, 164]

	CAPEX	Fixed OPEX	Var. OPEX
	[€/MW]	[€/MW/a]	[€/MWh]
Wind Onshore	1,406,509 (2025) 1,094,012 (2050)	43,331 (2025) 33,703 (2050)	0.18 (2025) 0.14 (2050)
Wind Offshore	3,240,256 (2025) 2,520,340 (2050)	77,995 (2025) 60,666 (2050)	0.40 (2025) 0.31 (2050)
Solar PV	601,428 (2025) 467,803 (2050)	7,799 (2025) 6,067 (2050)	- (2025) - (2050)

6.5.3. Plant Life Assumptions

Kozhemyatov et al. [165] presents the findings from an operational refinery. They evaluate that the lifetime of various equipment operating under excessive pressure lie in the range of 25-38 years. Meanwhile, the largest and relatively expensive equipment such as Columns, Pressure Vessels and Heat Exchangers easily reach an average service life of more than 30 years in such conditions. Although, Pavlenko et al. [122] and Bann et al. [159] have assumed a lifetime of various production facilities to be 20 years, it is suspected that the assumption is too conservative, leading to unnecessary CAPEX at later stages in the modelling period. Despite this, their claim is corroborated by the "*Handbook of Petroleum Processing*" as the engineering and design parameters of these facilities are set at 20 years [145], after which they are expected to be dismantled and sold. Even though it is probable that the SAF production plants may work beyond its design life, due to the findings of above-mentioned sources, the plant life is assumed to be 20 years.

For all renewable power plants, industry-accepted lifetime of 25 years are taken as the reference value and are corroborated by the EU commission estimates [164].

6.5.4. Energy Storage

On one side, due to the intermittency introduced by incorporating renewable electricity generation, and on other side, the fixed nature of the aviation demand; there exists a significant integration challenge. It is observed during various simulation runs that the model is extremely sensitive to the power and storage capacity of the storage and care must be taken in order to develop an optimum system.

6.5.4.1. Jet fuel Bunkering

In addition to the integration challenges, there also exist legislative requirements for conventional fuel storages in Germany. The EU Council Directive 2009/119/EC along with the German Petroleum Stockholding Act 2012 (Erdölbevorratungsgesetz – ErdölBevG) sets the minimum requirements for stockholding of conventional fossil fuels including aviation fuels. The laws stipulate a minimum stockpiling of 90 days within a 365 days period [166, 167]. Therefore, this 90-day requirement is also used as a modelling parameter for the maximum allowable limit of liquid fuel storage. Conventional fuel storage techniques are assumed in the modelled as there exists little to no perceivable difference in the properties of SAF produced from biogenic- & non-biogenic pathways and conventional jet fuel. The expected reduction in jet fuel demand will lead to surplus bunkering capacity which can be made available for storage use, hence the cost for deploying new storage for jet fuel is not explicitly modelled.

6.5.4.2. Hydrogen Storage

For hydrogen, currently there exist no clear guidelines or regulatory requirements regarding its storage. Therefore, a proxy with the natural gas storage is developed. For natural gas storages under the EU legislative framework, 30 days of high demand storage is required [168, 169]. In accordance with the legislations and on the similar lines with the fuel bunkering, for the hydrogen storage a 30-day maximum limit is set in the energy model. That aside, the selection of the storage technology for hydrogen is extremely difficult, as there exists no clearly defined industrial guidelines or practices, and due to the nascency of the sector multiple technology options concurrently exist – each offering certain advantages and disadvantages.

After reviewing the published research on hydrogen storage technologies by Reuß et al., Geburtig et al., Andersson et al., Abdin et al., Dickel, Runge et al., and Hurskainen et al. [85, 152, 170–174], it is concluded that due to the requirements of relatively longer time period for storage and the accompanying economic concerns, Liquid Organic Hydrogen Carrier (LOHC) storage provides the best compromise between various options to store hydrogen; the cost of storage, storage efficiency, and lack of high pressure and leakage are the key deciding factors to opt for LOHC storage. It may be noted that the LOHC technology does not offer relatively high energy density in comparison with other option [174], but due to stationary applications, the size of the storage is not a concerning factor.

With the innate concerns regarding the availability of critical raw materials for LOHC technology [175], traditional options like hydrogen liquification (LH_2) and compressed hydrogen storage (CGH_2) are also analyzed. Conversely, due to the extreme costs for infrastructure for liquification and compression [172], energy requirements [85], and high pressure raising safety concerns [171], LH_2 and CGH_2 storage are not considered in this analysis. It is worth mentioning that the LOHC technology is still under-development with no current large-scale storage installations [174], however the emergent hydrogen demand and accompanying storage demand for this model is expected to play a significant role after 2035, with larger demand forecasted between 2045 and 2050. Therefore, it is assumed that the technology would be sufficiently developed to be used in this application.

As the status regarding long-term seasonal storage for hydrogen and pipeline infrastructure is still unclear, the inclusion of the storage in the energy model is necessary for decoupling supply and demand. With emergence of dedicated infrastructure of hydrogen storage, similar to natural gas, such as caverns and under-ground pipeline storage [176], the demand for standalone units may reduce. However, this is not considered for this model and only LOHC is assumed as a dedicated hydrogen storage technology. A 500 tons of hydrogen capacity per day and a plant life of 20 years are used a reference system values [172], along with that a 1% annual system cost improvement is assumed. The table below summarizes the techno-economic estimates for 2025-2050 used to develop the energy model.

Table 23: LOHC hydrogen storage techno-economic parameters, 2025-2050

Source: Author-calculated based on reference values from [152, 172, 174, 177] and assumptions

Parameter	Value [Unit]
CAPEX	
Materials	130.75 (2025) 101.70 (2050) [€/MWh$_{H2}$]
Reactor	3,504.17 (2025) 2,725.62 (2050) [€/MWh$_{H2}$]
Storage	78.45 (2025) 61.03 (2050) [€/MWh$_{H2}$]
Total CAPEX	3,713.38 (2025) 2,888.35 (2050) [€/MWh$_{H2}$]
OPEX	
OPEX	4% [% CAPEX /a]
OPEX	148.54 (2025) 115.53 (2050) [€/MWh$_{H2}$/a]
Losses	
Losses	4% [% of round-trip efficiency]

Parameter	**Value [Unit]**
Electricity requirement as additional loss	3% [% of round-trip efficiency]
Overall loss	7% [% of round-trip efficiency]
Energy Consumption	
Electrical	0.02 [MWh_e/MWh_{H2}]
Heat	0.27 [MWh_{th}/MWh_{H2}]
Energy Production	
Electrical	0 [MWh_e/MWh_{H2}]
Heat	0.27 [MWh_{th}/MWh_{H2}]

The hydrogenation and dehydrogenation process requires electrical input for pumps and auxiliaries and is modelled as an energy loss for the round-trip efficiency of the process. The energy consumption of 65 KJ/mol during the hydrogenation of the LOHC material is assumed to fully recuperated during the dehydrogenation process and no additional heat energy is supplied to the system. This is, however, a gross estimation of the energetic process as the heat input and output occur at different temperatures, but incorporating the heat released with the district heating system can reduce the energy penalty of this process [152].

6.5.4.3. Electricity Storage

The model is observed to be extremely sensitive to the electrical energy storage parameters, especially during periods of high sustained demand and lack of RE supply. For this reason, allowance for up to 12 hours of battery storage is allowed in the model to counter the periods with lack of renewable generation. This is exacerbated by the fact that the energy model lacks any dispatchable electricity supply and only solar PV, offshore and onshore wind are used as the primary sources – the production of which does not necessarily align with the modelled demand. However, most modelled scenarios do not use the allowed quota and only deploy a few hours of battery storage under the cost optimization criteria.

The lithium-ion batteries are used as the reference electrical storage technology in this model due to their flexibility and ability to be deployed with decentralized power generation [178, 179]. Moreover, large scale pumped hydro-storage is practically infeasible in Germany due to lack of new sites, environmental concerns and existing potential being fully exhausted [180]. Similar to LOHC, the concerns regarding critical raw materials exists [175] and high investment costs are a persistent problem. However, with technological improvements, development of newer chemistries and second-life batteries [181], these concerns can be ameliorated to an acceptable level. Based on these reasons, battery-based storage is considered as a more pragmatic option for electrical energy storage in Germany.

For energy modelling purposes, latest estimates by NREL [182] for 2025 till 2050 are used as benchmark values and are presented in Table 24 for reference. Furthermore, based on the assumptions by NREL, a fixed OPEX of 2.5% of CAPEX per annum, a system life of 15 years, and a round-trip efficiency of 85% are assumed for the battery techno-economic parameters. The values are adjusted for inflation from the reference data and are presented in terms of 2025 values.

Table 24: Battery CAPEX and OPEX assumptions, 2025-2050

Source: Referenced from NREL publication [182] and extrapolated to 2025 values

	Energy Components Cost	Power Components Cost	Fixed O&M
Year	[€/MWh]	[€/MW]	[€/MW/a]
2025	275,536	275,536	6,888
2050	142,212	248,871	6,222

As the penetration of electric planes increases into the aviation market, a more innovative approach to energy storage can be deployed. For example, aviation-to-grid technology offers the ability to use parked planes as stationary batteries [183]. This can in turn substantially reduce the material limitations as multi-purpose use of existing batteries will be utilized. That being said, these technologies are still under development and no infrastructure for electric aviation exists at the time of writing this thesis. For this reason, such technologies are not considered in this model.

6.5.5. Carbon Pricing

Carbon pricing plays a crucial role in internalizing the cost of the emissions and provides a market-based measure (MBM) to reduce GHG emissions. The carbon price is multiplied by the carbon intensity of each pathway and included as an environmental cost in the energy model. For the reference value, the current CO_2 price of 80 € per ton in the EU ETS market is adopted. However, based on the forecast published by the German government under the Kopernikus Projekte [184], it is forecasted that the carbon price would rise to 160+ € per ton by 2030. Moreover, according to the German Environment Agency (Umweltbundesamt) the true societal cost of climate change lies in the range of 180-730 € per ton_{CO2eq} and recommends it as the carbon price [185]. In addition to that, non-compliance of GHG emissions under the German Emissions Protection Law (BImSchG) Section 37c carries a penalty of 0.60 € per kg_{CO2eq} or 600 € per ton_{CO2eq} [186]. For these reasons, a common CO_2 price of 600 € per ton_{CO2eq} is considered as the theoretical maximum carbon price in the model and various price points between 80-600 € per ton_{CO2eq} are modelled as various scenarios to observe the development of various technologies. More details regarding scenarios are provided in 6.7.

6.5.6. Hydrocarbons and Co-Products Price Estimates

Due to technological and economic reasons such as resources availability, depletion of easily accessible sites, and further reduction in permitting and drilling licenses, it is assumed that the fossil fuel and its related products will increase in price. In line with the assumptions made by Zhou et al. [132], an assumption of 1.5 times (linear) increase in fossil products' prices till 2050 is made. It is important to elaborate that this is not an unreasonable assumption for the model. Based on historical values, the crude oil in June 2008 has already traded at a value of $140 per barrel, juxtaposed with the current crude oil price of $80 per barrel (July 2023) [187], this equates to a price factor of 1.75 times; which is greater than the current assumption of 1.5 times in the model. Nevertheless, it is merely meant to be an assumption, as the long-term price forecasts for commodities are merely a speculation and can be significantly divergent from the market movements especially for longer time-frames such as 25-30 years, i.e., the modelling period.

Apart from unrefined crude oil, various refined products have different market prices due to their commercial application, however, these prices are indexed on the crude oil prices and largely represent similar price fluctuations. Therefore, price multipliers are also applicable to refined products such as jet fuel, diesel, and light ends. Various multipliers are used to assess the sensitivity of the model to the fossil prices and its impact on the technology selection. This is elaborated further in section 6.7.

Lights ends consist of gaseous and liquid fractions which condense at the top of the distillation column at a lower temperature; these include Propane, Butane, Gasoline, and Naphtha. However, for the sake of simplification and lack of concrete proportions of these light ends for each of the considered pathway, an assumption is made that the light ends are combined to form Naphtha which then can be sold to the market.

The prices and reference dates for jet fuel/kerosene, diesel and naphtha are tabulated below.

Table 25: Reference prices for jet fuel, diesel and naphtha, July 2023

Source: References listed in the table

Fuel	Price [Unit]	Source (Reference date)
Jet fuel/Kerosene	68.00 [€/MWh]	[188, 189] (20/07/2023)
Diesel	91.41 [€/MWh]	[190] (24/07/2023)
Naphtha	42.14 [€/MWh]	[191] (24/07/2023)

Apart from hydrocarbons, oxygen gas is also produced in various pathways as a co-product during electrolysis of water. In order to improve the economics of the electrolysis process, it is assumed that the oxygen gas is sold on the market at a price of 0.15 €/kg for the entire modelling period [132, 155].

6.5.7. Economic Parameters

The cost of capital varies significantly based on the country, novelty of the project, and prevalent interest rates, and reflects the perceived risks by the investors [192]. The weighted average cost of capital or WACC takes into account the cost of debt and equity, along with the Debt-Equity structure of the project given by the D/E ratio, and the tax rate in the project country [193, 194]. For the development of the energy model, a reference value of 7% WACC is assumed on the basis of the reference values by IEA for market-based revenues in Europe [194].

The discount factor is used to discount the future cash flows to account for the investments and operation costs occurring at a later stage in the modelling timeline and represents them as present values to develop a consistent comparison between various scenarios. The selection of an appropriate discount rate is crucial, as too high discount rates can negatively gauge the future benefits of the project [195], and too low estimates may not fully capture the general inflationary behavior in the economy. The report published by The European Council for an Energy Efficient Economy (eceee) & Ecofys in 2015 recommends a discount factor of 4% per annum for Europe [195]. However, due to the recent spikes in inflation a slightly higher discount factor of 5% is selected for this energy model. Same discount factor is selected by Peters et al. [147] for the development of their modelling estimates.

In order to convert the costs provided in terms of US Dollar (USD/$), a conversion factor 0.85 €/$ is assumed.

6.6. Water Consumption

Water serves as the primary feedstock for e-SAF pathways, therefore there is a general apprehension in public regarding the water consumption by e-fuel production. Although, a detailed assessment of water consumption for various pathways is not carried out in this analysis, nevertheless, the reports published by German Environment Agency [81, 82] provide estimates for the water intensity of various pathways considered in this analysis. According to the report, the water consumption of MeOH and FT synthesis pathway is 1-3 orders of magnitude (10^x) less than the water consumed in the biogenic pathways. Furthermore, the report calculates the water intensity of MeOH and FT synthesis as 4.1 $L_{H20}/L_{Jet\ fuel}$ and 3.7 $L_{H20}/L_{Jet\ fuel}$ respectively. For context, the water consumption of HEFA pathway with rapeseed oil is estimated 7680 $L_{H20}/L_{Jet\ fuel}$, and for the ATJ with sugar beet the water intensity exceeds 2200 $L_{H20}/L_{Jet\ fuel}$ [81, 82].

Due to the simplistic nature of the analysis, the water consumption during the cultivation process is not considered, and the cost impact of this is assumed to be included in the market price of the biogenic feedstocks. However, the water consumption as a feedstock for non-biogenic pathways and hydrogen production is considered. The consumed amount is based on stoichiometric calculations and is provided in the process flow of the respective pathways, these are already presented in the previous sections. For water cost, 2 €/m^3 is considered based on the estimates by Marchese et al. [155].

6.7. Definition of Scenarios

In order to assess the sensitivity of the model to various techno-economic parameters and develop an understanding of the underlying dynamics of the key variables, various scenarios for the energy model are developed. These scenarios are based on key variables including fuel technology type, optimization value for the energy model, CO_2 budget, carbon price, aviation demand forecast, and fossil fuel prices for jet fuel and co-products. For each demand forecast, 23 + 1 scenarios are modelled. The reference scenario (Ref) for each demand forecast assumes continuation of status quo with only fossil fuel-based aviation. A detailed table of the modelling constraints is provided in Table 26. The “x” in the scenario name is used as a general placeholder for demand cases i.e., base, low, and high demand forecast, representing different values for each demand case respectively.

In total 72 scenarios are modelled, accounting for all demand cases, key variables, and reference scenarios. It is evaluated that the scenario “x_23” is the most probable scenario, as it encapsulates the general trends in the market, based on the regional policies, costs of fuel and emissions, and studied constraints for Germany.

Table 26: Detailed description of energy modelling scenarios

Variables↓	Scenario→	Ref	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_10	x_11
Technology type	All Technologies (Fossil, Biofuels, Efuels)		X	X	X	X	X	X	X	X	X	X	X
	Fossil only	X											
	E-Fuels only												
Optimization value	Cost minimization	X	X		X	X	X	X	X	X	X	X	X
	Cost minimization with CO2 budget												
	CO2 minimization			X									
CO2 budget	No Targets	X	X	X	X	X	X	X	X	X	X	X	X
	2020 Cap												
Aviation Demand	Base	Used as prefix for the scenario names for "base", "low" and "high" demand scenarios, replaces "x" in the header for the corresponding demand case											
	Low												
	High												
CO2 Price [€/ton]	80	X	X	X					X	X	X	X	X
	160				X								
	200					X							
	600						X						
	100 (2025)→600 (2050)							X					
Fossil-based products' price [multiple of 2023 values]	0.5								X				
	1	X	X	X	X	X	X	X					
	1.5									X			
	1.75										X		
	2											X	
	1 (2025)→ 1.5 (2050)												X

Variables↓	Scenario→	x_12	x_13	x_14	x_15	x_16	x_17	x_18	x_19	x_20	x_21	x_22	x_23
Technology type	All Technologies (Fossil, Biofuels, Efuels)											X	
	Fossil only												
	E-Fuels only	X	X	X	X	X	X	X	X	X	X		X
Optimization value	Cost minimization	X	X	X	X	X	X	X	X	X	X		
	Cost minimization with CO2 budget											X	X
	CO2 minimization												
CO2 budget	No Targets	X	X	X	X	X	X	X	X	X	X		
	2020 Cap											X	X
Aviation Demand	Base	Used as prefix for the scenario names for "base", "low" and "high" demand scenarios, replaces "x" in the header for the corresponding demand case											
	Low												
	High												
CO2 Price [€/ton]	80	X					X	X	X	X	X	X	
	160		X										
	200			X									
	600				X								
	100 (2025)→600 (2050)					X							X
Fossil-based products' price [multiple of 2023 values]	0.5						X						
	1	X	X	X	X	X						X	
	1.5							X					
	1.75								X				
	2									X			
	1 (2025)→ 1.5 (2050)										X		X

7. Energy Model Results

"There is too much bad news to justify complacency. There is too much good news to justify despair"

\- *Donella Meadows (Co-author: The Limits to Growth, 1972)*

7.1. Total Costs

For all demand forecasts, in general, the total costs are observed to increase for all scenarios, however pertinent to various different factors. In the cases where the fossil prices and CO_2 prices are modelled to increase, the costs scale upwards and downwards due to the costs of fuel supply and the associated environmental costs. New investments in SAF production technologies are observed only in scenarios with high fuel costs, with high environmental costs and/or with a limit on emissions – in such cases new technologies are deployed to produce SAF from less carbon intensive sources which are observed to be costlier than conventional jet fuel. Alternatively, in cases where carbon pricing and fuel prices are modelled to be lower than the status quo, pre-disposed reliance on fossil fuel is witnessed. Extreme costs are observed for emission restrained scenarios (x_2) due to overnight costs of upfront investments and over deployment of SAF production and renewable energy capacity.

For base_1 scenario, the cost reduces due to the introduction of alternate technologies which are more energy efficient than kerosene combustion – as the energy demand reduces, the CAPEX and OPEX to meet this reduced demand is also minimized. However, as already established, SAF production technologies are more expensive, thereby the energy savings do not directly translate into cost savings and is clearly observable in the unitary analysis. This cost reduction is also observed for low and high demand scenarios.

It is observable in Figure 38, that the price variations with and without biofuels have little to no impact on the costs. In fact, various price points between "e-fuels only" and "all technologies" scenarios have identical total costs. This is due to the fact that even with availability of biofuels, the model under cost optimization predominantly opts for e-SAF production. This is attributed to the limited potential of the biofuel technologies and relatively higher emissions in comparison to e-fuels.

In all cases, investments and revenues are observable, especially at later stages of the modelling period, due to the penetration of hydrogen and electric aviation technologies from 2035 onwards, and the revenues generated from the sale of their associated co-products.

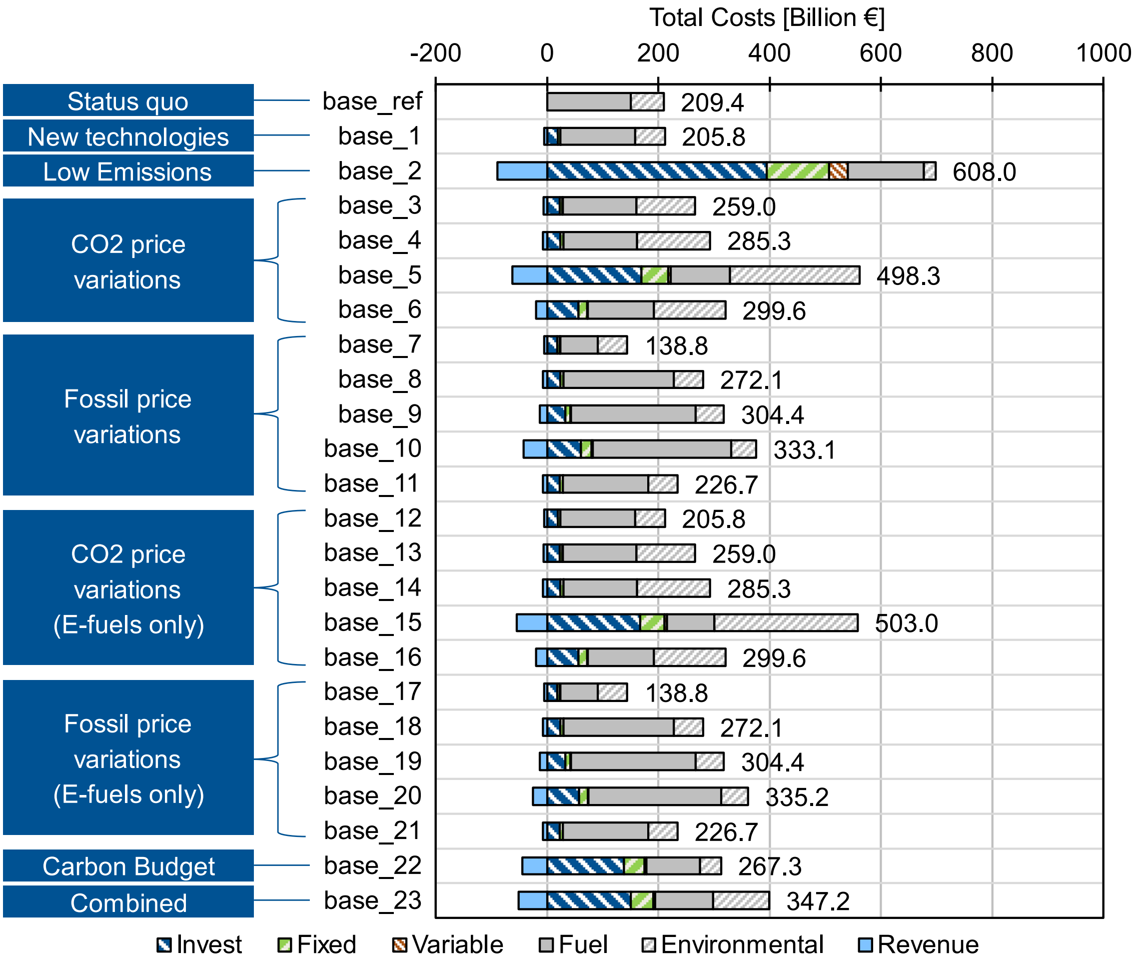

Figure 38: Base demand - Total costs for modelled scenarios (2025-2050)

Fossil fuel costs are observable in all cases, this is attributed to the low availability of cost-effective SAF production options between 2025 and 2040, afterwards abundance of RE capacity makes it economically viable to install dedicated or supplemental SAF production capacity, especially in cases where RE supply can be spilled over from hydrogen production and direct electrification.

Under low and high demand scenarios, the demand scales down and up respectively, thereby the total costs are also observed to scale in proportion to the demand – detailed cost structure for low and high demand scenarios are appended in Appendix E-1 and Appendix F-1.

7.2. Cost and Carbon Intensity

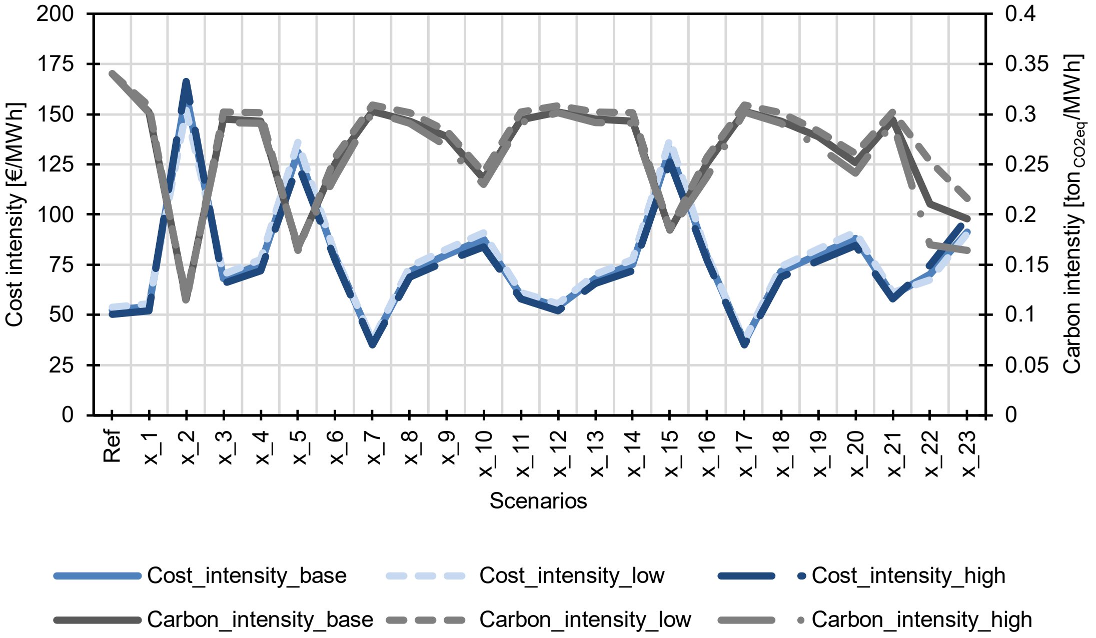

Figure 39: Cost- and carbon intensities of base, low, and high demand scenarios

The cost and carbon intensities are calculated by the ratio of total- costs and emissions with the total energy demand of the respective scenario for the entire modelling horizon (2025-2050). This unitary analysis reveals that the costs and emissions scale proportionally to the aviation demand, and corroborates that the model is unbiased towards technology selection. From Figure 39 it can also be deduced that the cost intensity and carbon intensity are inversely correlated, in other words, the decarbonization of the aviation sector requires CAPEX and OPEX for the underlying infrastructure including fuel conversion plants, RE generation and energy storage – reflected by the increase in the cost intensity. All of the modelled scenarios highlight an increase in the cost per unit of aviation fuel with respect to the reference case, apart from x_7 and x_17 scenarios where the fossil prices are modelled to be below the current levels.

In addition to this, it can be observed that, even under CO_2 minimized cases (x_2), the aviation sector does not fully decarbonize. This is attributed to the limited biogenic and non-biogenic SAF production capacity, especially between 2025-2035, and the need for blending of fossil jet fuel with some of the biogenic pathways. The x_23 scenarios illustrate different carbon intensities for the same cost point; this is identified as a function of proportions of carbon-neutral e-fuels and carbon-emitting fossil fuels in the overall energy mix of the respective scenario. Moreover, CO_2 budget with cost optimization scenarios (x_22 and x_23) provide an interesting insight into the effects of carbon neutral technologies. From Figure 39 it is evident that even at comparable cost intensities, the varied demand scenarios approach the SAF production in different manners, reflected by their carbon intensities. In low demand cases, where the CO_2 cap allows for a higher fraction of fossil fuel in the end-energy supply, the model under cost-optimization criteria limits the production of SAFs and the fraction of more sustainable technologies is gradually increased only in relation to the demand expansion. This again corroborates the analysis that, the overall cost of SAF production is higher than the conventional aviation fuel and any decarbonization, under the status quo would lead to price hikes.

7.3. Total Energy Mix and Renewable Generation

The Figure 40 corroborates the findings above, by illustrating the fractions of cheaper but carbon-intensive jet fuel and the expensive but less carbon-intense b-SAF and e-SAF in the total energy mix of the scenarios. It is clear that, all scenarios are heavily reliant on fossil energy, and the shift to other technologies only occur with external impetuses – in terms of costs or necessitated demand. Moreover, the figure also reflects a clear preference towards electrification, either for jet fuel production or alternate aviation; the scale of which is highly dependent on the cost impetus i.e., during fossil price and CO_2 price increases. Therefore, in order to have an early decarbonization, a level-playing field must be established between fossil fuels and SAFs.

One approach to achieve this goal is by internalizing the environmental cost into the price of fossil fuels, thereby providing an incentive to decarbonize. However, it is important to note that internalizing environmental costs into the aviation fuel price would lead to increased cost for end-energy users – and would also reflect in the air fare. Another approach would be to accelerate the development of e-fuel technologies and renewable generation, which could result in a price reduction of e-SAFs, making them more competitive with fossil fuels.

The pathways related to biogenic SAF presented limited opportunities for Germany for the modelled scenarios; the deployment of which only occurred in most emission-restrictive scenarios, and are associated with higher cost intensity, thereby making them practically infeasible. Out of which only GFT pathway showed any significant deployment, which is also the pathway that scored the highest in the biogenic pathway assessment, due to its energy substitution potential and lowest carbon emissions. Pathways based on rapeseed oil and sugar beet are largely ignored by the model.

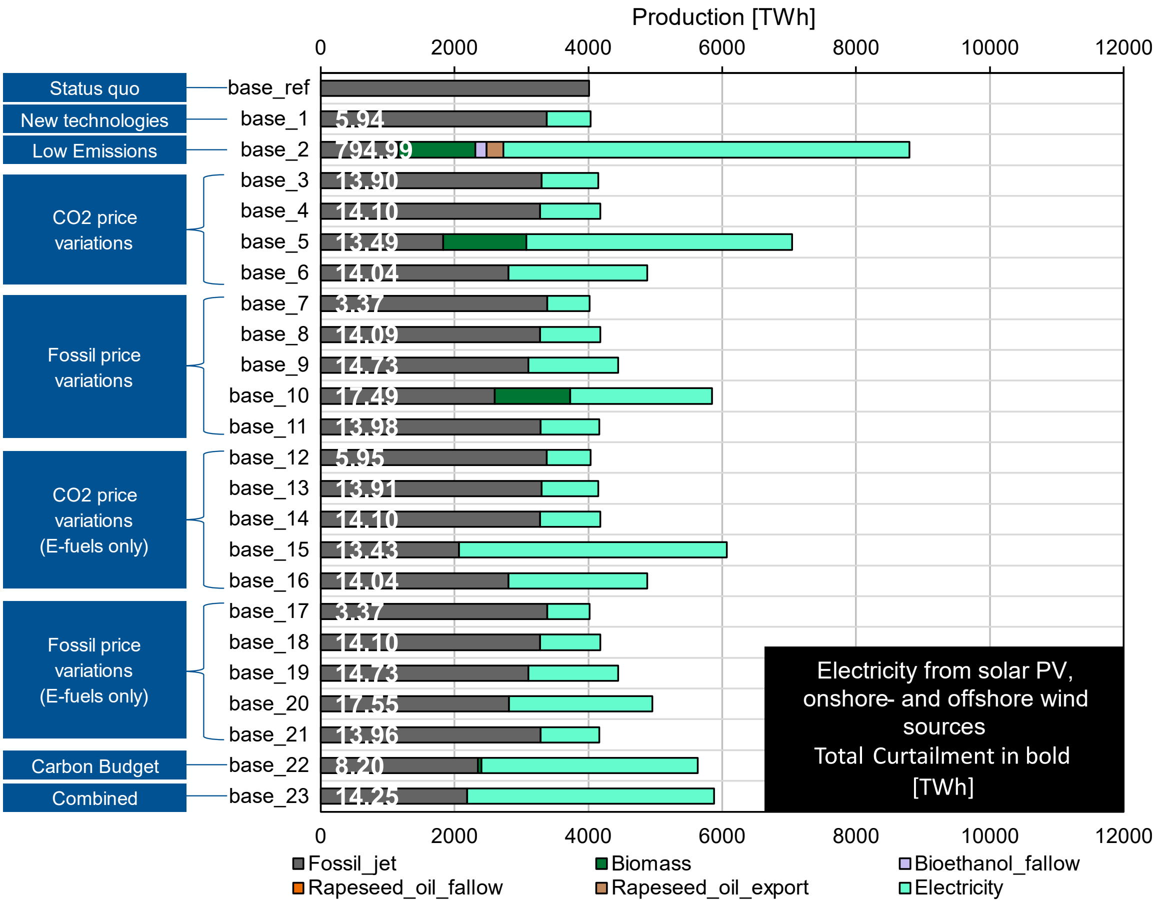

Figure 40: Base demand - Total energy mix of the modelled scenarios, 2025-2050

One more aspect observed with the primary energy distribution is the increase in the overall energy demand compared to the reference case. It may be noted that the aviation demand is identical for all the illustrated scenarios in Figure 40, even with that the overall energy consumption increases; this is due to the lower fuel conversion efficiency of the conversion pathways. Therefore, with the increase of SAFs in the final energy mix, more energy needs to be generated to offset the low conversion efficiency inherent to the pathways. This is also one of the primary factors associated with the higher cost intensity of the modelled scenarios. The behaviors described above are likewise observed in lower and higher demand forecast with proportional changes in the final energy mix. The detailed graphs for these demand cases are provided in Appendix E-2 and Appendix F-2.

The breakdown of electricity generation by source (see Figure 41) indicates a correlation between the economic parameter and generation technology; with higher energy costs preferentially more offshore wind capacity is deployed. It is determined that the correlation exists due to the coupling of intermitted electricity generation with SAF production plants with high availability. Therefore, it makes sense to couple technologies which are comparable or similar in terms of their annual capacity factor (ACF) to minimize costs. At second place, solar PV is deployed; this is associated with the relatively lower levelized cost of electricity (LCOE) of solar PV, however, the comparably lower ACF limits the potential to a certain extent for a cost-optimal operation of the whole system. With the offsetting of electricity from solar PV, the cost of SAF can be optimized, especially during summer months, where there can be an over-production of electricity. Thirdly, onshore wind lies in the middle of these two extremes, i.e., better ACF than solar PV and lower prices than offshore wind. Despite this, the model deploys onshore wind in cases where the capacity of offshore wind is exhausted and/or the fossil and CO_2 price are lower. Similar conclusions are also valid for lower and higher demand scenarios and detailed graphs are appended as Appendix E-3 and Appendix F-3 for reference.

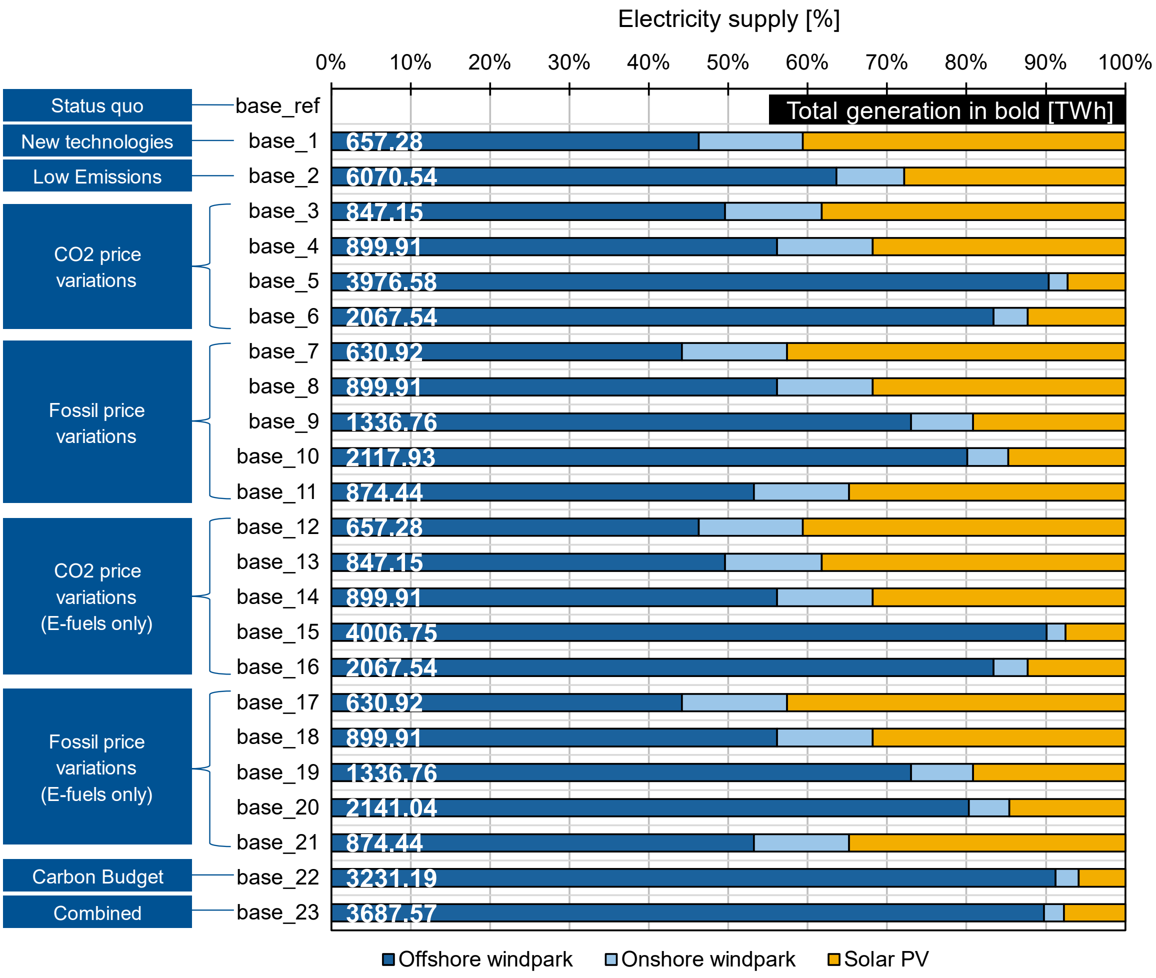

Figure 41: Base demand - Breakdown of renewable electricity supply, 2025-2050

Curtailment is also observed with increased electrification of the aviation sector, however for this model, curtailment of RE is largely associated with solar PV generation and occurs after 2045, hereafter abundant and cheap solar PV capacity is available. Curtailment is deemed to be necessary, otherwise, the storage requirement for this amount of energy exorbitantly increases the LCOE and ultimately the SAF costs. It may be noted that the model functions in a vacuum; with the coupling of the aviation energy demand with other energy sectors, the curtailment can be resolved. For example, the excess energy may be used to produce fuels for marine and road transport, or exported to neighboring countries, or perhaps even be used to produce green hydrogen.

7.4. Dynamics of SAF Production and Renewable Installations

The total energy requirements for the entire period discussed in previous sections generally overlook the dynamics of how the SAF production infrastructure and the associated RE supply develops over the modelling period. As the urbs energy model already provides high-resolution data at a 5-yr interval between 2025 and 2050, it is relatively easily to understand these dynamics. Thus, Figure 42 and Figure 43, along with Appendix E-4, Appendix E-5, Appendix F-4, and Appendix F-5 aim at illustrating the intrinsic subtleties of how the end-energy mix is developed in tandem with aviation energy demand forecasts presented in Figure 25 on pg. 56. The resulting observations bolster the already established analysis and provide some additional insights; these are discussed successively.

From the figures it is self-evident that the scenarios with either high fossil- and CO_2 price or a CO_2-cap incentivize an early adoption of SAFs in the aviation energy mix. Otherwise, most scenarios operate till 2035 with minimal contribution of SAFs due to costs concerns under cost minimization cases. Moreover, the dependency of the conventional jet fuel appears to continue throughout the modelling period; this is an artifact of the modelling parameters as the jet fuel infrastructure is assumed to have a life of 30 years. In fact, 2045 onwards the SAF production capacity is sufficient to meet the forecasted aviation demand.

Between 2035-2040, the demand for the jet fuel peaks during this period and gradually reduces due to the introduction of electric and hydrogen planes. Hence, the rise in SAF production capacity directly offsets the fossil jet fuel. Another factor to observe is the reduction or outright disappearance of the biogenic SAF pathways after 2040 (see Figure 42). As the technology cost improves for conversion plants and the RE generation, coupled with the reduction in fuel demand, the production of SAF from biogenic pathways does not make economic sense and is therefore excluded due to cost minimization by the model. It is worth mentioning that the capacity reduction only occurs after the technical life of the plant and assets already installed are optimized to reduce CAPEX.

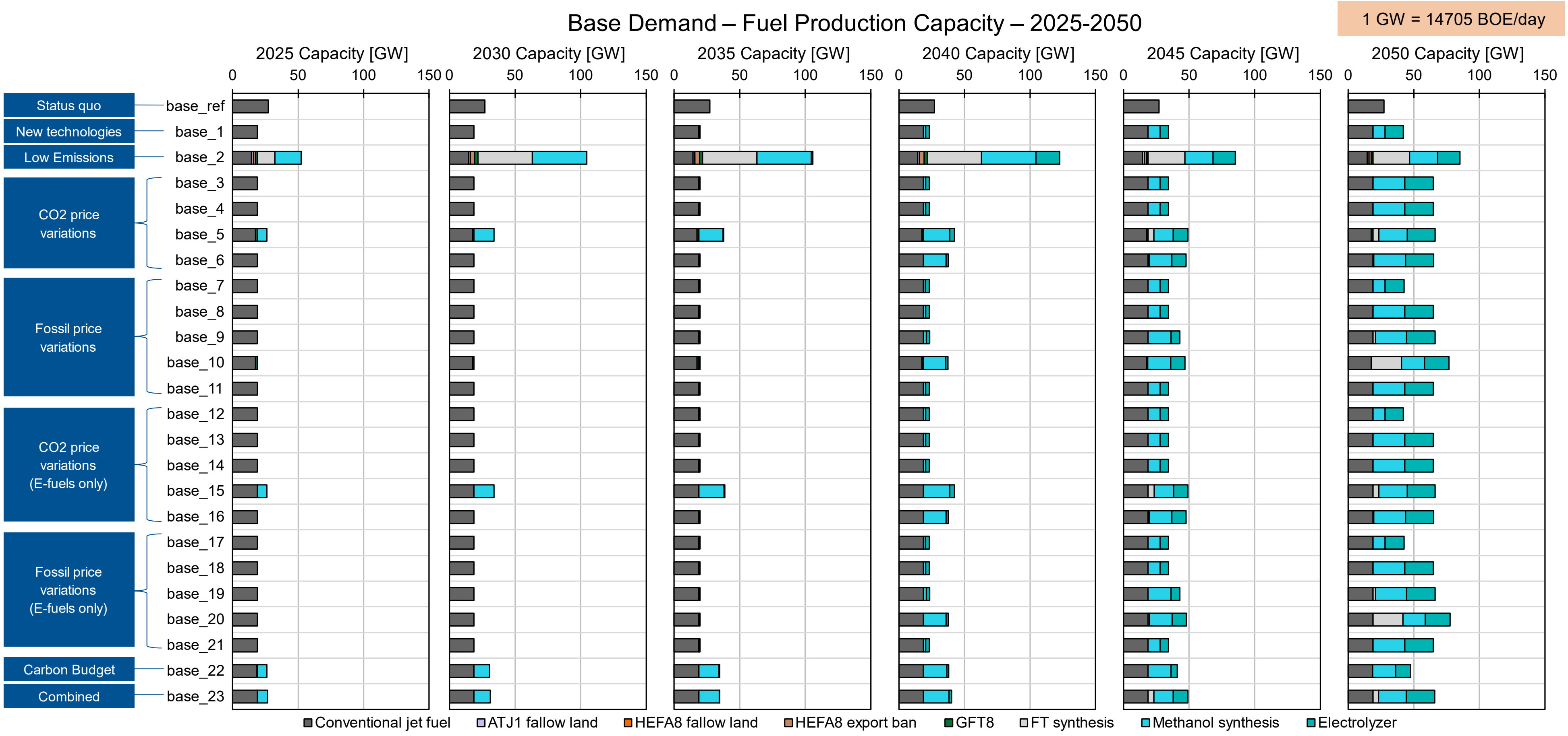

Figure 42: Base demand - Timeline of SAF production capacities by technology at 5-yr intervals, 2025-2050

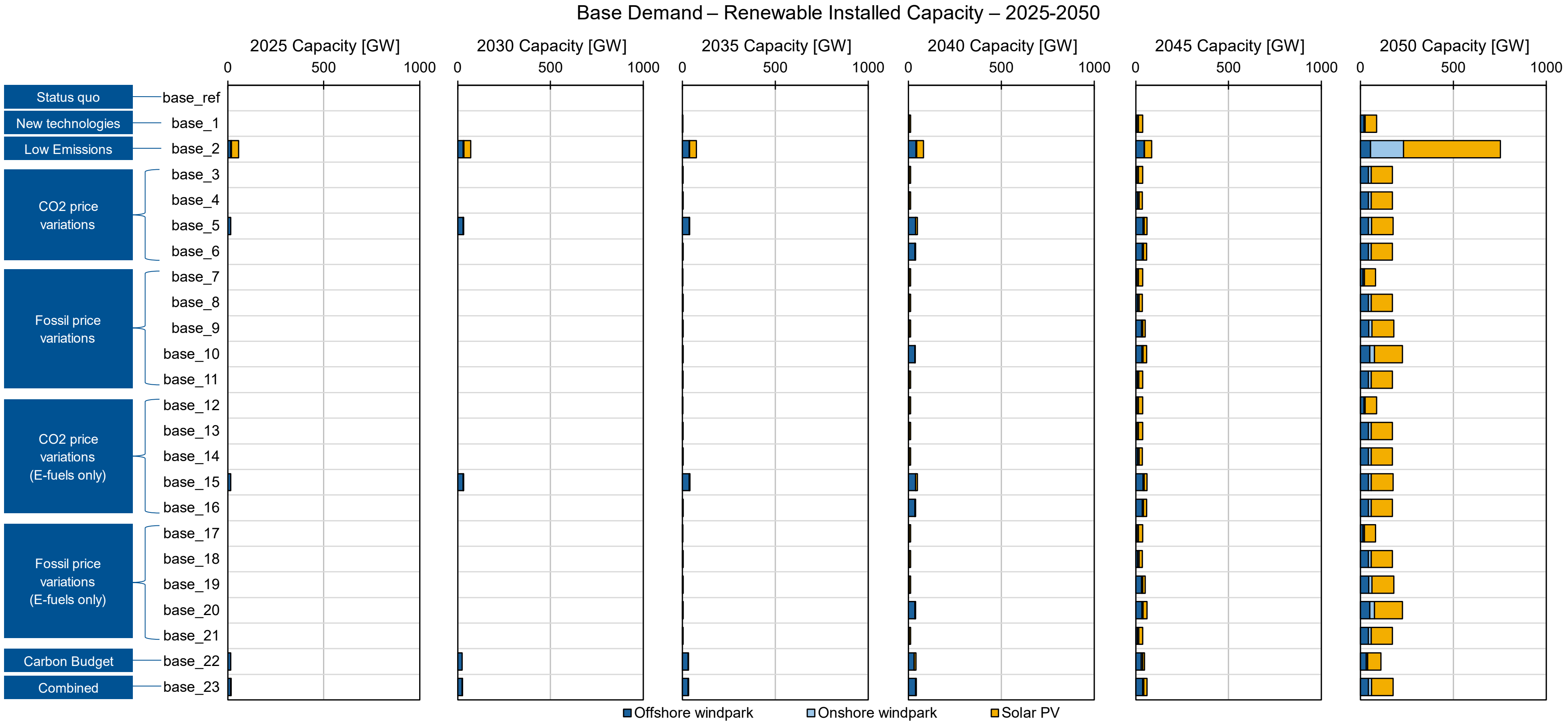

Figure 43: Base demand - Timeline of solar PV, onshore- and offshore wind capacities at 5-yr intervals, 2025-2050

Notably, there exists a clear trend in the conversion technology for e-SAF production (see Figure 42); the methanol synthesis route is preferred against the FT route due to the higher SAF fraction in the product-slate and a miniscule energy efficiency advantage. However, with high fossil cost, there is an observable expansion of the FT capacity, especially after 2045. This is attributed to the fact that FT synthesis produces relatively higher fraction of diesel and with the sale of co-products, especially at higher price points, the process economics becomes more favorable for FT synthesis. Though, this is only possible with abundance of cheap RE to offset the efficiency penalty of this pathway. Moreover, in case of a holistic energy model where other demand sectors may be considered, the FT route would make more sense, as the diesel produced can help simultaneously decarbonize the road and sea transport. Notwithstanding to the previous statement, from the aviation demand perspective, the methanol synthesis route offers a more effective approach and is evident from the distribution of e-SAF technology.

At large, the introduction of e-SAF appears in tandem with the use of electric and hydrogen planes after 2035. It is determined that the additional capacity of the RE generation, especially during periods of high availability is spilled over to run the SAF production plants to improve the capacity utilization of these plants. This behavior emerges from the underlying assumptions in the model, as the direct electrification and hydrogen production can only be operated with renewable electricity, meanwhile jet fuel could also be sourced from biogenic or even fossil sources.

Another aspect revealed by comparing Figure 42 and Figure 43 is that the RE capacity is significantly higher than the fuel production capacity. This is understandably linked with two technical parameters i.e., conversion efficiency of the SAF pathways and the ACF of renewable technologies. On one side, the SAF pathways sport an overall efficiency of approx. 50% which directly necessitates double energy input than the fuel output. Secondly, the ACF of the RE technologies also negatively affects the capacity requirements.

It is clearly evident in the scenarios predominantly based on technology with a higher ACF, such as offshore wind, comparably lower RE capacity is installed. Meanwhile in scenarios with significant solar PV contribution, extensive solar PV capacity is necessary to compensate for the lower ACF, especially in a region like Germany. For these reasons, the model is predisposed to install offshore wind to optimize the overall ACF of the entire pathway. Furthermore, 2040 is observed to be an inflection point, thereafter the reduction in technology cost of solar PV offsets these concerns to a certain extent and significant installations can be observed. However, the sector largely remains dependent on the offshore wind sector due to the nature of aviation energy demand and SAF production plants.

7.5. Storage Requirements

Storage is deemed an essential part of the energy supply due to dependency on intermittent renewable energy. It is observed that, in the absence of sufficient storage capacity the model either fails or exorbitant renewable capacity installation takes place – which is reflected on the price of SAF. However, even with relatively higher constraints allowed in the assumption in terms of storage capacity and power, the deployed storage capacity is substantially lower for all demand cases and scenarios, apart from CO_2 minimization (x_2) which requires extensive RE and coupled storage capacity to meet the aviation demand; this is determined to be infeasible with regards to economic concerns.

For batteries, a maximum limit of up to 12 hours of storage capacity at peak annual power demand is set. In spite of this, all demand cases settle for a 2 to 5 hours of storage, with most scenarios having a battery storage of only 3.5 hours. For hydrogen storage, a storage limit of up to 30 days (720 hours) is established in the model parameters. However, the deployed capacity is observed to be substantially lower; all demand cases and scenarios settle for an LOHC-based hydrogen storage in the range of 20 to 60 hours, with a median value of 25.5 hours. This determination and optimization by the model not only address the concerns regarding the cost of storage but also prevents strain on the supply of critical raw materials used to produce these storage technologies.

SAF storage is not considered as a critical parameter, due to a 90-day, legally-mandated fuel storage capacity in Germany; and with the reduction of aviation fuel demand after 2035, it is expected that this capacity would be sufficient to provide a reserve for SAF production from biogenic and non-biogenic SAF pathways. Moreover, this abundant capacity can also provide an opportunity for better integration of RE sources. For example, during periods of excess RE capacity, SAF can be produced and stored – allowing for optimal system sizing and operational costs.

For reference, detailed graphs for storage parameters for all scenarios for base, low, and high demand forecast are provided in Appendix D-5, Appendix E-6 and Appendix F-6 respectively.

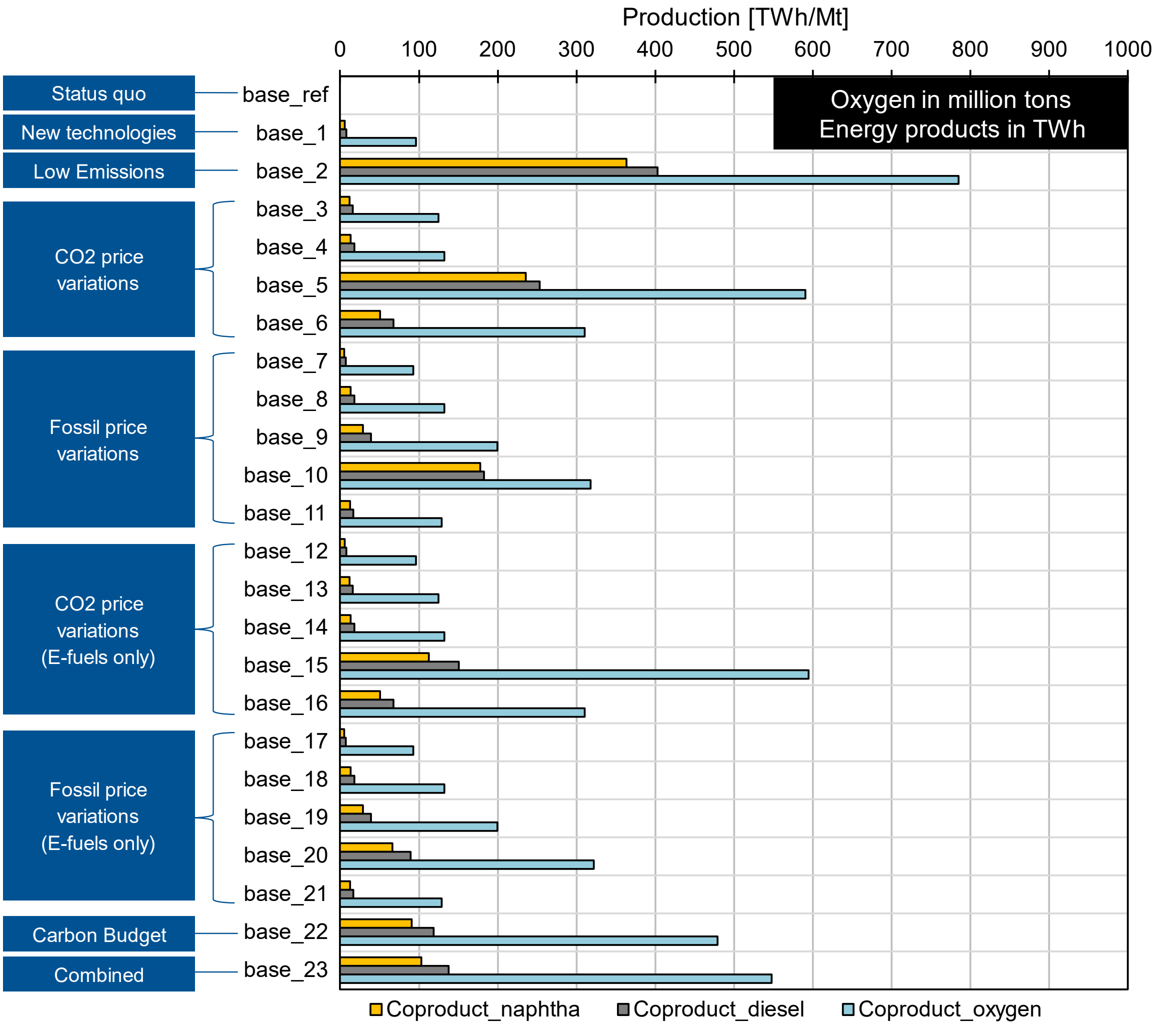

Figure 44: Base demand - Scenario-wise breakdown of co-products: diesel, naphtha, and oxygen, 2025-2050

7.6. Co-products

The co-production of diesel, naphtha and oxygen is unavoidable with the modelled technologies. Therefore, these co-products are sold to the market to generate additional revenue streams to improve the economics of the processes; this is presented as a negative cost called ‘Revenue’ in Figure 38. The production of co-products is directly dependent on the technology mix; hence, the volume of co-products also scales proportionally with respect to the demand case (see Appendix E-6 and Appendix F-6). Therefore, it is a legitimate concern that if these co-products can be easily integrated and sold in their respective markets.

From the statistics regarding German diesel consumption, approx. 390 TWh of diesel is consumed annually [196]. Even under most optimistic scenarios, the total diesel co-production falls below 400 TWh for the 25-year period. Therefore, it is concluded that integrating the diesel supply into the German market will not pose a challenge. Especially, with tightening emission standards, diesel from more sustainable sources would enjoy a sizeable demand.

As for the oxygen gas, the global demand is expected to double in the next ten years from 70 Bn USD to 158 Bn USD – this growing market is primarily driven by the industrial sector such as steel making and metal cutting, chemical industry applications, petrochemical, water treatment, pulp and paper processing [197]. Based on this, given the global dynamics and push towards sustainability, sale of co-products should not present a challenge, especially in the short- to medium-term.

7.7. Identified Short-Comings and Limitations

As elaborated multiple times before, the energy model is built upon simplistic assumptions due to time constraints in this thesis. Despite the time limitations, efforts were made to present the most accurate representation of the aviation market within these constraints. Throughout the analysis, several shortcomings in the energy model have been identified, stemming from certain modeling decisions and simplifications. It is essential to acknowledge these limitations as they may impact the reliability and generalizability of the model's findings.

Firstly, the modeling framework, urbs, imposes restrictions on the scaling of technology. urbs relies on linear optimization of cost and environmental emissions, assuming that technologies scale linearly. In reality, technologies often exhibit economies of scale, impacting CAPEX and OPEX. The linear nature of the model results in cost estimates being assessed at a specific scale and then multiplied to achieve the required system size, potentially leading to inaccuracies.

Secondly, due to the scope limitation, only the aviation market is modeled in isolation from the broader German energy market. Changes in demand within the aviation sector could influence other energy supply streams in Germany, altering price signals and technology selection. This interconnection is overlooked in the model, with analysis focusing solely on energy supply and demand relevant to aviation. The demand forecasting model, while pragmatic, relies on limited variables and timeseries, potentially causing significant under- or overestimation of future demand. Moreover, the demand forecast assumes continuation of the status quo in terms of energy efficiency, flight efficiency, and generally an incremental development of the aviation energy demand – this is clearly a continuation bias.

Thirdly, due to the isolated analysis, the interaction between various primary energy carriers is not considered. For instance, the assumption that hydrogen generation is directly consumed by the aviation sector neglects potential optimal utilization of electrolyser capacity to generate additional revenues based on energy market price fluctuations. An integrated approach could also facilitate the development of scenarios for additional generation export, enhancing economic incentives for such projects.

Moreover, the environmental impacts of technologies are not fully internalized due to the reliance on reference values from scientific papers, international, and global agencies. These values may not accurately represent the emission intensity of pathways in Germany. Specific values for Germany are crucial to ensure accurate environmental impact assessments.

Finally, the CAPEX and OPEX of modeled technologies are simplified and may not accurately reflect the installation- and operating costs in Germany. While efforts were made to use German and European estimates, global or international estimates were considered where data was lacking. The simplified cost structures do not fully encompass all expenses associated with project development, including but not limited to, land acquisition, project development costs, engineering and design, environmental studies, project financing, and insurance.

8. Conclusions

“Nothing in life is to be feared, it is only to be understood”
- *Marie Skłodowska-Curie (1867-1934)*

With the increasing concerns regarding climate change, dove-tailed with the push for sustainability from the public and governments alike, it is inevitable that a decarbonization of aviation sector would be realized by 2050. The extent of this decarbonization is a grave concern and is reliant on a plethora of factors, which are pedantically assessed within the scope of this thesis for Germany. The scope entails analyzing the fuel demand of the German aviation sector, which is used as a proxy for the aviation demand in the country. The predication model based on MRA forecasts a gradual increase of the aviation demand in Germany based on various techno-economic parameters, with the 2050-levels being 20% to 170% higher than the baseline level in 2019.

Even though the sector is forecasted to grow, this does not necessarily translate into a pro-rata increase in the aviation energy demand. The introduction of more efficient combustion technologies and alternative propulsion, namely, hydrogen and electric aviation, would bring about a substantial reduction in the overall energy demand - enabling fuel and emissions savings. Despite this, the earliest introduction of hydrogen and electric aviation is expected to occur at the end of 2030s, and a significant shift in the aviation propulsion is only forecasted to come into play after 2045. It is worth mentioning that these projections are highly optimistic as there is no currently available commercial-ready solution for any alternate propulsion technology. Therefore, there still remains a significant demand for kerosene-based aviation fuel; this is the fundamental reason SAF are projected as a certain strategy to decarbonize the ‘hard-to-abate’ aviation industry.

The production of SAF possess its own challenges in terms of regulatory, resources, societal, economics, and certainly, technical aspects. The most-developed SAF production options lie in the realm of biogenic pathways. Despite having matured technologies and already established supply-chain for feedstocks, the biogenic pathways offer limited opportunities for a land-constraint country like Germany. These opportunities are further stifled by the regulatory framework amid concerns regarding their impact on the environment and competition with feed and fodder production. Even under most-favorable conditions, for Germany, the biogenic pathways, namely, HEFA, ATJ, and GFT, are restrained due to their low conversion efficiencies, mandated blending with fossil jet fuel and higher cost of SAF production relative to fossil fuel. This directly hampers their ability to offset conventional jet fuel in any substantial manner; the maximum identified potential for the period 2025-2050 remains below 12%, with maximum annual substitution observed to be reaching 19% due to the forecasted reduction in kerosene demand in 2050.

Attributable to mandated substitution of jet fuel under EU law, with clearly defined targets till 2050; it is clear that these targets have to be met. For this reason, SAF produced from non-biogenic pathways proposes a technically-viable alternative to fossil jet fuel in Germany. Although the conversion technology of the SAF production, namely, MeOH and FT synthesis can be deployed at industrial-scale, the production of hydrogen and carbon capture for feedstock from sustainable and economical sources remains a challenge. In addition to this, the overall conversion efficiency of these processes is approx. 50%, necessitating additional energy input which further increases the cost of e-SAF.

In order to keep the non-biogenic pathways in compliance with REDII, it is only possible to produce carbon and hydrogen feedstocks from RE-supplied processes. This requires substantial expansion of the RE infrastructure including generation, transmission, and storage. When analyzed within the framework of German RE targets, there is ample capacity available to meet the additional demand expected from decarbonized aviation. Delving further into the analysis reveals a characteristic harmony between offshore wind and e-SAF production, owing to the inherent nature of the demand and higher ACF of offshore wind. For economic reasons, it makes more sense to couple technologies with similar availability to avoid unnecessary system capacity and storage – prompting reduced CAPEX and OPEX and ultimately reduced SAF price.

Nonetheless, this analysis does not include other energy demand vectors, and with ongoing decarbonization of industry, residential, transport sector, it is fair to conclude that proposed target may not be sufficient to accommodate all demand vectors including aviation. This limit is most apparent for offshore wind as only a limited capacity expansion plan is put-forward by the German government. Supplementing offshore wind with onshore wind and solar PV is not only essential to ensure sufficient capacity, but also for the reason of better economics due to lower technology cost. Even though, it is expected that hydrogen and electric aviation along with combustion improvement would significantly reduce the direct energy consumption of aviation, however, due to additional conversion processes involved, the forecasted energetic gain is either substantially reduced or even more energy is required. On one hand, this increased demand puts pressure on the already-contested

RE supply, on the other hand offers an opportunity to integrate RE in a better manner by storing electricity as fuel during periods of high availability and avoid curtailment.

In conclusion, the decarbonization of aviation in Germany requires expansion of the RE supply along with installation of e-SAF production facilities. This necessitates significant infrastructure investments and higher technology-related operating costs – indicative of an increase cost of energy for the aviation sector. In fact, the degree of decarbonization is directly correlated with increased costs, and no scenario is observed where decarbonization would lead to a reduction in the energy cost for the aviation sector. An aggressive decarbonization strategy would result in a fuel cost increase of 250%, with a more moderate, and perhaps a probable approach resulting in a cost increase of approx. 100%.

Even with increased cost, in the short- and medium-term fossil fuel is expected to remain the primary energy supply for aviation, unless a breakthrough in fuel production, renewable electricity generation or storage technology is made leading to substantial cost savings or efficiency improvements. Furthermore, option regarding SAF import from regions with more favorable techno-economic conditions cannot be discounted, however would negatively impact the energy autarky of Germany.

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Appendix A: History

Appendix A-1: Major milestone towards the development of the sustainable aviation sector in Europe

Source: Adapted from [62], with additions and modifications referenced in the table

Year	Organization	Name of the Agreement/Event	Ratifying Member Nations	Nature of the Agreement	Event
1947	ICAO		191		Formation of ICAO as a specialized agency of UN for planning and development of international aviation
1981	ICAO	Chicago Convention	191	Non-binding	Aircraft Engine Emission
1992	UNFCCC		154	Non-binding	Formation of UNFCCC
1992	UNFCCC	Kyoto Protocol	Current: 192 Annex I: 38 + EU Annex II: 21 + EU US and Canada are prominent countries that have not ratified (or withdrew) from this agreement [198]	Legally binding	Commitment to reduce greenhouse gas emissions set under Berlin Mandate (1995)
2005	EU	Directive 2003/87/EC of the European Parliament and the European Council EU Emission Trading System (EU ETS)	Original Kyoto Protocol signatories of EU, with additional member later added in Annex B	Legally binding	Launch of Phase-I (2005-2007)
2007	UNFCCC	COP13 - Bali Action Plan [199]	114	Legally binding	The Bali Action Plan is centered on four main building blocks i.e., mitigation, adaptation, technology, and financing with: Measurable, reportable, and verifiable mitigation commitments or actions from all developed countries; Nationally appropriate commitments from developing countries.

Year	Organization	Name of the Agreement/Event	Ratifying Member Nations	Nature of the Agreement	Event
2008	EU	EU ETS	Original Kyoto Protocol signatories of EU, with additional member later added in Annex B	Legally binding	Launch of Phase II (2008-2012)
2009	UNFCCC	COP15 - Copenhagen Accord	114	Non-binding	Agreement to hold the global temperature below 2 degrees Celsius [200]
2010	UNFCCC	COP16 – Cancun	196	Non-binding	Establishment of approaches to achieve carbon reduction in anthropogenic activities and establishing the “standardized baseline” [201]
2012	UNFCCC	COP18 – Doha Amendment [202]	196	Legally binding	Regulate 2013-2020 Amendments to the Kyoto Protocol New Market Mechanisms
2013	EU	EU ETS	Original Kyoto Protocol signatories of EU, with additional member later added in Annex B	Legally binding	Launch of Phase III (2012-2013)

Year	Organization	Name of the Agreement/Event	Ratifying Member Nations	Nature of the Agreement	Event
2015	UNFCCC	COP21 – Paris Agreement	196	Legally binding (2016 onwards)	Milestone agreement to reduce GHG emissions by 2025-2030, and keep global warming limited to 1.5-2 degrees Celsius in accordance with the IPCC recommendations. Major emitters, like China and EU submitted ambitious commitments [203].
2016	ICAO	Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)	119	Pilot phase (2021-2023) Phase I (2024-2026) Second phase (2027-2035)	Global market-based carbon offsetting measure Airline are required to monitor emissions on all international routes and; offset emissions from routes included in the scheme by purchasing eligible emission units [9, 204]
2018	EU	EU ETS	Original Kyoto Protocol signatories of EU, with additional member later added in Annex B	Legally binding	Launch of fourth phase (2021-2030); Linear reduction factor of 2.2% per year is applied to the aviation cap 2021 onwards (modified to 4.2% under Fit for 55 package); Only EU Aviation Allowances (EUAAs) and EU Allowances (EUAs) are eligible for compliance [205]
2020	EU	EU Green Deal	EU member states	Legally binding	No net emissions of GHG by 2050 with economic growth decoupled from resource use.
2021	EU	Fit for 55 Package and ReFuelEU Aviation	EU member states	Legally binding	To reduce the GHG emission to 55% compared to 1990 level by 2030; Binding SAF targets, starting with 2% in 2025 and reaching 5% in 2030 [27]

Year	Organization	Name of the Agreement/Event	Ratifying Member Nations	Nature of the Agreement	Event
2021	Consortium of Airlines in Europe (A4E, ACI-Europe, ASD, CANSO, ERA)	Destination 2050	Airlines in EU, EFTA, and UK	Industry-led commitments	Presenting a road map to net-zero emissions from the aviation sector [206]
2021	Airbus [65]	ZEROe	-	Product	Announcement of the development of world's first hydrogen powered commercial aircraft to be operational by 2035; Fuel used: Liquid Hydrogen
2021	IATA and ICAO [207]	Long-term aspirational goal (LTAG)	IATA members and ICAO member states	Guidelines (not legally binding)	Achieving long-term net-zero aviation by offsetting carbon through: 65% with the use Sustainable Aviation Fuel (SAF); 13% will be accounted by new technology including electric aviation and hydrogen; 3% through efficiency improvements in terms of Infrastructure and operations; 19% is expected to be achieved by offsetting and carbon capture technologies.
2023	EU	Fit for 55 Package and ReFuelEU Aviation	EU member states	Legally binding (provisional agreement) [208]	2% of jet fuel must be sustainable as of 2025, with increasing share every five years i.e., 6%, 20%, 34% and 42% in year 2030, 2035, 2040 and 2045 respectively; With a target of 70% sustainable jet fuel by 2050; Green status accepted for Hydrogen and fuel produced from cooking oil or waste gases; Feed and food crop-based fuels will not be acceptable alternatives; A specific proportion of the jet fuel (1.2% in 2030, 2% in 2032, 5% in 2035 and 35% in 2050) must comprise synthetic fuels like e-kerosene. 2025 onwards flights will boast an EU environmental performance label

Appendix B: Feedstock Data

Appendix B-1: Germany's primary crops used for the production of biofuels in terms of total production (top) and specific yield in tons per sq. km (bottom) for years 2020-2022

Source: Data published by the federal statistics office [209], potential usage as reported by [210]

Crop	Classification	Potential usage for X pathway	Total Production [1000 Tons]		
			2020	2021	2022
Wheat	Food and Energy Crop	Bioethanol	22,172.1	21,459.2	22,587.3
Rye and winter cereal mixtures	Food and Energy Crop	Bioethanol	3,513.4	3,325.6	3,132.3
Sugar beet without seed production (including ethanol production)	Food and Energy Crop	Bioethanol	28,618.1	31,954.4	28,201.4
Winter rape	Energy Crop	Biodiesel	3,522.2	3,496.6	4,281.2
Spring rape and turnip rape seeds	Energy Crop	Biodiesel	5.1	8.0	13.7

Crop	Classification	Potential usage for X pathway	Yield [Tons per Sq. Km]			
			2020	2021	2022	Average
Wheat	Food and Energy Crop	Bioethanol	782	730	758	757
Rye and winter cereal mixtures	Food and Energy Crop	Bioethanol	552	527	532	537
Sugar beet without seed production (including ethanol production)	Food and Energy Crop	Bioethanol	7,415	8,177	7,117	7,570
Winter rape	Energy Crop	Biodiesel	369	351	396	372
Spring rape and turnip rape seeds	Energy Crop	Biodiesel	155	211	204	190

Appendix B-2: Amounts of agricultural raw materials used for biofuel production in Germany, in tons (2015-2020)

Source: Published by Fachagentur Nachwachsende Rohstoffe e.V. (FNR) [46]

Energy Carrier	Feedstock	2015	2016	2017	2018	2019	2020
		Values in tons					
Biodiesel	Rapeseed oil	2,230,000	2,040,000	1,850,000	1,970,000	2,060,000	1,910,000
	Palm oil	121,000	132,000	231,000	68,100	72,300	47,000
	Soya oil	69,500	165,000	264,000	272,000	398,000	438,000
Bioethanol	Grains	1,740,000	1,990,000	1,940,000	1,810,000	1,730,000	2,180,000
	Sugar beet	3,170,000	2,310,000	1,700,000	1,480,000	890,000	1,270,000
Total		7,330,000	6,630,000	5,980,000	5,600,000	5,150,000	5,850,000

Appendix B-3: Breakdown of technical potential of forestry biomass constituents in Germany

Source: Adopted from [51, 52]

	Technical potential	
	[Mio. $t_{air\text{-}dry}$/annum]	[PJ/annum]
Fuel wood, used round wood, bark	12.8	246
Logging residue > 7cm Ø	5.8	111
Logging residue < 7cm Ø	2.8	53
Unused annual growth	5.1	101

Appendix B-4: Agricultural yield of various crops used for the production of bioethanol (top) and biodiesel (bottom) in Germany, along with specific yield for various feedstocks

Source: Published by Fachagentur Nachwachsende Rohstoffe e.V. (FNR) [125]

Biofuel	**Raw Materials**	**Yield**	**Biofuel yield**		**Biomass required per liter of fuel**
		[t/ha (wet)]	[liters/t (dry)]	[l/ha]	[kg/l]
Bioethanol	Corn maize	9.90	400	3,960	2.50
Bioethanol	Wheat	7.70	380	2,926	2.60
Bioethanol	Rye	5.40	420	2,268	2.40
Bioethanol	Sugar beet	70.00	110	7,700	9.10
Bioethanol	Sugar cane	73.00	88	6,424	11.40
Bioethanol	Straw	7.00	342	2,394	2.90
Biodiesel	Rape seed	3.90	455	1,775	2.20
Biodiesel	Palm oil	20.00	222	4,440	4.50
Biodiesel	Soya	2.90	222	644	4.50
Biodiesel	Jatropha	2.50	244	610	4.10

Appendix B-5: Second generation feedstocks sustainable technical and unused potential in Germany

Source: Synthesized data from [51–53]

Type	**Technical Potential**	**Available Potential**	
	[PJ/annum]		
		Low	High
Forestry Biomass	265.0	58.4	134.1
Straw	36.8	8.1	18.6
Biodegradable and green waste	23.0	5.1	11.6
Waste and industrial wood	58.0	12.8	29.3
Total	382.8	84.3	193.7

Appendix C: Pathways Assessment

Appendix C-1: Energy substitution potential for biogenic pathways [%]

Scenario Name	Low demand	Base demand	High demand
HEFA_1	0.98%	0.82%	0.67%
HEFA_2	3.16%	2.64%	2.16%
HEFA_3	3.25%	2.71%	2.23%
HEFA_4	10.52%	8.78%	7.20%
HEFA_5	0.98%	0.82%	0.67%
HEFA_6	3.16%	2.64%	2.16%
HEFA_7	3.25%	2.71%	2.23%
HEFA_8	10.52%	8.78%	7.20%
ATJ_1	11.36%	9.48%	7.77%
GFT_1	2.37%	1.98%	1.62%
GFT_2	4.38%	3.66%	3.00%
GFT_3	2.37%	1.98%	1.62%
GFT_4	4.38%	3.66%	3.00%
GFT_5	5.44%	4.54%	3.72%
GFT_6	10.07%	8.40%	6.89%
GFT_7	5.44%	4.54%	3.72%
GFT_8	10.07%	8.40%	6.89%

Appendix C-2: Total SAF produced by biogenic pathway including blending of conventional jet fuel - [tons]

Scenario Name	Low demand	Base demand	High demand
HEFA_1	27,568,520	27,568,520	27,568,520
HEFA_2	89,192,271	89,192,271	89,192,271
HEFA_3	91,710,969	91,710,969	91,710,969
HEFA_4	278,180,738	293,521,331	296,392,302
HEFA_5	5,513,704	5,513,704	5,513,704
HEFA_6	17,838,454	17,838,454	17,838,454
HEFA_7	18,342,194	18,342,194	18,342,194
HEFA_8	59,342,392	59,342,392	59,342,392
ATJ_1	64,056,267	64,056,267	64,056,267
GFT_1	13,347,336	13,347,336	13,347,336
GFT_2	24,717,288	24,717,288	24,717,288
GFT_3	6,673,668	6,673,668	6,673,668
GFT_4	12,358,644	12,358,644	12,358,644
GFT_5	30,651,454	30,651,454	30,651,454
GFT_6	56,761,951	56,761,951	56,761,951
GFT_7	15,325,727	15,325,727	15,325,727
GFT_8	28,380,975	28,380,975	28,380,975

Appendix C-3: Total emission of the period 2025-2050 for biogenic pathways based on various demand scenarios in [tons$_{CO2eq}$]

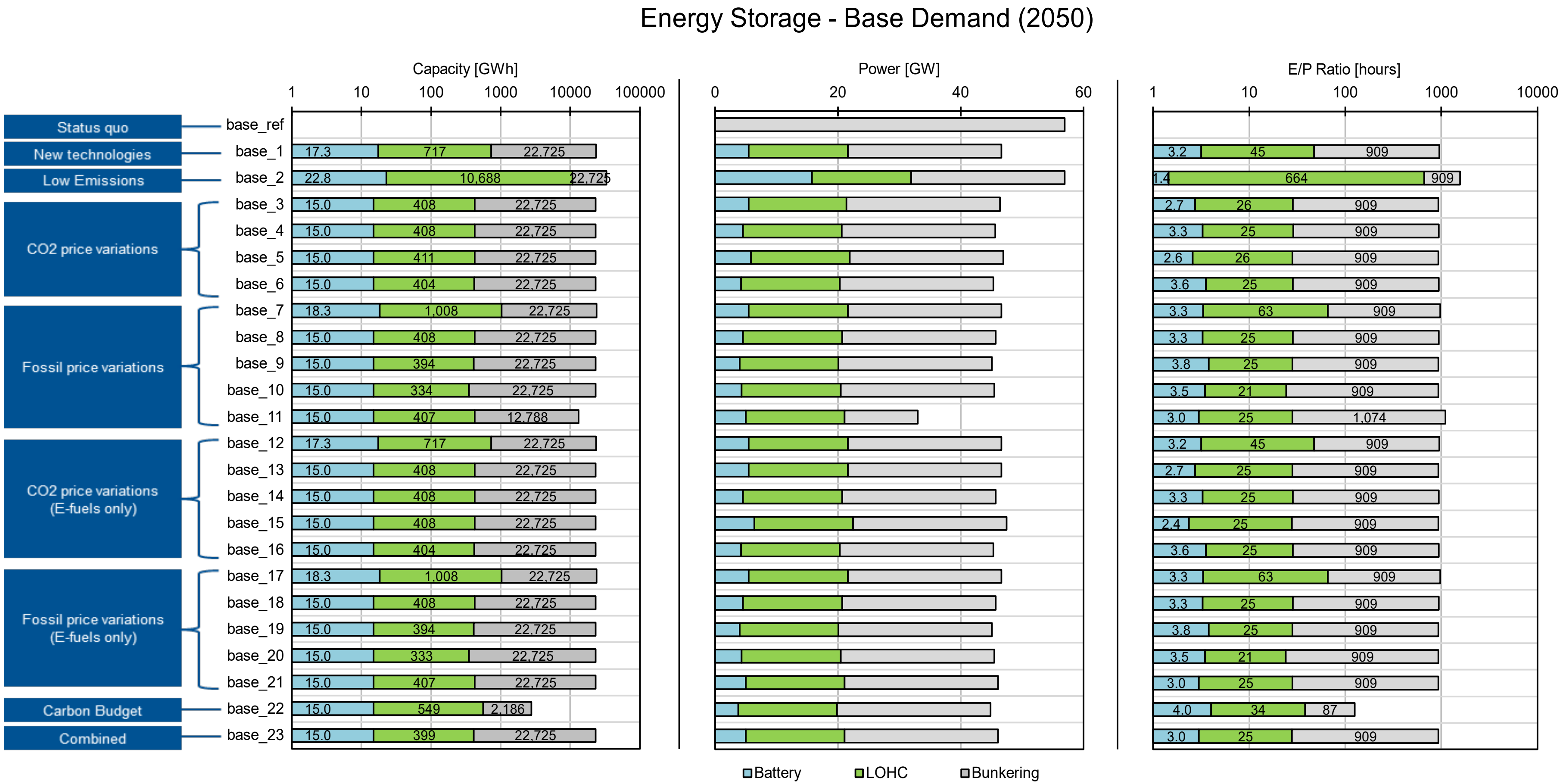
Scenario Name	Low demand	Base demand	High demand
HEFA_1	1,160,388,811	1,374,563,026	1,706,964,571
HEFA_2	1,148,810,201	1,362,984,416	1,695,385,961
HEFA_3	1,148,336,958	1,362,511,173	1,694,912,718
HEFA_4	1,076,868,005	1,286,150,719	1,617,636,826
HEFA_5	1,160,388,811	1,374,563,026	1,706,964,571
HEFA_6	1,148,810,201	1,362,984,416	1,695,385,961
HEFA_7	1,148,336,958	1,362,511,173	1,694,912,718
HEFA_8	1,109,818,912	1,323,993,127	1,656,394,672
ATJ_1	1,071,257,392	1,285,431,606	1,617,833,152
GFT_1	1,142,632,387	1,356,806,602	1,689,208,147
GFT_2	1,123,094,033	1,337,268,248	1,669,669,793
GFT_3	1,142,632,387	1,356,806,602	1,689,208,147
GFT_4	1,123,094,033	1,337,268,248	1,669,669,793
GFT_5	1,112,896,645	1,327,070,859	1,659,472,405
GFT_6	1,068,027,844	1,282,202,058	1,614,603,604
GFT_7	1,112,896,645	1,327,070,859	1,659,472,405
GFT_8	1,068,027,844	1,282,202,058	1,614,603,604

Appendix C-4: GHG reduction of biogenic pathways compared with only fossil-based jet fuel in [tons$_{CO2eq}$]

Scenario Name	Low demand	Base demand	High demand
HEFA_1	5,179,904	5,179,904	5,179,904
HEFA_2	16,758,514	16,758,514	16,758,514
HEFA_3	17,231,757	17,231,757	17,231,757
HEFA_4	88,700,710	93,592,211	94,507,649
HEFA_5	5,179,904	5,179,904	5,179,904
HEFA_6	16,758,514	16,758,514	16,758,514
HEFA_7	17,231,757	17,231,757	17,231,757
HEFA_8	55,749,804	55,749,804	55,749,804
ATJ_1	94,311,324	94,311,324	94,311,324
GFT_1	22,936,328	22,936,328	22,936,328
GFT_2	42,474,682	42,474,682	42,474,682
GFT_3	22,936,328	22,936,328	22,936,328
GFT_4	42,474,682	42,474,682	42,474,682
GFT_5	52,672,071	52,672,071	52,672,071
GFT_6	97,540,872	97,540,872	97,540,872
GFT_7	52,672,071	52,672,071	52,672,071
GFT_8	97,540,872	97,540,872	97,540,872

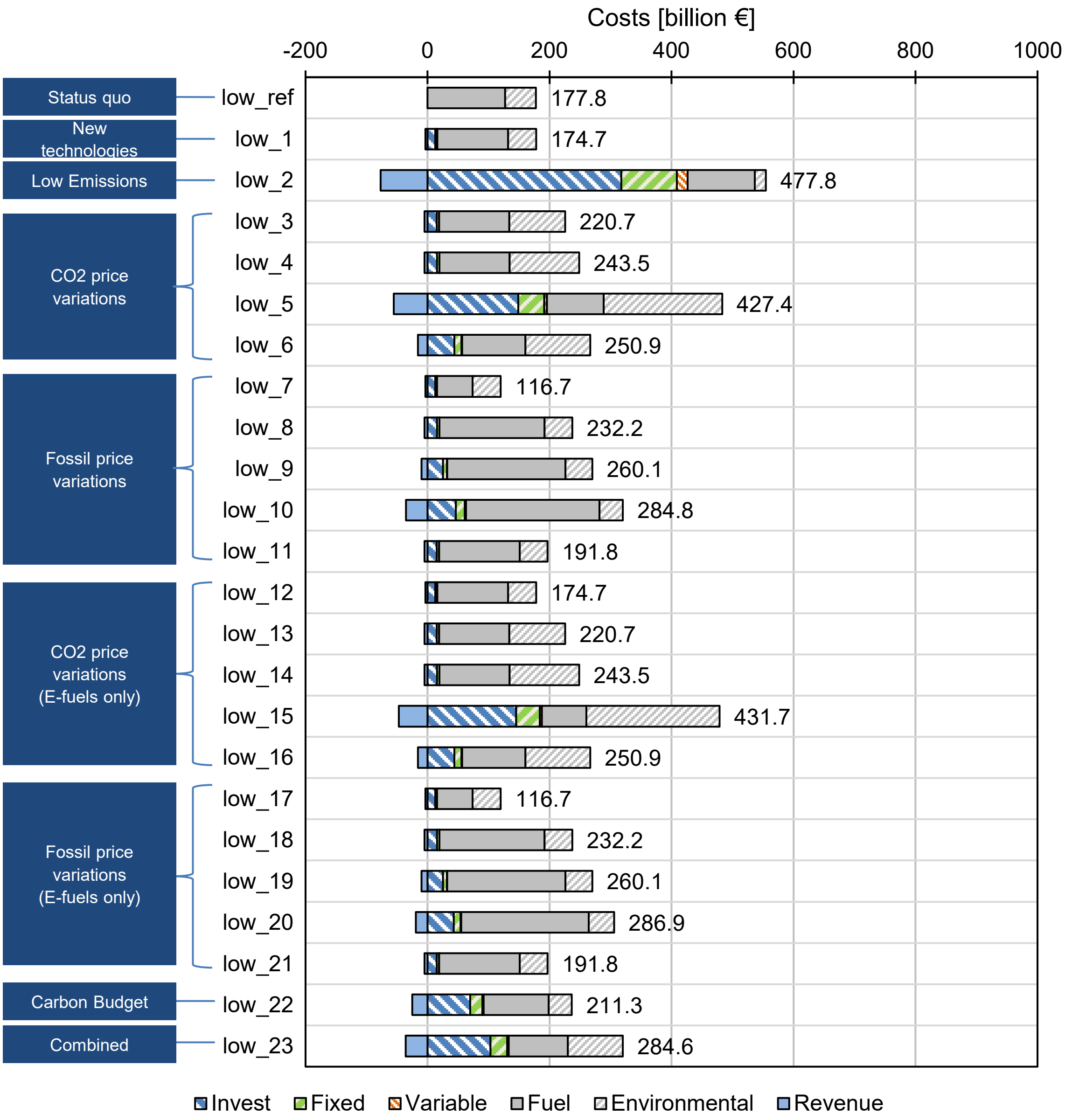
Appendix D: Base Demand Results

Appendix D-5: Base demand - Storage parameters for 2050 in terms of capacity, power, and E/P ratio

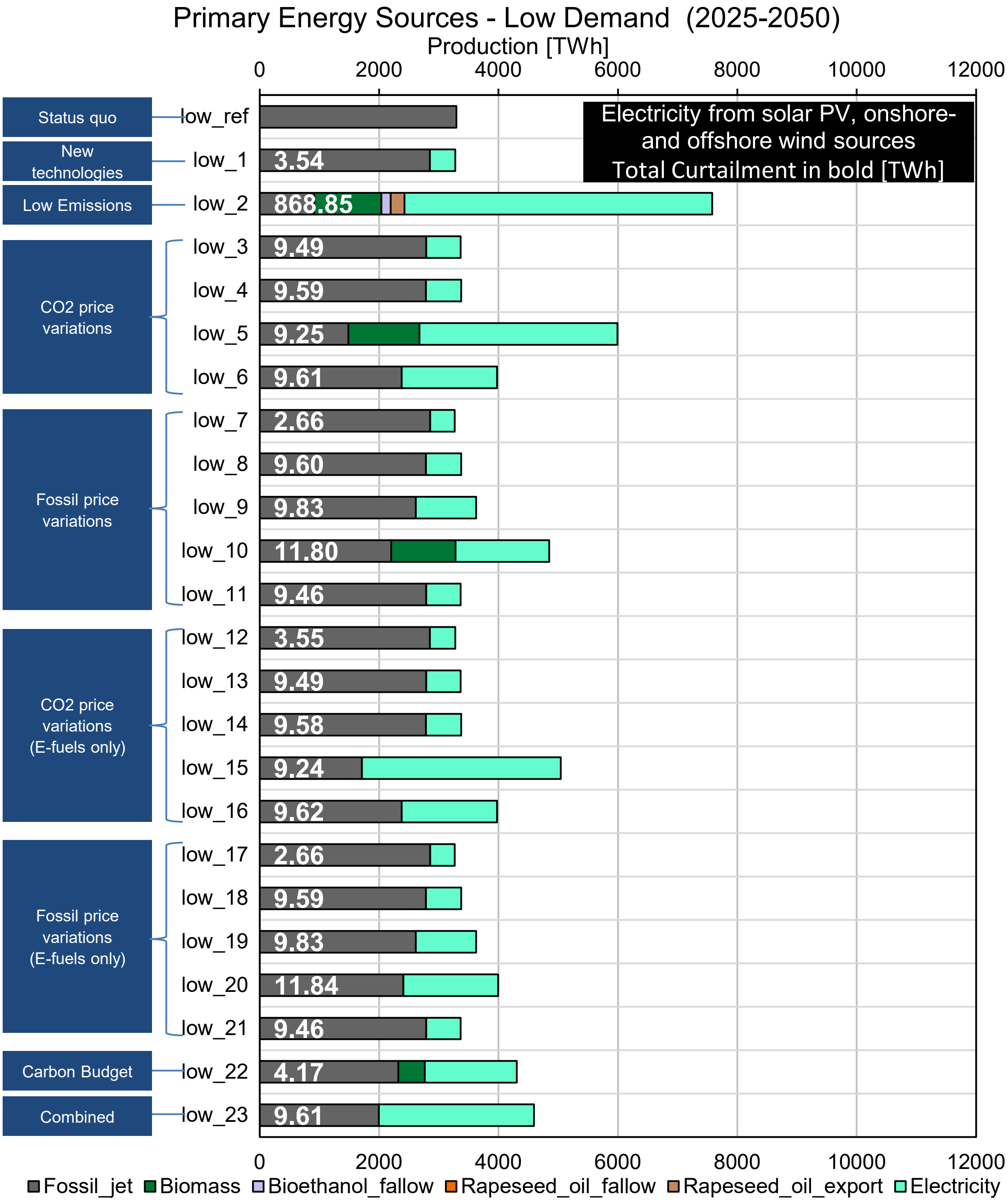


Appendix E: Low Demand Results

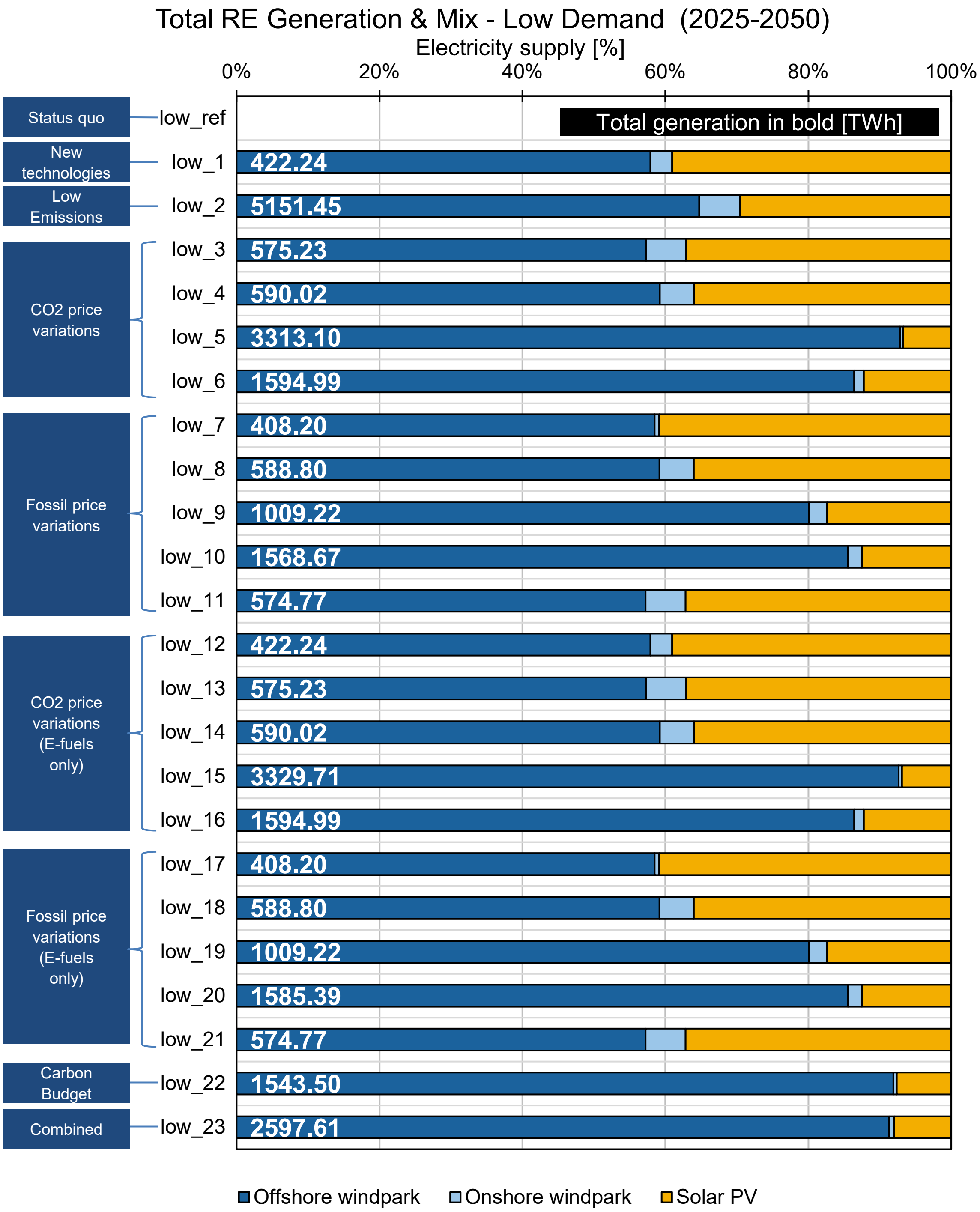
Appendix E-1: Low demand - Total costs for modelled scenarios (2025-2050)



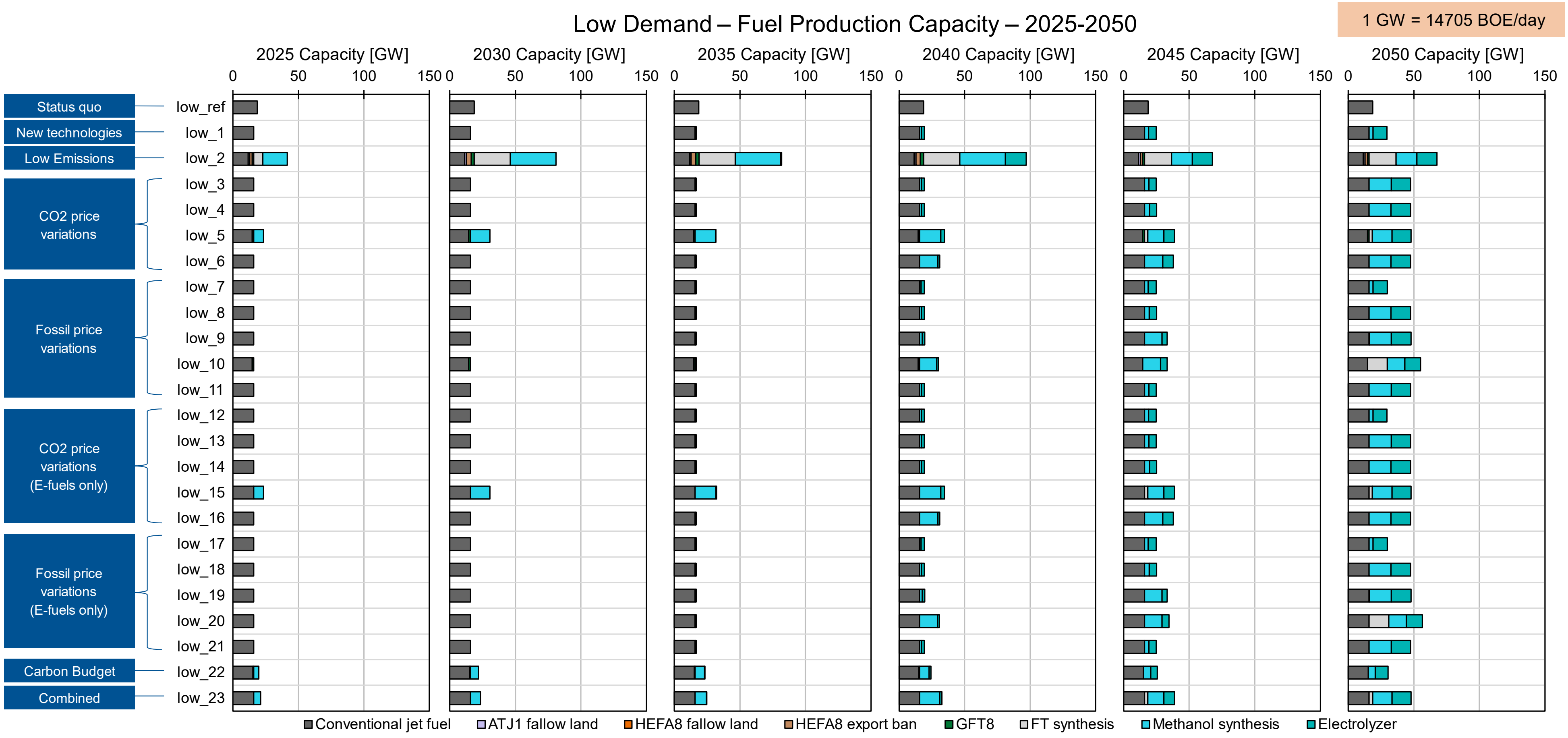
Appendix E-2: Low demand - Primary energy mix, 2025-2050



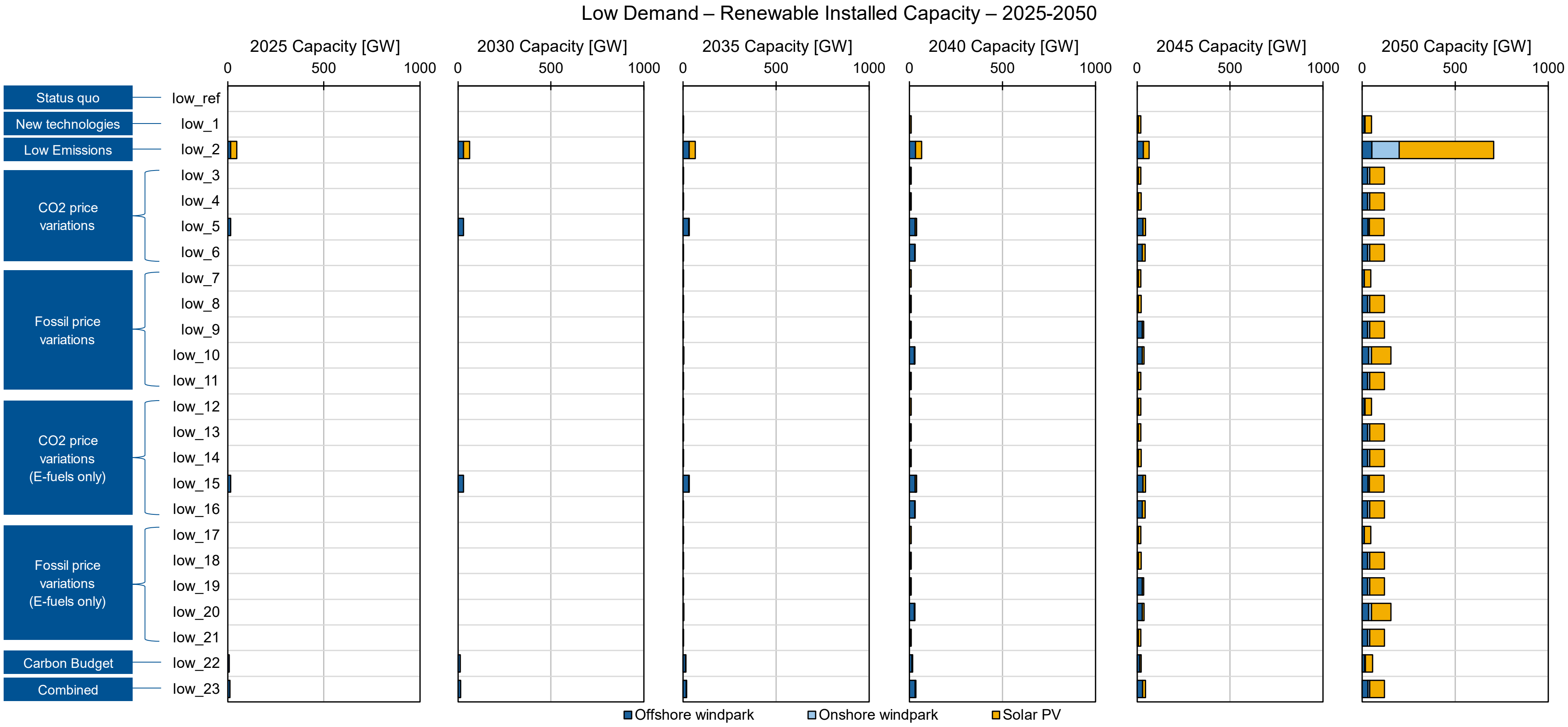
Appendix E-3: Low demand - Breakdown of renewable electricity supply, 2025-2050



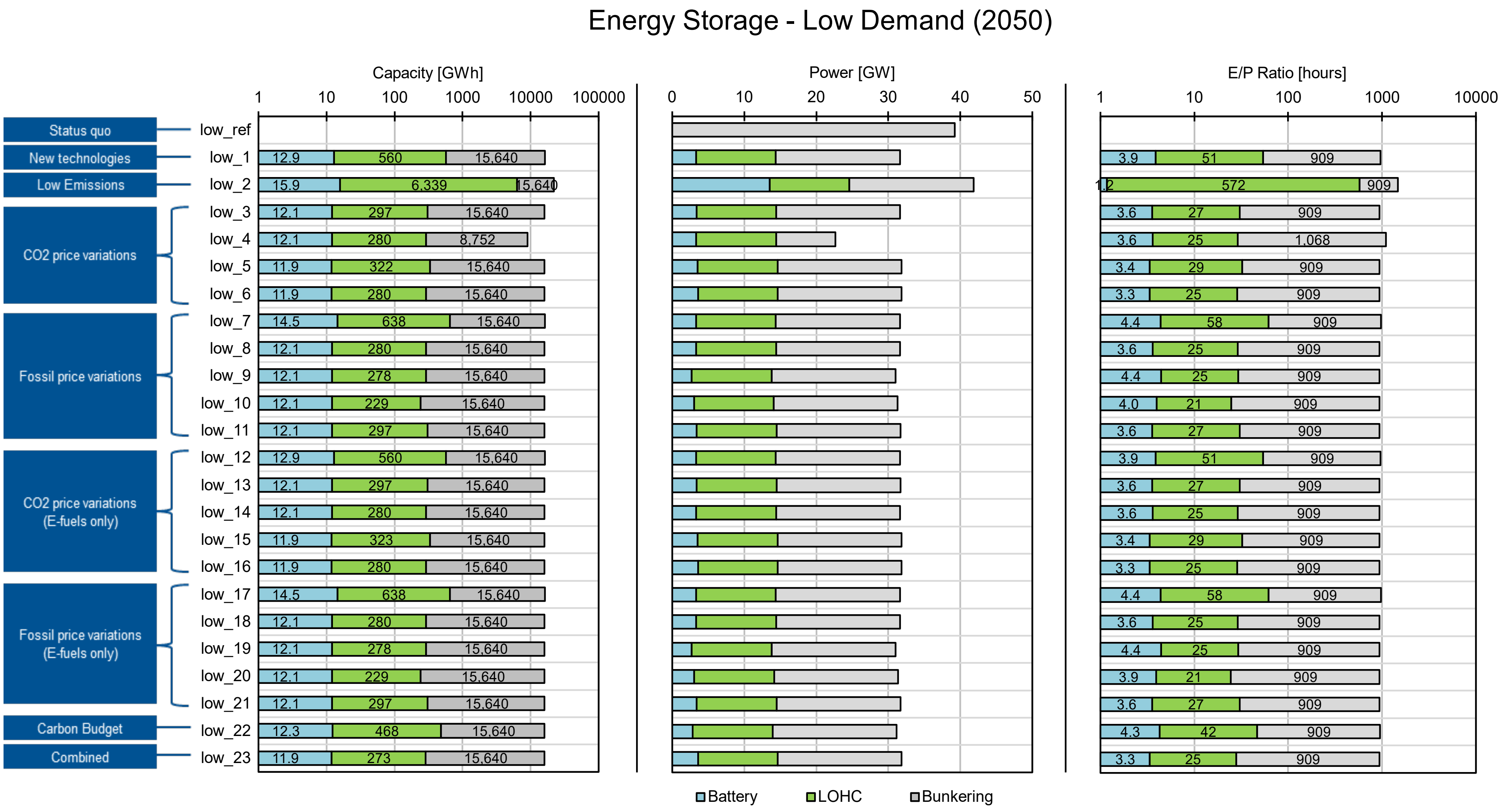
Appendix E-4: Low demand - Timeline of SAF production capacities by technology at 5-yr intervals, 2025-2050



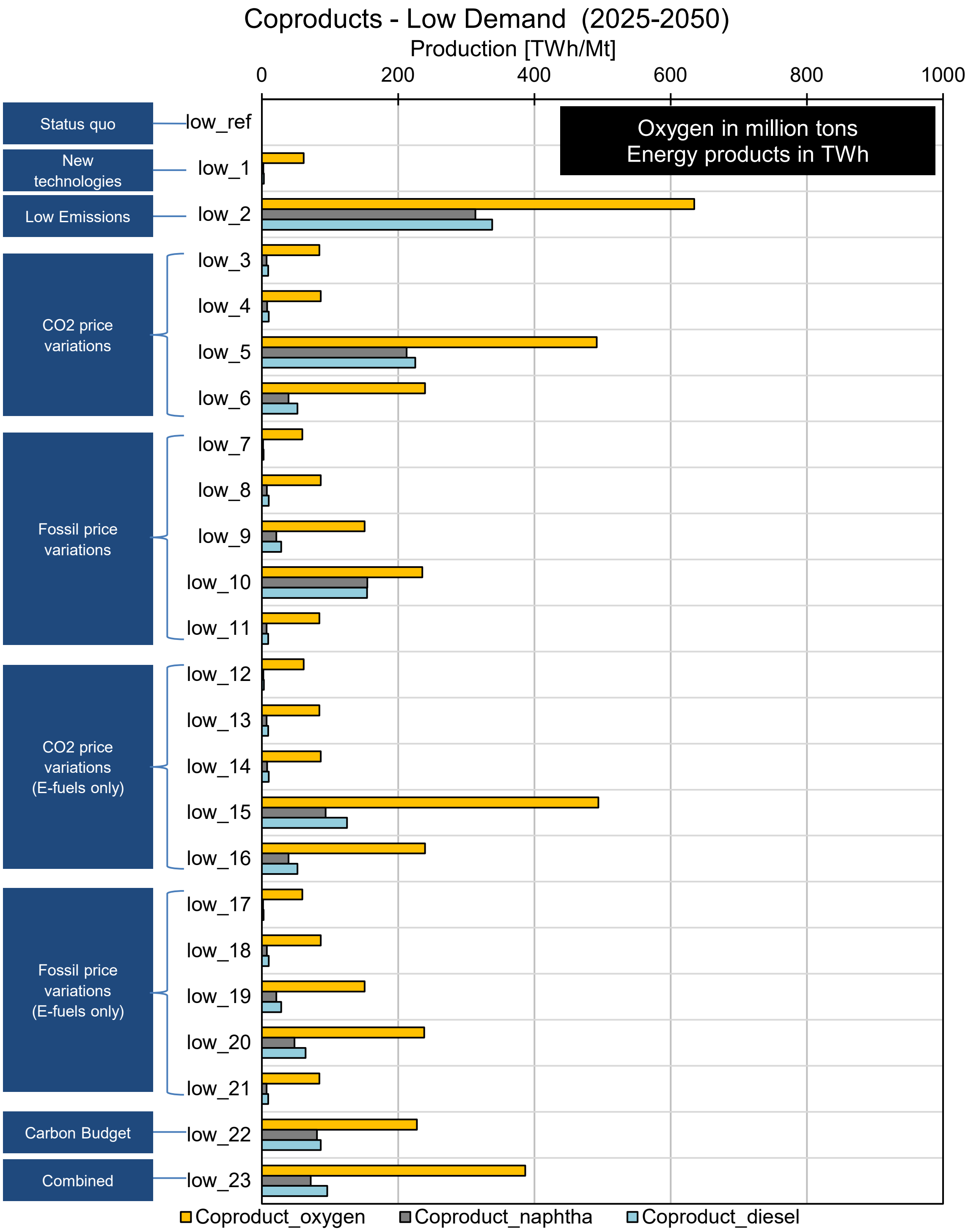
Appendix E-5: Low demand - Timeline of solar PV, onshore- and offshore wind capacities at 5-yr intervals, 2025-2050



Appendix E-6: Low demand - Storage parameters for 2050 in terms of capacity, power, and E/P ratio

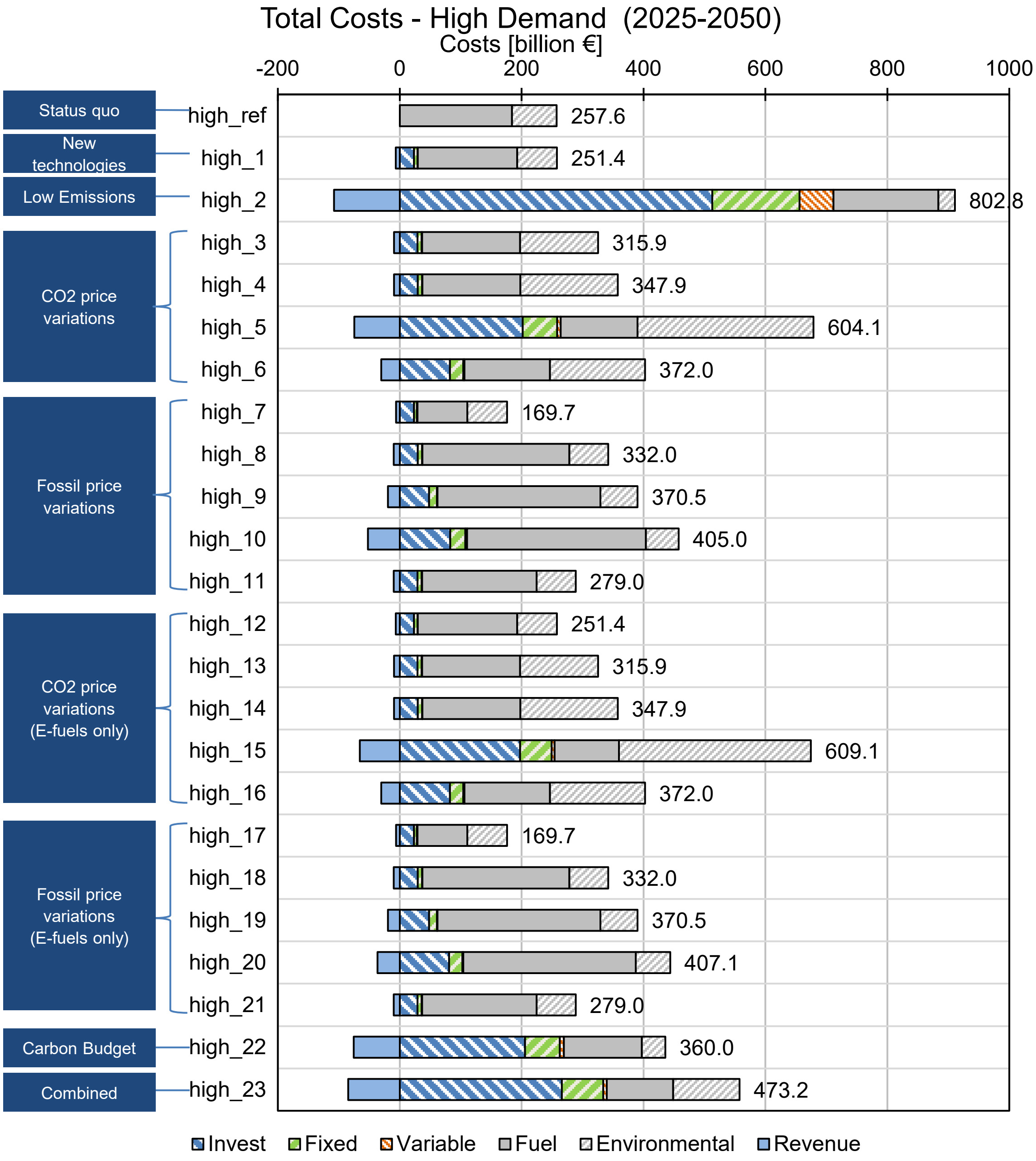


Appendix E-7: Low demand - Scenario-wise breakdown of co-products: diesel, naphtha, and oxygen, 2025-2050

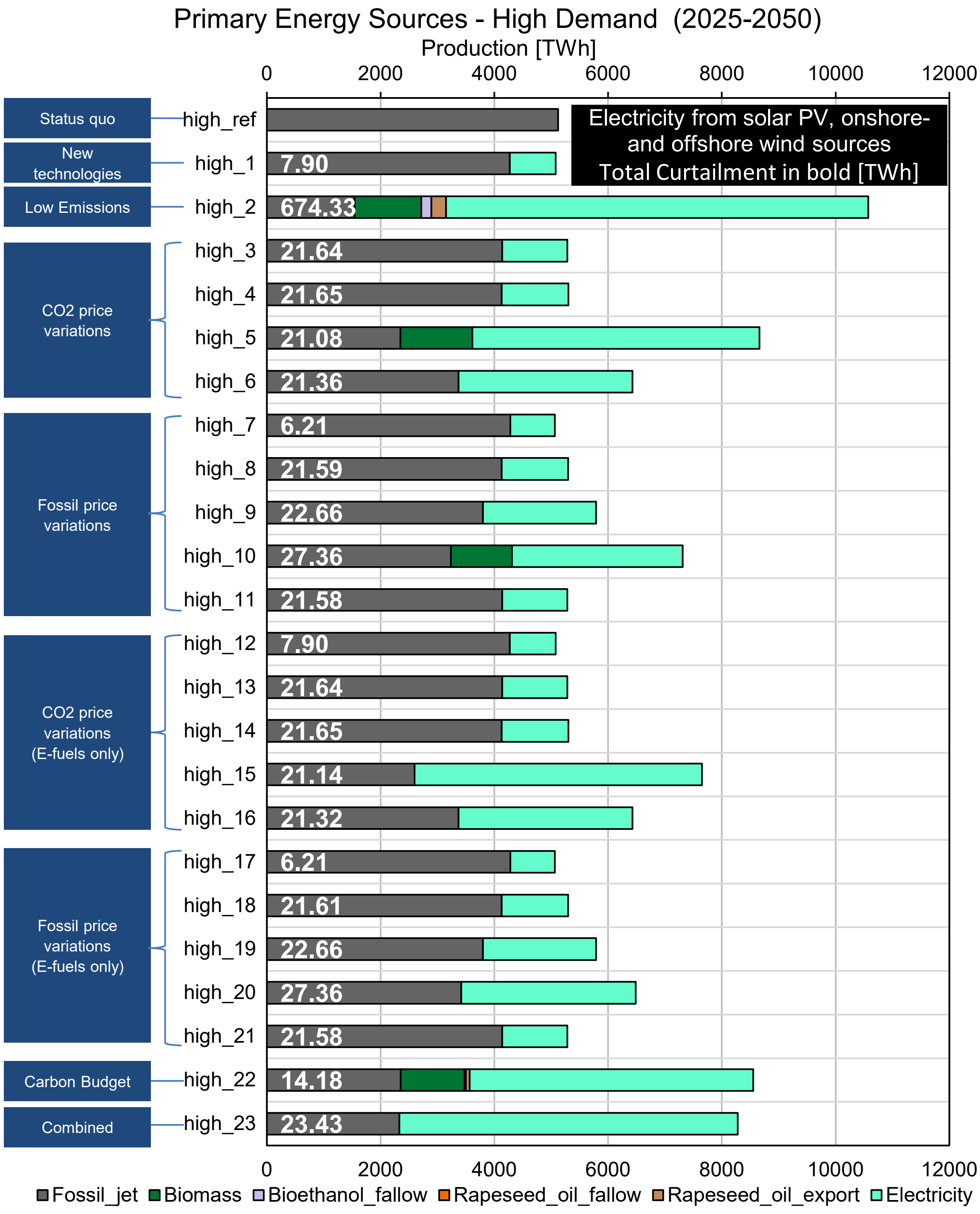


Appendix F: High Demand Results

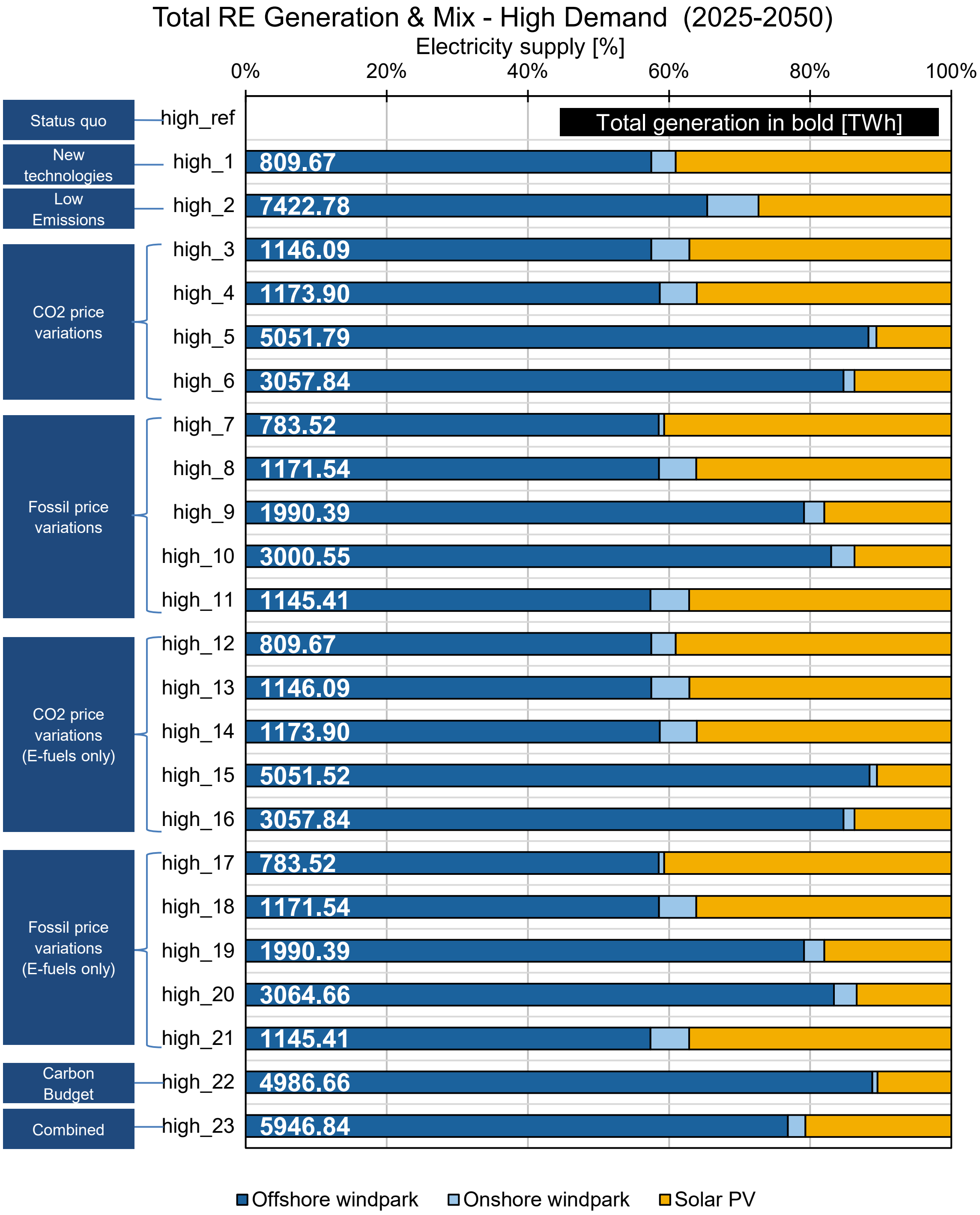
Appendix F-1: High demand - Total costs for modelled scenarios (2025-2050)



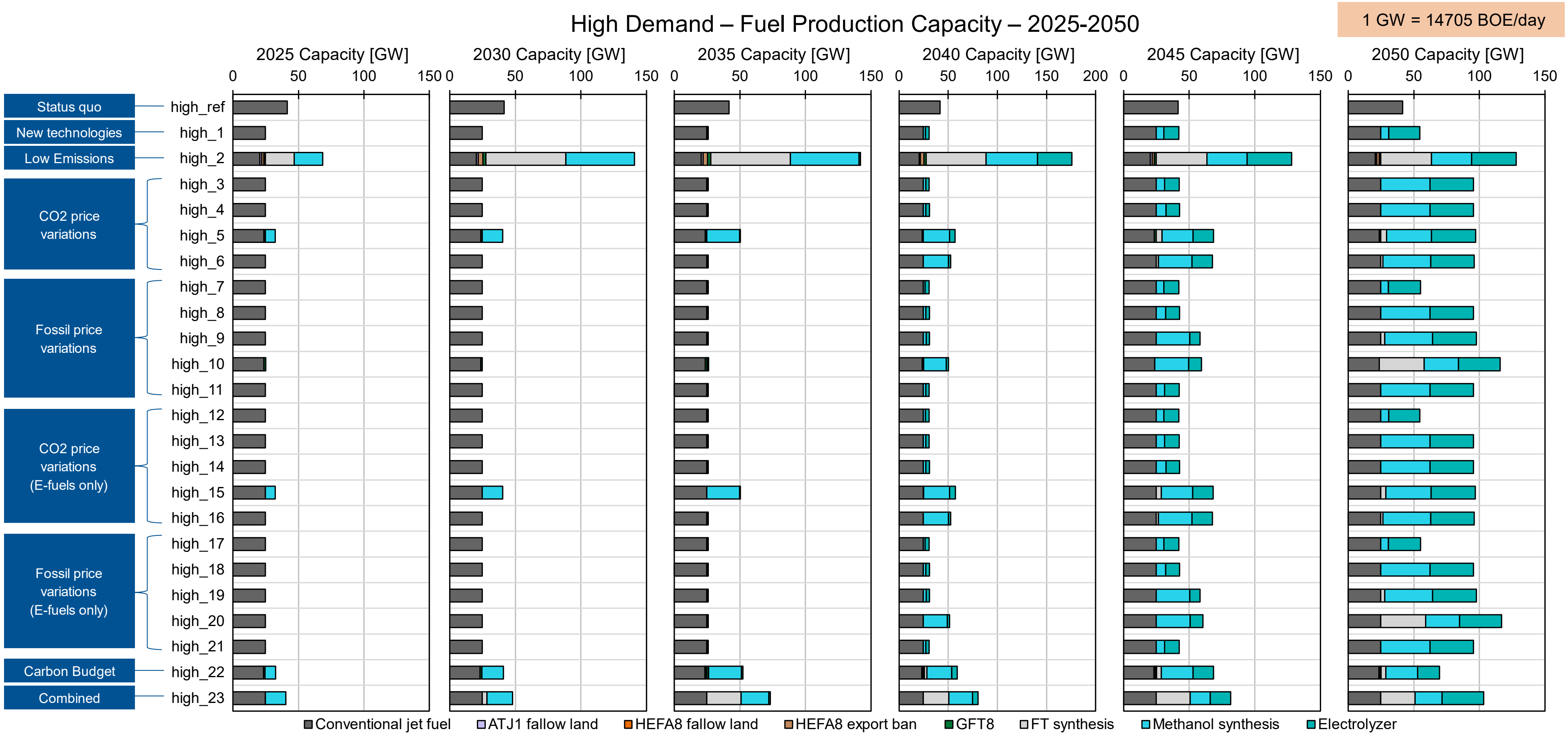
Appendix F-2: High demand - Primary energy mix, 2025-2050



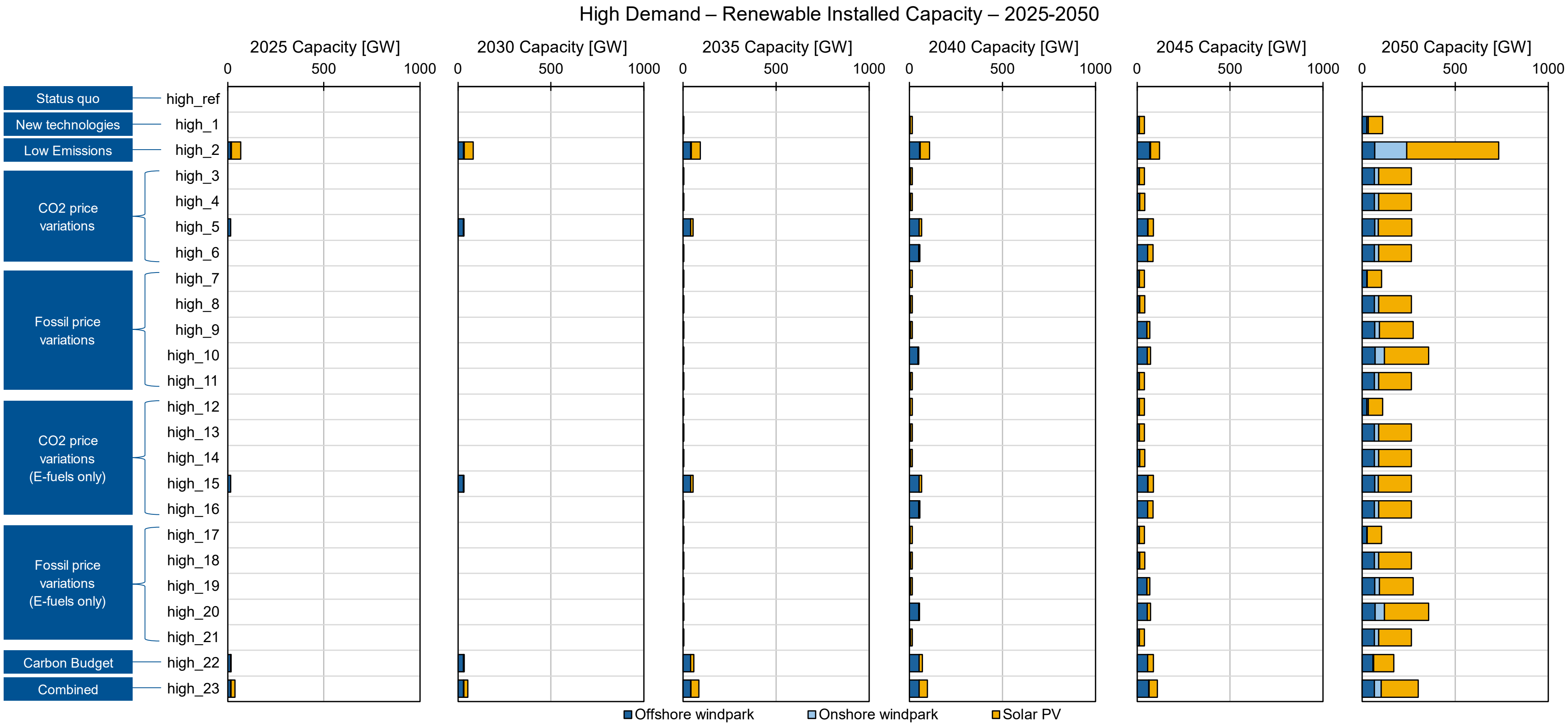
Appendix F-3: High demand - Breakdown of renewable electricity supply, 2025-2050



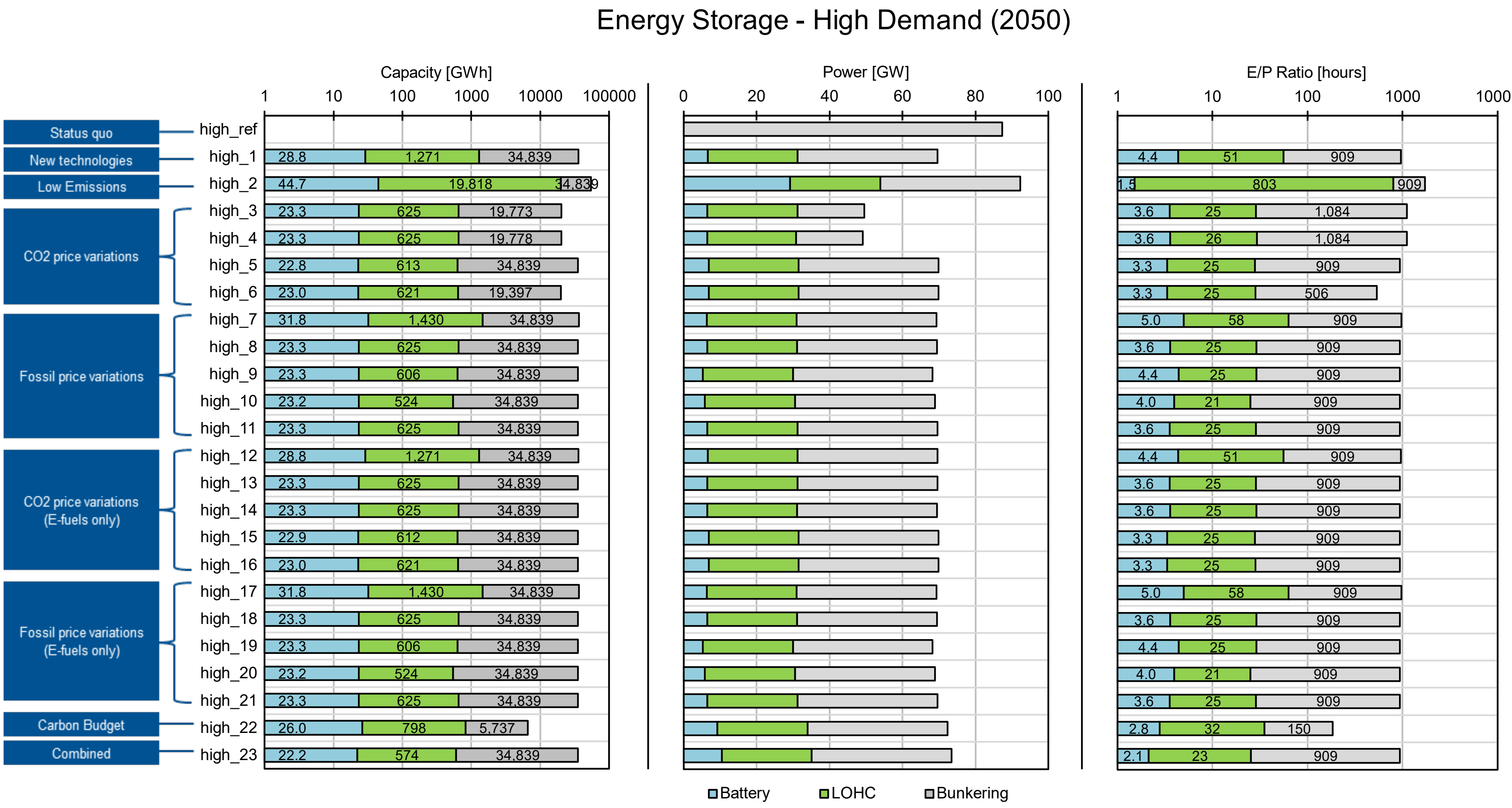
Appendix F-4: High demand - Timeline of SAF production capacities by technology at 5-yr intervals, 2025-2050



Appendix F-5: High demand - Timeline of solar PV, onshore- and offshore wind capacities at 5-yr intervals, 2025-2050



Appendix F-6: High demand - Storage parameters for 2050 in terms of capacity, power, and E/P ratio



Appendix F-7: High demand - Scenario-wise breakdown of co-products: diesel, naphtha, and oxygen, 2025-2050