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Exploring the market for Sustainable Aviation Fuel in Germany and Spain: Opportunities, Challenges, and Future Prospects

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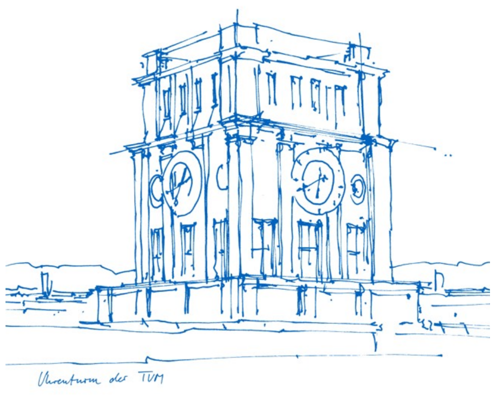

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Abstract

This thesis examines the potential of sustainable aviation fuels (SAF) in achieving net-zero emissions in aviation by 2050, focusing on Germany and Spain as emerging European production leaders. While SAF holds promise, challenges such as supply constraints and high production costs persist. Using Ridge regression, this study forecasts aviation energy demand under three scenarios, finding that Spain will require slightly more non-fossil kerosene than Germany from 2030 to 2050. Despite Spain's higher planned production capacity, both countries must expand production to meet domestic demand in the next decades. Each country has distinct feedstock resources: Spain benefits from agricultural strengths, while Germany emphasizes waste-based feedstocks. Spain's renewable resources offer a competitive advantage in Power-to-Liquid (PtL) technology, while Germany's established policies and PtL projects support further its development. All in all, although SAF production costs are expected to decline overall, significant economic investments and cooperative efforts between stakeholders are essential for both countries to meet rising aviation energy demands and lead in the global SAF market.

Keywords: aviation decarbonization; sustainable aviation fuels; aviation Germany; aviation Spain; policy analysis; jet fuel forecasting; feedstock availability; production costs

Contents

List of Figures

List of Tables

Abbreviations and Acronyms

ABtL: Advanced Biomass to Liquids
AtJ: Alcohols to Jet
CAGR: Compound Annual Growth Rate
CAPEX: Capital expenditures
CCS: Carbon Capture and Storage
CO_2: Carbon dioxide
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
CPI: Consumer Price Index
DAC: Direct Air Capture
DLR: Deutsches Zentrum für Luft- und Raumfahrt
DLUC: Direct Land-Use Change
ETS: Emission Trade System
FFA: Free Fat Acids
FT: Fischer–Tropsch process
FOG: Fats, Oils, and Greases
GDP: Gross Domestic Product
GHG: Greenhouse Gas
HEFA: Hydro-processed Esters and Fatty Acids
HRD: Hydrotreated Renewable Diesel
HVO: Hydrotreated Vegetable Oil
ICAO: International Civil Aviation Organization
ILUC: Indirect Land Use Change
INTA: Instituto Nacional de Técnica Aeroespacial
LASSO: Least Absolute Shrinkage and Selection Operator
LCA: Life Cycle Assessment
LTAG: Long-Term global Aspirational Goal
MSE: Mean Squared Error
OLS: Ordinary Least Squares
OPEX: Operational expenditures
PEM: Polymer Electrolyte Membrane
PtL: Power to Liquid
RPK: Revenue Passenger Kilometers
SAF: Sustainable Aviation Fuel
TRL: Technological Readiness Level
UCO: Used Cooking Oil
USD: US Dollar

1 Introduction

Climate change is one of the biggest challenges humankind has ever faced. The escalating emissions are projected to induce an average global temperature increase of 2.2 ºC by the year 2100, potentially precipitating the activation of numerous climate tipping points. This underscores the urgency of a rapid decarbonization across all sectors, including energy production, transportation systems, and industrial processes [7].

In this context, the aviation sector holds an elevated responsibility to significantly reduce its carbon footprint. Between 1990 and 2019, the world's commercial aviation CO_2 emissions increased by an average of 203% per year, due to the escalation of demand for jet fuel [8]. Consequently, aviation currently contributes more than 2.5% of global anthropogenic (human-caused) CO_2 emissions, what is equivalent to one billion tonnes of CO_2 being emitted into the atmosphere annually, and around 5% to global warming if non-CO_2 emissions are included [9][10][11]. Aviation is therefore the second largest source of GHG emissions in the transportation sector with 13.9%, following the land transport [12]. Moreover, the Cirium Fleet Forecast (2023) predicts the delivery of 46,260 new passenger and freighter jet and turboprop aircraft over the next 20 years, with the resulting risk of increasing the climate damage [13].

On the other hand, aviation provides the only rapid worldwide transportation network, being indispensable for tourism and facilitates world trade. Air transport moved around 4.5 billion passengers and 61 million tonnes of freight in 2019. It generated a total of 87.7 million jobs globally, and aviation's global economic impact was estimated at USD 3.5 trillion (including direct, indirect, induced and tourism catalytic) [14]. In 2022, the world fleet size was 28,674 aircraft, including 6,845 airplanes in Europe, of which 23,513 were actively operated by over 5,000 airlines [8].

CO_2 emissions of aviation are determined by three aspects: the transport volume, the (energy) efficiency of aircraft, and the type of energy carrier used [15]. In order to reduce aviation emissions and comply with the Paris Agreement, International Civil Aviation Organization (ICAO) Member States met at the 41st ICAO Assembly in October 2022 and adopted a goal of net-zero carbon emissions for international aviation by 2050 [16]. The approaches to reach the net-zero goal can be classified into the following categories: avoidance/shift to other modes of transport, technological innovation, aircraft operational efficiency and infrastructure improvements, and the use of alternative, less carbon intensive, fuels. Within these approaches, the use of alternative fuels represents the largest proportion, with an estimated contribution of 65%, to achieving the net-zero target by 2050 [10]. Hence, net zero CO_2 drop-in sustainable aviation fuels (SAF) would be the main decarbonization means for aviation until 2050.

However, the slow commercialization of SAF is primarily attributable to two connected factors: high costs and lack of policy support. Different factors influence the final costs of SAF production. Investments up to USD 5.3 trillion, in the 27-year period (2023-2050), in technological advancements, infrastructure developments, and operational improvements are required to enable a net zero transition of aviation by 2050 [17]. Policy can be designed to address the cost challenges specific to the SAF production pathway with greater climate mitigation potential. Only with a predictable policy framework, encompassing all aspects of regulation, can all industry stakeholders confidently invest these amounts with the necessary speed.

SAF supply is expected to account for 83% of the total fuel consumption by 2050 in Europe, abating 80% of emissions across the fuel's lifecycle, in comparison to traditional jet fuel [8]. Europe is a major player in the global aviation ecosystem, characterized by its extensive air traffic and robust aviation industry. Within this context, Germany and Spain stand out as two of the continent's aviation powerhouses. Germany, home to some of the busiest airports and leading aerospace manufacturers, plays a pivotal role in both passenger and cargo transport across Europe and beyond. Similarly, Spain, with its strategic geographic location and thriving tourism sector, sees substantial air traffic, making it a key aviation hub. SAF in these two countries is not only crucial for reducing aviation emissions but also sets a precedent for sustainable practices within the European aviation industry.

1.1 Former contributions and new insights

The study of SAF has garnered considerable attention over the past decade, as the aviation industry faces the dual challenge of reducing carbon emissions while supporting continued growth in air travel.

Many researchers have explored various aspects of SAF, focusing on feedstock availability, technological pathways, regulatory frameworks, and environmental impacts, such as Pechstein et al. (2018) [2]. For instance, studies by Watson et al. (2024) and López Gómez et al. (2023) have extensively examined SAF production methods such as Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), and Alcohol-to-Jet (ATJ). These works assess the technical feasibility and lifecycle emissions of each SAF type, analyzing their potential to reduce GHG emissions compared to conventional fossil fuels [18][19]. Similarly, Pavlenko et al. (2019) and Detsios et al. (2023) have focused on the costs associated with supporting alternative jet fuels within the European Union [20][21].

Research on feedstock availability, such as that by O'Malley et al. (2021), has largely centered on SAF production within the broader European Union context [22]. However, there remains a gap in studies specifically analyzing feedstock availability in countries like Germany and Spain, where factors such as agricultural practices, land use, and waste management are critical to the SAF supply chain.

Germany has made notable strides in Power-to-Liquid (PtL) technology, supported by significant economic investments. The country aims to become a European leader in PtL production through numerous R&D projects and large-scale initiatives in this field [23][24][25]. On the other hand, Spain's abundant solar and wind power resources, coupled with its strong agricultural sector, position it as a potential leader in SAF production, as supported by recent studies [26][27].

In addition, a prior research in the Netherlands has provided a valuable framework for studying its SAF market, particularly through a techno-economic assessment of how government policies and market mechanisms accelerate SAF adoption. This study projected the future of Dutch aviation through 2050 under three policy-driven scenarios, serving as a key inspiration for the present thesis [15].

This thesis addresses several gaps in the existing literature by providing a country-specific market analysis of SAF in Germany and Spain. It evaluates how national regulations and local aviation ecosystems are shaping the SAF market in these countries, offering deeper insights into how regional policies influence SAF adoption.

A novel contribution of this research is the development of an aviation energy demand prediction model using Ridge regression, which forecasts future aviation fuel demand. This model provides crucial insights into the long-term feasibility of SAF in Germany and Spain, particularly in determining whether the planned national SAF production capacities would be sufficient to meet future demand.

Additionally, by focusing on the availability of SAF feedstocks in both Germany and Spain, this study provides a country-level comparison. Unlike previous global or regional assessments, this research highlights the importance of local conditions in shaping SAF production potential in each country.

Finally, this thesis analyzes the economic feasibility and market readiness for SAF in Germany and Spain, taking into account factors like production costs, fuel pricing, and economic incentives. This practical focus aims to provide policymakers and industry stakeholders with actionable insights into the future of SAF adoption in both markets.

1.2 Structure of the thesis

Therefore, this study aims to conduct a quantitative and qualitative analysis to answer the following main research question:

What key factors make either Germany or Spain a more favorable environment for leading sustainable aviation fuel production in Europe?

To address the main research question, several sub-questions can be formulated, providing a more comprehensive understanding of the topic and contributing to filling the identified gaps in the existing literature.

1. To what extent will Germany and Spain have sufficient SAF production capacity to meet their aviation decarbonization goals by 2050?
2. Is it feasible for Germany and Spain to meet their SAF production targets relying solely on domestic feedstocks, or would imports be necessary?
3. What are the key cost drivers influencing the production of SAF in Germany and Spain, and how do these factors impact the feasibility of achieving competitive SAF prices by 2050?

This paper is structured as follows: First, the concept and framework of SAF are introduced within the context of the global aviation sector's decarbonization needs. Next, the technical aspects of SAF and the aerospace industries in Germany and Spain are examined. Following this, the research methods are explained in detail. The results are then presented and discussed in four sections: aviation energy demand forecasts, domestic SAF production capacity, domestic feedstock availability, and SAF production costs—comparing both Germany and Spain in each section. Finally, the paper concludes with a critical evaluation of the findings, addressing potential limitations and suggesting areas for future research.

2 Literature Review

2.1 Measures to Net-Zero Emissions in aviation

Reducing aviation emissions takes flight with the switch from a linear to a circular economy. Circular Economy stands out as a fundamental trend in promoting environmental sustainability, and therefore reducing GHG emissions. Distinct circular practices adopted in the aerospace industry can be identified through the six action areas of the Circular Economy's ReSOLVE framework (regenerate, share, optimize, loop, virtualize, exchange). The most relevant ones are the use of renewable energies and alternative fuels, changes in aircraft operations, and switching from traditional to ecological friendly materials. But many initiatives can be implemented such as the reuse of second-hand products, the collaboration and cooperation between sectors, waste management, infrastructure improvement, digitization and automation, reduction of aircraft mass, acquiring aviation technologies to improve efficiency of processes, etc [28].

Furthermore, sources of pollution in the commercial aviation supply chain can be differentiated into four stages of the aircraft life cycle: extracting and preparing the raw materials, aircraft manufacturing, flight operations, and end-of-services. All four create terrible environmental impacts, such as soil degradation, water acidification, biodiversity loss, damage to ecosystem functions, and worsening climate change [8].

Extracting and processing the raw material leave a large quantity of residual waste (e.g. rocks and mill tailings). Unwanted materials (e.g. dust or solid and liquid wastes) and chemical substances (e.g. hazardous gases and organic solvents) are discharged during manufacturing. Moreover, waste from end-of-service aircraft continues to increase globally. Between 2016 to 2022, for example, commercial passenger flights generated 5.2 million Tn of waste, costing USD 400 million annually, most of which went to landfills or incineration. Additionally, with an average lifetime of 25 to 28 years for passenger aircraft and 31 to 38 years for freighters, 15,534 commercial aircraft retired worldwide between 1980 and 2015. With the growing number of aircraft in service, over the next ten years, 11,000 more aircraft are expected to be retired, while about 90% of the weight content of retired aircraft will be reused or recycled. Each aircraft has more than 350,000 valuable components, such as engines and electronics. In 2017, the members of the Aircraft Fleet Recycling Association organization recycled 30,000 tons of aluminium, 1800 tons of alloys, 1000 tons of carbon fibre, and 600 tons of other rare materials [8].

However, not all aircrafts are recycled. Currently, there are about 6,000 aircraft stored at aircraft cemeteries worldwide, representing nearly a quarter of the total fleet of over 26,000 airliners in 2020 [29]. From a legal point of view, there is no obligation for aircraft recycling, and it is up to the owners' aircraft. The market for aircraft recycling is growing. The main drivers of this emerging market are the growth of the global commercial aircraft fleet, the prices increase of re-used aircraft parts and materials, the environmental political regulations for aircraft recycling and the technological options for recycling of aircraft composite parts and materials [29].

The use of composite materials in aeronautics affects the cost of development, in addition to consuming a large amount of energy in the manufacturing process. Hence, the recovery of these materials could provide a series of benefits. Nonetheless, while the use of composite materials in aircraft design offers various advantages, such as weight reduction and fuel efficiency, there are also challenges, including higher costs and potential complexities in repair and recycling. No satisfying technological recycling solution for composites material exists today, and thus its costs are unknown [29].

Comparing all sources of emissions reveals that 99.9% of environmental relevant emissions occur during the commercial operating phase of commercial aircraft [29]. In other words, both aircraft development and production and the decommissioning, disassembly and dismantling of aircraft result in a very low proportion of environmental impact compared with their operational phase. A large emphasis must be put in the operational phase. Accordingly, SAF now will be focused as the best solution to slow down this. It is estimated that SAF could contribute around 65% of the reduction in emissions needed by aviation to reach net-zero in 2050 [10]. The development and commercial deployment of SAF offers the most promising opportunity for reducing net GHG emissions from aviation operations.

SAF deliver a net reduction in CO_2 emissions across its life cycle. This is because the feedstocks that are used to produce SAF acquire the carbon from the atmosphere, via photosynthesis or carbon capture, and not out of petroleum that is sequestered in the ground [30]. The CO_2 life cycle of fossil fuels is linear, whereas the one of SAF mostly circular, depending on the production path [31].

More than 490,000 flights have already been made using blend of alternative fuels and more than 300 million litres were produced globally in 2022. Although, more than 449 billion litres are expected in 2050 [10]. Demand for SAF is growing even more rapidly, and it is foreseen to exceed the supply by 2027 [32].

The principal limiting factors of supply of SAF are the availability of feedstocks and the demand for fuel from non-aviation sectors. A wide range of feedstocks for bio-aviation fuel production is available with different economic potential and environmental benefits. In the short- to medium-term, low-cost, and high-yielding oil-rich feedstocks could be an effective transitionary solution. The negative environmental consequences of land-based crops, such as palm oil and jatropha, can limit their applicability, while the uncertainty and variability of waste streams such as used cooking oil (UCO) and municipal solid waste (MSW) can limit their contribution. The great potential of microalgae as a feedstock, due to its higher yield than oil-bearing crops, must still be proven economical in the long-term [33].

Besides, the best production process for producing SAF can depend on various factors, including feedstock availability, economic viability, and environmental considerations. Hence, there is some inconsistency among the existing literature. A recent study implemented a multi-criteria decision support framework that determined the importance order as: HEFA > direct sugar to hydrocarbon (DSHC)> fast pyrolysis (FP) > AtJ > gasification and FT Process [34].

Nonetheless, many studies, such as a report in 2022 from PwC [11], stand out three SAF conversion pathways. First, HEFA is currently the most mature technology and processes vegetable oils, waste, and residue lipids. It is commercially successful and a solution for the immediate, cost-effective implementation of SAF. Second, Advanced Biomass to Liquid (ABtL) transforms biomass and municipal solid waste into hydrocarbons (or alcohols) via a FT Process (or AtJ) synthesis. Its greatest advantage is the variety of biomass inputs that can be used. Lastly, PtL converts green hydrogen from electrolysis and green CO_2 into jet fuel with the FT synthesis. Green hydrogen, one major PtL component, can be produced in large quantities from wind and solar energy, especially in regions of the world with favourable renewable energy conditions. PtL holds the highest percentage of GHG emissions savings in comparison to fossil kerosene.

Similarly, SAF demand is subject to many challenges. In order to achieve the ramp-up of SAF, there is a need of commitment on the part of all the stakeholders, individuals, industry players, and policymakers. Increasing attention is on the role of policy to accelerate the commercial deployment of SAF. While the aim of policy measures worldwide is similar, the approach and configuration of such policy measures are different. In the European Union, ReFuelEU Aviation Initiative is expected to start in 2025 with a minimum volume of SAF at 2%. While in the United States, the Congress introduced the Sustainable Skies Act and new governmental policies aim to increase the production of SAF to at least 3 billion gallons per year by 2030 [35].

The main barrier to the large-scale implementation of SAF is its cost-effectiveness [34]. Several factors contribute to the current higher cost of SAF compared to conventional fossil jet fuel, including limited production scale, feedstock costs, and the complexities of the production process. Although ongoing developments and initiatives are aimed at reducing these costs and achieving price parity, those are not yet sufficient. Considering a situation when the estimated cost of the actual environmental damage caused by emitting one ton of CO_2 is taken as a basis, HEFA would reach cost parity with fossil-based jet fuel in 2027. Due to cost regression and initially high costs, ABtL and PtL will reach this break-even point much later, approximately in 2040 [11].

Last, it is important to mention that the aviation industry might witness a rebound effect, if SAF's benefits for the environment become so widely accepted that people increase the demand for air travel. This increased demand might offset some of the emissions reductions achieved using SAFs, and the overall net emissions impact would then increase [11][36].

2.2 Propulsion options substitutes to jet fossil fuels

As previously discussed, the complete decarbonization of aviation necessitates the use of net-zero CO_2 sources of energy and energy carriers. For the foreseeable future, the available propulsion technological options that serve as alternatives to fossil fuels can be divided into two categories: traditional turbine engine architectures, where fuel is combusted internally to power propulsion systems, and electric propulsion systems [15].

2.2.1 Classical turbine engine architecture

This is the established technology used in all currently operating commercial aircraft. There are essentially three alternative fuel options: biofuels, synthetic fuels, and hydrogen. Decarbonization pathways for turbine engines involve replacing fossil-based fuels with those that do not emit CO_2 throughout their entire life cycle. This transition may necessitate certain adjustments to engine technology to accommodate the specific properties of alternative fuels; however, such modifications can be readily implemented in state-of-the-art systems. Moreover, SAF, including both bio-based and synthetic fuels, can be utilized as "drop-in" replacements for conventional jet fuel. This means they can be used in existing engines without requiring modifications to engine design or other engineering components.

Bio-based fuels The climate neutrality of bio-based fuels is rooted in the fact that the CO_2 molecules released during combustion are originally captured from the atmosphere by the bio-feedstock during its growth. This contrasts with fossil fuels, where carbon atoms, and consequently CO_2, originate from subterranean sources. When ignoring possible emissions during the production and distribution phases, bio-based fuels can be considered to have net-zero CO_2 emissions across their life cycle. Various methods exist for producing bio-based fuels, with HEFA and technologies based on gasification and the FT process being highlighted.

Synthetic fuels Synthetic jet fuel, also known as e-fuels or PtL, can be produced from hydrogen—generated via electrolysis using renewable electricity—and a carbon source. The primary advantage of e-fuels is their independence from bio-based feedstocks, thereby avoiding limitations related to bio-feedstock availability. However, synthetic fuels have significant requirements for large quantities of green energy and a reliable source of CO_2. In advanced stages of decarbonization, conventional CO_2 sources such as flue gases will become scarce, necessitating reliance on CO_2 capture from the atmosphere through the direct air capture (DAC) process. Currently, DAC technology has not yet reached commercial maturity and demands considerable energy input. Therefore, the pathway for synthetic fuel production and scaling up is still constrained by many challenges.

Hydrogen Hydrogen can be produced from water via electrolysis using renewable electricity, with current efficiencies ranging from 59–82% [37]. While jet engines can burn hydrogen, its storage requires new aircraft designs to accommodate large storage tanks, and the lack of hydrogen infrastructure at airports presents further challenges. Hydrogen is expected to become a significant aviation energy source, but its low energy density limits its use to short-haul flights. Its broader application in commercial aviation is likely post-2040, contingent on the development of necessary infrastructure for hydrogen distribution and storage.

2.2.2 Electric engine architecture

An electric engine can generate mechanical energy to drive propulsion systems, offering significant benefits such as fuel and emissions savings and noise reduction. NO_x emissions, inherent to the high temperatures of burning fuels, are completely avoided with electrical designs. There are two potential onboard sources of electricity for this architecture: batteries and fuel cells.

Nonetheless, technical challenges associated with battery energy and power density remain yet. Therefore, even though electrification is commonly seen as a promising strategy for decarbonizing the road sector, the aviation sector will likely remain reliant on liquid fuels largely through 2050, particularly for long-haul flights.

Energy stored in onboard batteries The battery–electric aircraft concept is rapidly advancing. However, without a significant breakthrough in battery technology, electric aircraft will remain limited in their operational scope. This limitation arises primarily from the disparity in energy density: batteries have an energy density of 265 Wh/kg compared to 11,950 Wh/kg for jet fuel[38]. This 45-fold difference, even considering the higher efficiency of the battery–electric propulsion chain, constrains the large-scale deployment of battery–electric aircraft.

Electricity produced on board in fuel cells The low energy density of batteries can be complemented by generating electricity on board using fuel cells. This hybrid approach involves using fuel cells to produce electricity and batteries to provide additional power during peak demand moments, such as takeoff and go-arounds. However, this solution is constrained by the current limitations in hydrogen infrastructure. Additionally, fuel cells come with a significant weight penalty; current generation fuel cells weigh approximately 0.1 kg per kW of power [39]. For instance, a typical Boeing 737 or Airbus A320 requires around 10–15 MW for cruising, which would add roughly 10 Tn to the aircraft's weight just for the fuel cells. Considering that the empty weight of these aircraft is between 40 and 50 Tn, this weight increase poses a challenge [15]. Therefore, scaling up this technology for larger aircraft remains uncertain.

2.3 SAF Technologies

SAF are nearly chemically identical to conventional jet fuel, allowing them to be easily blended and making them a drop-in technology. Currently, SAF can be blended with traditional fossil jet fuel in ratios of up to 50%, as certified for use in aviation [11]. It has already been proven that modern aircraft components are capable of operating on 100% SAF. However, at present, blending limitations are not a critical issue due to the limited availability of SAF.

As of July 2023, 11 SAF production pathways have been certified as drop-in fuels by ASTM International, with 11 additional conversion processes under evaluation [40]. The standard regulating the technical certification of SAF is ASTM D7566. This standard specifies the technologies and conditions under which SAF can be produced to meet required specifications. In practice, SAF is first produced in a bio-refinery and can then be blended with conventional jet fuel, up to the maximum certified blending limit. After blending, the fuel is certified under the ASTM D1655 standard, at which point it is treated as conventional Jet A or Jet A1 kerosene [41]. In addition, in order to be eligible for use within the ICAO CORSIA, SAF must also meet a set of sustainability criteria. More information is available on the dedicated *CORSIA Eligible Fuels* website [42].

Besides, a variety of feedstock can be used to produce SAF. Under the CORSIA framework, such feedstocks are broadly categorized into five categories: primary, co-products, by-products, wastes, and residues. During this study, different types of feedstock are assessed. It has to be considered that under the CORSIA framework, by-products, wastes, and residues are entitled to an ILUC value of zero on the calculation of the Life cycle emission value of the SAF. Nevertheless, primary and co-products can also be entitled to zero ILUC value with the use of low LUC risk methodologies defined by ICAO [42].

After an exhaustive research, HEFA, ABtL-FT, ABtL-AtJ, and PtL are the identified leading technologies towards the targeted fuel transition of the aviation sector. For each of the technologies, multiple feedstocks are assessed. Table 1 shows all the possibilities under study during this thesis, which all have a blending ratio of 50% with conventional fuel and are approved by ASTM.

SAF Technology	**Feedstock**	**Yield**	**Feedstock Price**	**Life Cycle Emissions**
HEFA	FOGs = fat, oils and grease	0.83	$580/Tn	18.2
	soybean oil	0.83	$809/Tn	64.9
ABtL-FT	MSW = municipal solid waste	0.31	$30/Tn	32.5
	forest residues	0.18	$125/Tn	8.3
	agricultural residues	0.14	$110/Tn	7.7
ABtL-AtJ	corn ethanol	0.6	$0.41/L	90.8
	agricultural residues ethanol, stand alone	0.6	$0.41/L	39.7
	agricultural residues ethanol, integrated	0.6	$0.41/L	24.6
	isobutanol - low, corn	0.75	$0.89/L	77.9
	isobutanol - low, sugarcane	0.75	$0.89/L	33.1
	isobutanol - high, corn	0.75	$1.20/L	77.9
	isobutanol - high, sugarcane	0.75	$1.20/L	33.1
PtL-FT	DAC CO_2, green H_2, wind electricity	0.24	$300/Tn	7
	DAC CO_2, green H_2, solar electricity	0.24	$300/Tn	25
	DAC CO_2, green H_2, grid electricity	0.24	$300/Tn	279
	waste CO_2, green H_2, wind electricity	0.24	$300/Tn	31
	waste CO_2, green H_2, solar electricity	0.24	$300/Tn	49

Table 1: SAF technologies under study during this thesis

Table 1 presents estimates of yields (Tn SAF distillate/Tn feedstock), feedstock prices ($/Tn or $/L), and life cicle emissions (gCO_2e/MJ)[42], which are provided by the ICAO SAF Rules of Thumb [43]. This data was calculated based on US costs and financial assumptions, and exact values for prices and emissions will vary depending on regional factors and specific production conditions. However, these figures provide a valuable basis for qualitative comparisons between SAF technologies and feedstocks, even when analyzing the European context.

2.3.1 HEFA

The HEFA process is currently the most mature bio-jet fuel production pathway. It refines vegetable oils, waste, and residue lipids into SAF through a hydrogenation process. In the first step of the HEFA process, the oxygen is removed by hydrodeoxygenation. Next, the straight paraffinic [1] molecules are cracked and isomerized (transformed to a different structure or configuration, while retaining the same chemical composition) to produce a pure hydrocarbon fuel blending component (further information in Annex A). The HEFA process is similar to that used for Hydrotreated Renewable Diesel production (HRD), such as HVO, only with more severe cracking of the longer chain carbon molecules [44]. For this reason, most HRD refineries are increasingly being used to also produce HEFA.

HEFA was approved by ASTM for incorporation into ASTM D7566 (Annex 2) in June 2011, and can be blended to a level of up to 50% with fossil kerosene. With the HEFA process, it is possible to achieve emission savings of 74-84% compared with fossil-based jet fuel. However, the biological origin of HEFA imposes a natural limit on the available feedstock. To be classified as SAF and ensure official recognition of associated emission reductions, the feedstock must meet stringent sustainability standards, such as those outlined in the EU's updated Renewable Energy Directive (RED III). These standards are designed to prevent deforestation and avoid competition with food production [45].

No significant capital expenditure reductions can be expected for HEFA. Economies of scale and learning effects may help to reduce investment costs, but steeply rising prices for biogenic feedstocks have recently driven HEFA production costs to record levels. Many HEFA feedstocks are monocrops, reliant on fertilizers, that are vulnerable to climatic and geopolitical price shocks. This shows the sensitivity of HEFA production costs to market fluctuations.

Many HEFA feedstocks, such as palm oil and soy, compete directly with food crops for both agricultural land and water resources, reducing their overall sustainability. Furthermore, the actual origin of feedstocks like UCO is often obscured, leading to claims of sustainability without transparent verification [46]. In fact, it is estimated that in 2019,

[1] Paraffin is the common name for a group of alkane hydrocarbons with the general formula C_nH_{2n+2}, where n is the number of carbon atoms.

one-third of the UCO used in Europe's biofuel market was likely fraudulent [47]. It is important to note that the EU waste-based biodiesel association, EWABA, has "strongly rejected" these allegations, which were based on an unnamed source. While it is not the responsibility of the aviation industry to oversee the certification systems for biofuels, it is accountable for the sustainability of its feedstock supply chain. Moreover, a CE Delft study estimates that the global availability of UCO is limited to 3.3 MTn/year [48], which is far below the needs of the European aviation industry. Alternative non-food feedstocks that offer greater sustainability and potential for increased production, such as algae, are still in early development stages.

2.3.2 ABtL

ABtL processes refer to technologies that convert biomass feedstocks, such as agricultural residues, forestry waste, and other non-food organic materials, into liquid fuels. ABtL fuels are considered second-generation biofuels, as they utilize non-food biomass, addressing concerns about competition with food crops and land use. They offer significant potential for carbon emission reductions, especially in hard-to-decarbonize sectors like aviation and shipping. However, challenges such as high capital costs, feedstock collection, and process efficiency continue to limit their large-scale commercial deployment. Despite these hurdles, ABtL fuels are a promising pathway for achieving greater sustainability in the energy and transportation sectors.

In 2025, ABtL is expected to be 25% more expensive than HEFA, as it is not that mature yet. Due to the development of economies of scale, a more accelerated cost reduction is expected. This can reduce the price difference with HEFA by up to 7% until 2050 [11].

Two key technologies can be distinguished: AtJ pathway, and a gasification followed by a FT synthesis.

Alcohol-to-jet The AtJ pathway involves two distinct production phases: first, the feedstocks are converted into alcohol, which is then processed using the AtJ method to produce SAF. Multiple routes are available within this pathway, including direct fermentation of the feedstocks or conversion into syngas, followed by fermentation. Ethanol or butanol can serve as the intermediary alcohol, offering flexibility in feedstock selection, from cellulosic materials and MSW to syngas produced through PtL processes.

The relatively low value of the feedstocks results in a more balanced distribution of production costs between raw materials and infrastructure. The ethanol production technology is already well-established, supported by a global ethanol industry primarily catering to road vehicles. This reduces the technical risk for part of the process and offers the potential to utilize already produced ethanol or retrofit existing infrastructure, further lowering costs. Feedstock availability is broad, and the industry is unlikely to face significant supply constraints in the coming decades.

The AtJ pathway is highly efficient, with the ability to produce a high percentage of SAF, reaching up to 90% in some cases. The carbon reduction achieved through this technology varies based on the feedstock, with baseline CORSIA values ranging from 73% for forestry residues to 56% for corn grain. These reductions can be further improved by incorporating renewable energy and carbon capture and storage (CCS) technologies [49].

Fischer-Tropsch FT fuels are already produced from natural gas and coal reserves, with fully developed technologies for large-scale gas-to-liquid (GtL) and coal-to-liquid (CtL) processes that include necessary upgrading and refinement steps.

The FT synthesis requires a feed stream of hydrogen and carbon monoxide at a ratio of approximately 2:1, commonly referred to as synthesis gas (syngas). Instead of obtaining syngas through natural gas reforming or coal gasification, it can be derived from biomass gasification or from water electrolysis and CO_2 [23]. FT evolves via chain growth reactions. The resulting product contains a mixture of linear hydrocarbons which is not yet suitable as jet fuel. Further process steps, notably hydrocracking, isomerization, and distillation are necessary to produce finished fuels.

Despite its maturity, FT remains an expensive process, primarily due to its high capital costs and the complexity of the infrastructure required for gasification and subsequent catalytic conversion. The process also demands significant energy inputs, particularly in the gasification phase. This adds to both the operational costs and the carbon footprint if renewable energy is not used. Additionally, the efficiency of converting biomass into liquid fuels via FT is lower than other pathways, which can drive up costs. However, its ability to produce high-quality, drop-in liquid fuels suitable for aviation and heavy transport, as well as its flexibility in feedstock usage, continues to make FT an attractive but capital-intensive option for Sustainable Aviation Fuel (SAF) production.

2.3.3 PtL

A single common taxonomy, however, has not yet been established for this alternative jet fuel. The terms ‘PtL’, ‘powerfuel’, ‘e-fuels’, ‘e-kerosene’, ‘renewable fuels of non-biomass origin’, or simply ‘synthetic fuel’ are often used synonymously. PtL-based SAF production converts green hydrogen from electrolysis, and CO_2 from sustainable carbon sources, into jet fuel and other hydrocarbon products – either via FT synthesis, or methanol synthesis. The ASTM jet fuel standard already allows for a 50% blend of FT synthetic fuel. PtL via the methanol pathway, on the other hand, is not yet approved for civil aviation [23].

PtL production includes three fundamental steps. First, the production of hydrogen via water electrolysis employing renewable electricity, which is predominantly produced from solar and wind power. Second, the provision of renewable CO_2 and conversion into CO (where needed). Third, the production of liquid hydrocarbon and its conversion to jet fuel [23].

PtL reaches a technological readiness level (TRL) of 6 to 8 on a scale of 1 to 9, which is a high technology maturity. When it comes to the provision of renewable CO_2, concentrated streams from established industrial-scale processes can be utilized, with these methods reaching a high TRL of 9. To gain independence from these "point-sources" and enhance production potential, CO_2 can alternatively be extracted from the air, which is currently at TRL 6-8. For the production of renewable hydrogen, water electrolysis is employed. Low-temperature electrolysis methods, such as alkaline and polymer electrolyte membrane (PEM) electrolysis, offer high technological maturity (TRL 9), while high-temperature electrolysis, though less developed (TRL 7-8), can significantly improve process efficiency. The generation of renewable electricity is continuously scaling up, and hybrid solar-wind systems are achieving higher capacity factors. Additionally, the costs associated with renewable electricity generation have been decreasing steadily over recent years.

CO_2, being inert, can be stored in a liquefied form, with buffer storage considerations at the plant site similar to those for H_2, though CO_2 storage tends to be less costly. However, the transportation of CO_2 presents a logistical challenge that must be addressed individually for each PtL plant not co-located with a suitable CO_2 source. Additionally, renewable electricity from sources like solar and wind produces a fluctuating power profile, while continuous operation is preferable for efficient fuel synthesis. As a result, PtL plants are likely to incorporate H_2 storage to buffer short-term power fluctuations. Commonly used hydrogen storage methods include pressure vessels, storage pipes, and salt caverns. For longer-term storage, the decision to store hydrogen or design downstream conversion processes to handle load flexibility will depend on the techno-economic optimization of the plant. Nonetheless, the main uncertainties of PtL relate to future technological assumptions such as energy efficiencies of electrolysers, conversion steps or CO_2 air capture systems.

2.3.4 Technology related emissions

As it can be seen from Table 1, the environmental emissions are not directly linked to a SAF technology itself, but to the feedstock used to produce the jet fuel.

The environmental performance of HEFA and ABtL vary significantly depending on factors like feedstock production processes, regional conditions, land-use changes, crop yields, water availability, and climate. Both compete with agricultural resources and have land and water use implications. In contrast, PtL offers a near carbon-neutral pathway when CO_2, H_2O, and electricity are sourced from renewables, with cleaner combustion and lower toxicity compared to conventional kerosene. Unlike biomass-based pathways, PtL is more favorable in terms of land and water use, as it does not require arable land; the main area demand arises from renewable energy generation, where solar and wind installations use land more efficiently. As such, PtL has an advantage in resource efficiency, while HEFA and AtJ face challenges tied to feedstock availability and land competition.

ICAO has developed a methodology for calculating the life cycle emissions of a specific SAF, allowing operators to claim emission reductions under the CORSIA framework. The emission reductions are based on the life cycle emissions value of the SAF. This value consists of two main components: Core Life Cycle Assessment (LCA) emissions, which account for emissions from feedstock cultivation, processing, transportation, and fuel combustion, and Induced Land-Use Change (ILUC) emissions, which consider the greenhouse gases released due to land-use changes, both direct and indirect, caused by SAF production. Direct land-use change (DLUC) emissions are also factored in, and if DLUC emissions exceed the default ILUC value, they are used instead. The total life cycle emission value of a SAF is the sum of core LCA and ILUC emissions [50].

2.4 Aviation industry in Germany and Spain

Germany and Spain are both key players in the European Union, each contributing to the continent's economic and cultural diversity. Germany, situated in the heart of Europe, is bordered by nine countries, making it a pivotal economic and political hub. It boasts the largest economy in Europe and among the top five largest in the world, driven by its strengths in manufacturing, engineering, and exports. Germany is renowned for its automotive industry, with global giants like Volkswagen, BMW, and Mercedes-Benz, and its leadership in sectors such as machinery, chemicals, and renewable energy. The country's economic model is characterized by a strong emphasis on industrial production, technological innovation, and a highly skilled workforce.

Spain, located on the Iberian Peninsula, benefits from its strategic position as a gateway between Europe, Africa, and Latin America. With a diverse landscape that includes sunny coastlines, mountainous regions, and fertile plains, Spain is a popular destination for tourists, which significantly boosts its economy. The Spanish economy is the fourth largest in the Eurozone, with key sectors including tourism, automotive, agriculture, and services. Spain is also a leading producer of renewable energy, particularly wind and solar power. Its economy is characterized by a blend of traditional industries, such as agriculture and fishing, and modern sectors like aerospace and information technology.

2.4.1 Current state of aviation

The global aviation industry is currently experiencing a dynamic period marked by recovery and growth following the significant disruptions caused by the COVID-19 pandemic. Passenger traffic is rebounding, with airlines witnessing increased demand for both domestic and international travel. Regions like North America, Europe, and Asia-Pacific are seeing substantial recoveries, driven by a surge in leisure travel and a gradual return of business travel. North America remains the largest aviation market, with hubs such as Atlanta, Chicago, and Los Angeles seeing high volumes of air traffic. In Europe, major airports like London Heathrow, Paris Charles de Gaulle, and Frankfurt continue to be central nodes in international travel. Asia-Pacific, home to some of the busiest routes, including those through airports in Beijing, Tokyo, and Singapore, is also experiencing significant traffic, particularly with the rapid growth of air travel in China and Southeast Asia.

The United Kingdom was the State in Europe recording the highest average number of daily flights in 2023 (5,290/day), a 13% increase on 2022. The second busiest State in 2023 was Spain (4,616 flights/day, +9%), followed by Germany (4,532 flights/day, +7%). Compared to 2022: Germany and Spain have swapped places. Germany has recovered more slowly due to the weakness of internal flights (remaining stable in Germany at just +0.4% in 2023 vs 2022). Domestic flows in Germany are at 63% of 2019 levels, whereas Spain is at 100%. Air activity in Germany is still depressed compared to pre-COVID levels [51].

The distribution of air traffic is certainly not homogenous in either country, with 58% of the German flights occurring at the top 5 airports (Frankfurt/Main, Munich-Franz Josef Strauss, Berlin-Brandeburgo Willy Brandt, Hamburg, and Düsseldorf) and 51% in the case of Spain (Adolfo Suárez Madrid-Barajas, Josep Tarradellas Barcelona-El Prat, Palma de Mallorca, Málaga-Costa del Sol, and Alicante-Elche Miguel Hernández).

Spain is a world's top tourist destinations, known for its favorable climate, rich cultural heritage, beautiful beaches, and vibrant cities. Tourism is a crucial part of Spain's economy, and a significant portion of tourists arrive by air. Germany, while also a popular tourist destination, is more known for business travel, conferences, and trade fairs, which contribute differently to the GDP. Germany has a more diversified economy with significant contributions from industrial sectors, manufacturing, and technology, which are less dependent on air travel and tourism. Spain's geographical location and its islands (the Balearic and Canary Islands) make air travel essential for accessing many tourist spots. What is more, Spain has heavily invested in tourism infrastructure, including airports, hotels, and tourist facilities, making it more accessible and attractive to international tourists.

Consequently, 9.2% of the Spain's GDP in 2017 is supported by inputs to the air transport sector and foreign tourists arriving by air. Whereas, it is much lower for Germany, where it holds only a 2.5% of the country's GDP. The forecast trend for both countries is to increase by a 49% in the next 20 years [52][53].

The aviation in Germany is largely dominated by passenger traffic – in line with the global trends. In 2023, 197.19 Million passengers were counted at German airports, which is a 19.5% more passengers than in the same period in 2022. The German recovery rate is only 78.8% compared to 2019. Despite the positive trend, Germany remains at the lower end of the major European aviation markets. High ticket prices and high regulatory location costs are preventing a better recovery. Apart from passenger traffic, approx. 4.7 million tons of freight was transported in 2023 through flights originating from or terminating in Germany [54].

Spanish airports closed the year 2023 with a historical record of 283.2 Million passengers, 16.2% more than in 2022 and 2.9% more than in 2019, before the pandemic. The Adolfo Suárez Madrid-Barajas Airport registered the highest number of passengers in 2023, followed by Josep Tarradellas Barcelona-El Prat and Palma de Mallorca. In 2023, airports operated 2,403,918 aircraft movements and 1,079,676 tons of cargo were transported across the network [55].

2.4.2 Aviation related emissions

As mention in Section 1, the ground of this study is the significant GHG emissions coming from the aviation sector. When discussing aviation-related emissions, it is important to distinguish between different types of GHG and their effects, as well as between CO_2 and non-CO_2 emissions. Aviation emissions impact the climate not only through CO_2

emissions but also through various non-CO_2 factors such as water vapor, nitrogen oxides (NO_x), and contrails, which can have a significant warming effect and are also detrimental to human health. The uncertainty of the warming effect of non-CO_2 emissions is large. NO_x and water vapor emissions are inherent in the technology of the jet engine where fuel is burnt [56].

In terms of CO_2 emissions, EUROCONTROL reports publicly the CO_2 emissions released by their partner countries. As of its data on their website, Germany has reduced its aviation CO_2 emissions by a 10.2% in September 2024, compared to same month in 2019. Whereas, Spain has suffered an increase of 1.2% comparing September 2024 and 2019. This different behaviour is related to the development of air traffic of both countries, above explained in Section 2.4.1.

Emissions from German-administered aircraft operators totaled approximately 7.2 million tonnes of CO_2 equivalent ($MTCO_2e$) in 2022. However, these emissions remained below pre-COVID-19 pandemic levels, reaching about three-quarters of 2019 emissions [23]. In contrast, Spain's aviation fuel consumption in 2019 amounted to 6.9 million Tn, resulting in 22.3 $MTCO_2e$. Of this, 3.2 million Tn came from domestic flights within Spain, while 19.1 $MTCO_2e$ was attributed to international flights. According to ETS credits redeemed by Spanish airlines in 2019, intra-EU flights contributed 5.5 $MTCO_2e$ to the total emissions [27].

2.4.3 Future demand for air travel

Between 2010 and 2019, air travel grew by slightly more than 5% per year. During the unprecedented shock due to the COVID-19 pandemic, air travel collapsed and is expected to reach 2019 demand levels again by around 2025. Assuming a return to a continued growth path of around 3% on average per year after 2025 results in an air travel demand which is slightly more than twice as high in 2050 as in 2019 [57]. As the European market is already mature, air travel growth is expected to grow at a slower pace in the EU compared to the global average [58].

However, there are two factors that would probably reduce demand for travel with respect to the autonomous demand growth trend. The first factor is behavioral, namely, the long-term shift in business practices related to the COVID-19 pandemic. Businesses are now used to teleconferences as a substitute for physical meetings, as well as a more broad population awareness of the environmental impact of aviation. The second factor is purely economical, as the higher ticket prices due to the use of more expensive aviation fuels will reduce demand for air travel [15]. Many organizations argue that achieving

Net Zero Emissions by 2050 intrinsically requires a significant reduction in air transport activity.

Growing air travel demand does not directly translate into a fuel demand growth with the same pace, as aircraft fleets and operational procedures have continuously become more fuel-efficient. Regarding operational procedures, improved air traffic management (such as more direct routing of aircraft, less air space congestion, electric taxiing, etc.) and higher seat load factors could lead to a long-term fuel burn reduction of up to 10%. With respect to aircraft fuel burn, historical trends of efficiency improvements are expected to continue [59], but at a slightly lower pace of slightly below 1% per year. This would result in a relative, fleet-wide fuel burn reduction of around 20% in the next 30 years if evolutionary technologies are considered [23].

2.4.4 Regulation

Achieving net zero emissions by 2050 in the aviation sector will necessitate strong policy support to incentivize and facilitate the widespread adoption of greener technologies and fuels, as decarbonization will likely incur significant additional costs [60]. Policy can be split into three levels: international policy, European policy and domestic policy. A serious complicating factor for national and European aviation policy is the fact that aviation operates on a global scale. If policy is applied at national or European levels, there will be leakages to other jurisdictions [61].

2.4.4.1 International policy The Paris Climate Agreement outlines the responsibility for addressing the climate impact of international aviation, delegated to the ICAO. In response, the ICAO adopted in 2016 the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to address this challenge. CORSIA is the first global market-based measure, that offers a harmonized way to reduce emissions from international aviation, minimizing market distortion, while respecting the special circumstances and respective capabilities of ICAO Member States. [62].

The 41st ICAO Assembly adopted a long-term global aspirational goal (LTAG). The LTAG does not attribute specific obligations or commitments to individual States. Instead, it recognizes that each State contributes to the LTAG within its own national circumstances and capabilities. Most European states (such as Germany and Spain) are members of the ICAO, and therefore, LTAG agreements apply to their national aviation sector.

2.4.4.2 European policy In 2021, the EU proposed an ambitious climate policy package in the form of the FitFor55 program. For aviation, it includes three major components: the ReFuelEU Aviation initiative that mandates the share and type of SAFs in jet fuel; the participation of aviation in the EU Emission Trade System (EU ETS) with no free emission permits for intra-EU flights; and the inclusion of jet fuel into the EU Energy Taxation Directive (ETD) [2]. The obligations under ReFuelEU require a 63% share of SAFs in 2050 (Table 2); the EU ETD may establish a tax of EUR 0.37 per liter of fossil jet fuel; and the EU ETS may add EUR 0.24 per liter at the permit prices of EUR 90 per metric ton of CO_2 (July 2023)[15].

Once fully implemented, these policy measures together will have a strong impact on fuel costs and, thus, transportation unit costs, making flying passengers and freight substantially more expensive than without these policies. Moreover, ReFuelEU initiative sets a clear policy signal for the introduction and expansion of an advanced-only SAF industry producing ultra-low carbon fuels. This shift to exclusively CO_2-free energy carriers will result in a 15% reduction in the number of passengers in 2050 compared to the market development [15].

Besides, the Renewable Energy Directive (RED) is the legal framework for the development of clean energy across all sectors of the EU economy, supporting cooperation between EU countries towards this goal. Both RED II and RED III are driving the aviation industry to prioritize SAF production and adoption. In particular, the 2018 RED II restricts the use of food crops as energy sources for transport. Consequently, only feedstocks that do not compete with food production or that are byproducts or waste from food production chains are considered viable long-term sources for the production of aviation biofuels [60]. RED III, an updated version of the directive, has a more specific focus on aviation. It accelerates the aviation industry's transition towards SAF and other renewable energy sources, making them essential for airlines to meet emissions reduction targets in line with the European Union's climate goals [63].

2.4.4.3 Domestic policy The implementation of EU FitFor55, along with the introduction of CORSIA, together creates a framework where individual member states (such as Germany and Spain) can develop their own tailored aviation fuel policies.

SAF can be produced from a variety of renewable feedstocks and renewable energy sources. Such flexibility provides opportunities to the individual countries to develop their own and more suitable SAF policies, which could feed SAF value-chains and generate opportunities to their industries and citizens. But before implementing SAF policies, each country should first develop a coherent national SAF strategy.

German Policy The 2019 German Climate Action Program 2030 outlines programs and measures to support R&D as well as financial incentives for the market adoption of carbon-neutral e-fuels in aviation. In line with the national implementation of the EU RED II, Germany has committed to a blending quota for PtL kerosene, starting in 2026 with a 0.5% PtL blend, and 3% by 2030, based on the total kerosene volumes sold in the country. Furthermore, Germany's National Hydrogen Strategy reinforces the promotion of hydrogen derivatives, such as PtL, for aviation. In 2021, the Federal Government, together with German states, the aviation and petroleum industries, and plant manufacturers, developed the *PtL Roadmap for Aviation*, a coordinated plan to facilitate the market ramp-up of sustainable aviation fuels produced from renewable energy sources [24].

Spanish policy In 2019, the Spanish government introduced two legislative frameworks that included a SAF mandate for aviation fuel suppliers. The first is the 2021-2030 *Integrated Plan for Energy and Climate*, submitted to the EU, which emphasizes the importance of SAF, particularly the development of advanced biofuels. The second is the *Spanish Climate Change Law*, approved in 2021, which empowers the government to set annual renewable energy targets specifically for the aviation sector, with a focus on advanced biofuels and renewable fuels of non-biological origin. To further support these initiatives, a public-private platform called *Bioqueroseno* was established in 2011 to foster collaboration across the SAF value chain, setting a roadmap for SAF deployment and R&D projects like ITAKA. Although the platform's website is no longer actively maintained, it still offers valuable references. Additionally, the Spanish Centres of Excellence, promoted by the Civil Aviation Authority (AESA), have identified SAF deployment as a key element in aviation decarbonization. The creation of the Green Hydrogen for Aviation Alliance further highlights Spain's commitment, bringing together stakeholders from government, airports, airlines, fuel producers, and hydrogen logistics. This alliance promotes the production and adoption of e-fuels, supporting projects with roadmaps, working groups, and access to funding mechanisms.

2.4.5 Targets

The EU is at the forefront of global efforts to decarbonize the aviation sector, with SAF playing a central role in achieving its climate targets. Under the European Green Deal and the FitFor55 package, the EU has set ambitious goals to reduce GHG emissions by at least 55% by 2030, with a clear focus on transitioning the aviation industry towards cleaner energy sources. In line with these broader objectives, the ReFuelEU Aviation mandates a gradual increase in SAF usage by airlines, aiming for a 2% SAF by 2025, rising to 6% by 2030, and 70% by 2050. The proposal also includes a sub-obligation of

0.7% blending for PtL fuels from 2030, gradually increasing to 35% in 2050 (Table 2) [63].

At the national level, countries like Germany and Spain have established specific frameworks and targets to support the development and adoption of SAF. Table 2 shows a comparative about the established target shares in the EU, Germany, and Spain, from 2025 to 2050.

	SAF-EU	**PtL-EU**	**SAF-Germany**	**PtL-Germany**	**SAF-Spain**
2025	2%	0%	2%	0.5%	2.6%
2030	6%	0.7%	10%	3%	4.6%
2035	20%	5%	30%	20%	
2050	70%	35%	100%	50%	100%

Table 2: SAF and PtL mandatory shares in the EU, Germany, and Spain

In Germany, the Aviation Initiative for Renewable Energy in Germany (*aireg*) has set itself the following ambitious SAF utilization targets in order to establish the country as the leading SAF market, specifically produced by PtL technology [24]. Apparently, Germany has more ambitious targets than the EU and Spain, putting a special focus on PtL.

On the other hand, Spain's airports, operated by Aena, have set ambitious goals under their *Climate Action Plan*, which aims to incorporate 0.6% SAF in fuel supplies by 2022, increasing to 2.6% by 2025 and 4.6% by 2030 [61]. However, these targets are contingent on the issuance of European or national regulations mandating SAF production and usage percentages, indicating that Aena's commitment may align closely with regulatory requirements. Additionally, Aena has pledged to achieve net-zero emissions by 2040, a full decade ahead of the Destination 2050 initiative's target [61]. In partnership with Avikor, Aena also offers passengers the option to contribute to SAF costs, allowing climate-conscious travelers to offset the fuel consumption per passenger for their flights, helping meet future compliance requirements like ReFuelEU Aviation. Nonetheless, Spain does not have any specific requirements in terms of PtL yet.

2.4.5.1 Penalties for non-quota compliance Penalties for non-quota compliance in net zero emissions within aviation policies are designed to enforce adherence to emission reduction targets and encourage industry players to invest in greener technologies. These penalties may include fines, restrictions on flight operations, or increased fees and taxes for non-compliant aviation stakeholders. Additionally, non-compliance could lead to limitations on market access or restrictions on landing rights at certain airports, particularly those in regions with strict environmental regulations. Such penalties not only serve as a obstacle but also aim to ensure that stakeholders committed to reducing their carbon footprint are not at a competitive disadvantage compared to those that do not prioritize emissions reduction.

If penalties continue to be included in the investment decision as a kind of "negative incentive", they must reach an effective level. Otherwise, it is to be expected that penalties will be preferred as an economically more favorable option to investing in PtL plants. The current german penalty for non-compliance with the PtL quota of approx. EUR 3,000 per tonne represents precisely this [25].

On the other hand, many respondents in a UK governmental consultation stated that it is not necessary to introduce any additional penalties if a well-designed buy-out mechanism is implemented. In their view, the buy-out mechanism will already provide a safety net should SAF supply fall short of the obligation and further penalties risk being passed onto the consumer or incentivising imports over domestic SAF [64].

2.4.5.2 SAF Accounting Once SAF is integrated into the jet fuel supply chain and becomes interchangeable with conventional jet fuel, it's crucial to establish a robust accounting mechanism. This will enable airlines to accurately track and claim the environmental benefits of their SAF purchases in relation to their various decarbonization commitments. Additionally, such an accounting system allows for the decoupling of environmental claims from the physical movement of the fuel, which is essential for scaling up SAF. This type of SAF accounting should also enable aircraft operators and their customers to jointly address their shared emissions responsibilities, while preventing double counting and double claiming of emissions reductions through transparent and reliable registry systems.

Moreover, transparent differentiation of SAF based on feedstocks, technologies, and GHG intensity would be possible, creating clear supply and demand signals for different types of SAF. This way, SAF stakeholders could better understand and respond to the market's preferences for more environmentally friendly options. A system called "book and claim" supports this process by allowing to report the use of SAF based on purchase records, rather than the physical use of SAF in the aircraft. This method can help increase the production and use of SAF because it simplifies tracking and claiming the environmental benefits. The CORSIA already recognizes and supports this approach [65].

2.4.6 The aviation ecosystem

Achieving meaningful decarbonization in the aviation industry cannot be accomplished by a single stakeholder group alone. Instead, its complex roadblocks to decarbonization require collaboration across all industry stakeholders (airlines, fuel producers, energy generators, airports and fuel distributors, lessors and investors, and regulators and policy-makers) to be effectively addressed [65]. Each group facing distinct challenges and opportunities.

Both Germany and Spain are in an excellent position to provide technological support for the development of a greener aviation and to play an active role in shaping it worldwide. Both host a robust mix of private and public stakeholders that significantly contribute to the global aerospace and aviation sectors.

2.4.6.1 German aviation ecosystem Germany is not only one of the largest aviation market in Europe, the center of European aviation research (e.g. DLR) and a hotspot for aircraft production. The country also has large and systemically relevant refinery capacities for its own fuel supply and an internationally leading industrial base in important production areas such as chemicals, energy and plant engineering.

Germany is one of the world's leading aviation and aerospace nations. Almost three quarters of the German aerospace value created (73%) is exported. Around 17% of global aircraft production comes from this country. Germany has the third-largest aerospace and defense market in Europe, with 2022 revenues at EUR 39 billion, following UK and France. Overall, Germany's aerospace industry accounts for more than 100,000 industry employees working in more than 200 companies and related institutions [66].

In addition, Germany also has a very well-developed research infrastructure. The pace of innovation in the sector is faster than ever before, with autonomous flight and electric aviation making major advances. The aviation industry is one of Germany's most innovative industry sectors, a 7% (EUR 3 Bn) of annual revenue were spent on R&D in 2022 [66].

In Germany, entities such as Airbus Deutschland GmbH, MTU Aero Engines AG, and OHB SE play crucial roles in aerospace technology and innovation. Lufthansa, as the country's flagship airline, dominates both passenger and cargo transport. Frankfurt and Munich airports, managed by Fraport AG and Flughafen München GmbH respectively, are critical hubs in global air travel. German fuel producers, such as Shell Deutschland GmbH, are actively involved in the development of cleaner aviation fuels. The BDLI (Bundesverband der Deutschen Luft- und Raumfahrtindustrie), Germany's aerospace industries association, represents the interests of the national aerospace sector. Public organizations like DLR (Deutsches Zentrum für Luft- und Raumfahrt) in Germany are instrumental in driving research and development, ensuring these countries remain at the forefront of aerospace advancements and sustainable aviation.

2.4.6.2 Spanish aviation ecosystem Spain's expertise in the aviation and aerospace sectors has grown over the last decade (24% since 2012)[67], making it one of today's world leaders in many fields, including composite materials for aircraft structures, low-pressure turbines, air traffic management systems and military transport aircraft.

Spain ranks 5th in Europe in volume of sales and number of people employed. In 2022, the Spanish market saw EUR 12.34 billion in turnover and over 51,000 direct people employed. The industry is characterized by its significant investment in R&D, which accounts for 10% of the industry's sales [67].

The aerospace and defense industry is a strategic sector for the Spanish economy, since it creates high-quality employment, accounts for almost 1.3% of total Spanish GDP and 9.3% of the Spanish Industrial Production Index, and is key for the foreign sector. In 2022, 49% of sales in the aeronautics sector and 75% in the space sector were from exports [67].

In Spain, companies like Airbus España SL, Indra SA, and SENER Aeroespacial SA are key players in aircraft manufacturing and aerospace engineering, while national carriers such as Iberia and Vueling lead in air transport. Major airports like Madrid-Barajas and Barcelona-El Prat are managed by AENA, Spain's leading airport operator, which oversees airport infrastructure and air traffic management. Industry association TEDAE (Asociación Española de Tecnologías de Defensa, Aeronáutica y Espacio) represents the interests of the Spanish aerospace, defense, and security sectors. Fuel producers like Repsol are pioneering efforts in developing sustainable aviation fuels. Similarly to Germany, the public organism INTA (Instituto Nacional de Técnica Aeroespacial) drives research and development.

2.4.7 Sustainable energy in Germany and Spain

Renewable energy, biofuel production for other industries, and land usage in a country are deeply interconnected and vital for the development of SAF and a greener aviation industry. Renewable energy sources like wind, solar, and hydropower provide the necessary clean electricity to produce SAF, especially in power-intensive processes such as the creation of electro-fuels and hydrogen-based fuels, ensuring that the fuel production itself has a low carbon footprint. Meanwhile, established biofuel production for other industries bring valuable experience in feedstock sourcing, processing technologies, and supply chain management, which can be leveraged to scale up SAF production. The existing infrastructure can often be adapted or expanded to accommodate SAF production, reducing the need for new investments and speeding up deployment. Additionally, the workforce trained in biofuel technologies provides a ready pool of skilled professionals who can transition to SAF production. Thus, having a mature biofuel industry provides a strong foundation upon which SAF production can be built, accelerating efforts towards sustainable aviation [68].

Sustainable land usage practices are essential to balance the cultivation of biofuel crops with food production and biodiversity conservation, avoiding issues like deforestation and habitat loss, which would undermine the environmental benefits of SAF.

2.4.7.1 Renewable energy production Renewable energy production plays a critical role in the global effort to reduce GHG emissions and mitigate climate change. As two of Europe's leading economies, both Germany and Spain have made significant strides in the adoption of renewable energy sources, such as wind, solar, and biomass, which now constitute substantial portions of their national energy mixes. These efforts not only help in reducing overall carbon emissions but also provide a foundation for transforming sectors traditionally reliant on fossil fuels, such as aviation, by supporting the development of sustainable aviation fuels and electrification of airport operations. As both countries continue to innovate and expand their renewable energy capabilities, they set examples of how transitioning to cleaner energy sources can support broader sustainability goals and reduce the carbon footprint of industries beyond the energy sector.

Germany, known for its ambitious *Energiewende* policy, has rapidly expanded its renewable energy capacity, becoming a leader in Europe in solar PV, wind energy and biomass [69], and aiming to phase out coal by 2038 [70]. Figure 1 shows graphically the net installed electricity generation capacity in Germany in 2023, which data is extracted from [71]. On the other hand, Spain, with its abundant solar and wind resources, has also made impressive gains, particularly in concentrated solar power, making it a key player in the European renewable energy landscape [69]. With the strong growth of solar PV in Spain, it has almost caught up with combined cycle in installed MWs and will soon become the second largest generation source by installed capacity [72]. Both countries generated a record of more than half of its electricity from renewable sources in 2023 [73]. Figure 1 shows in green the renewable sources of energy, and in browm the non-renewables.

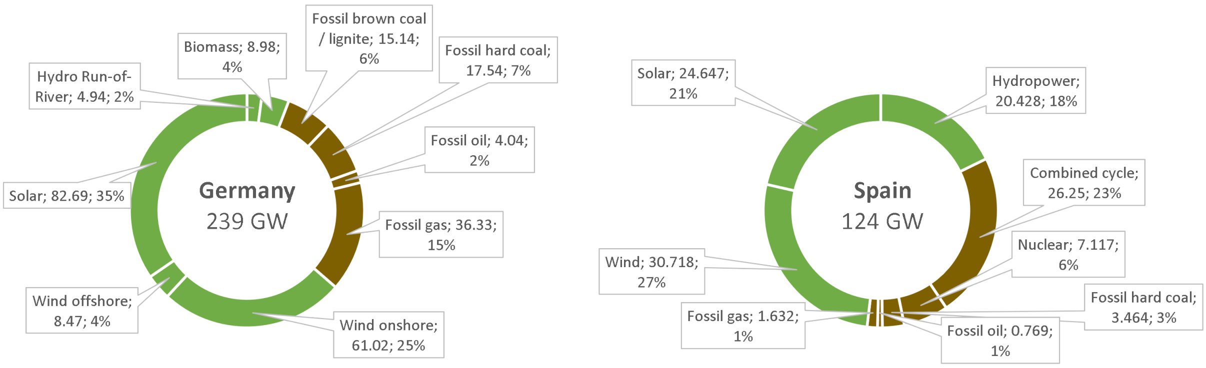

Figure 1: Net installed electricity generation capacity in Germany and in Spain in 2023

2.4.7.2 Biofuels production Germany leads Europe in biofuel production, with an emphasis on both bioethanol and biodiesel. It has focused on diversifying its feedstock to include agricultural products like corn, wheat, and rapeseed, alongside the use of waste materials. Biodiesel being primarily based on rapeseed oil, one of the most commonly cultivated crops in the country [74]. Germany's robust agricultural industry, strong infrastructure, and supportive government policies have all contributed to a thriving biofuel sector.

Germany produces around 800,000 Tn of bioethanol annually, largely used as a blending component with gasoline for road transport. Bioethanol is derived from fermenting sugars found in crops like corn and wheat. In addition, biodiesel remains a key biofuel produced from rapeseed and used cooking oils. The country's biodiesel industry is the largest in Europe, producing over 3 million Tn per year [74] (accounting for nearly 25% of the total European production [75]). Germany's biofuel sector benefits from strong governmental support, tax incentives, and European Union regulations such as RED II.

Spain has a strong biofuel industry, focusing primarily on biodiesel, while bioethanol production is smaller but growing. Spain's feedstock is more diverse compared to Germany, as the country uses used cooking oil, animal fats, sunflower oil, and wheat for its biofuel production. Spain has a favorable climate for cultivating biofuel feedstocks such as sunflower, rapeseed, and maize [76]. Spain produces around 450,000 Tn of bioethanol annually, primarily derived from grains like wheat and corn. Spain is also a major producer of biodiesel, with annual production levels exceeding 1.5 million Tn [77].

Spain's proximity to Mediterranean countries allows for easier access to a variety of feedstocks, especially waste oils and fats, aligning with the EU's push for a circular economy and the use of waste-derived energy. Governmental policies, including blending mandates and the promotion of renewable fuels, have spurred biofuel production, making Spain one of the leading producers in Southern Europe [75][78].

3 Methodology

3.1 Ridge regression for aviation energy demand prediction

3.1.1 The regression model

Initially, several macroindicators were considered as potential predictors for the model. However, after conducting stationarity tests using the Augmented Dickey-Fuller (ADF) method, some datasets were excluded to ensure the time series suitability for further analysis (Annex B.1 and B.2).

Following this, a multicollinearity test is conducted on the remaining variables. As shown in the cross-correlation matrices in Section 4.1.1, many predictors are highly correlated, making ordinary least squares (OLS) regression unsuitable due to its tendency to produce unstable coefficient estimates. To address this, Ridge and LASSO regression models are considered. However, LASSO was ultimately discarded due to its tendency to exclude certain variables, which could lead to a loss of valuable information. A Granger causality test was also performed on the selected predictors, and based on the results, some variables are lagged in the model (Annex B.3). For Germany, *GDP per capita* and *international tourism expenditures* are lagged by 1 time frame, while *fuel efficiency* is lagged by 2. For Spain, *international tourism expenditures* is lagged by 1 time frame, while *fuel efficiency* is lagged by 2.

A Ridge Regression is chosen as it effectively addresses multicollinearity by applying an L2 regularization penalty, which shrinks the coefficients of correlated predictors toward zero but ensures all variables remain in the model. This reduces overfitting while stabilizing coefficient estimates, especially in cases where the number of predictors exceeds the number of observations. The regularization parameter α controls the degree of shrinkage: when $\alpha = 0$, Ridge reduces to OLS, and as α increases, the coefficients are further penalized [79].

LASSO (Least Absolute Shrinkage and Selection Operator) regression, which applies an L1 penalty, is also initially proved. Unlike Ridge, LASSO zeros out some coefficients, effectively performing variable selection [79]. This can simplify the model and reduce redundancy by eliminating less important predictors. However, due to the risk of excluding potentially important variables, LASSO is not selected for the final forecasting model (see Annex C for details).

3.1.2 Aviation energy consumption historical data

The historical Spanish aviation energy data is retrieved from [80] and the German data from [81] (using the conversion factor of 1 Tn=$29.3076 \cdot 10^9$ J, as stating in the data source article). The time period considered for the analysis is from 2004 (due to Germany's data availability) to 2019 (due to COVID-19). The sector has returned in 2023 to the pre-pandemic levels, for this reason the historical data until 2019 can be used to predict the future behaviour of aviation. Figure 2 shows that historically the aviation energy consumed in Germany is higher than in Spain. Nonetheless, the Spanish aviation energy consumed has suffered a faster increase in the last decade, surpassing the German levels in 2019.

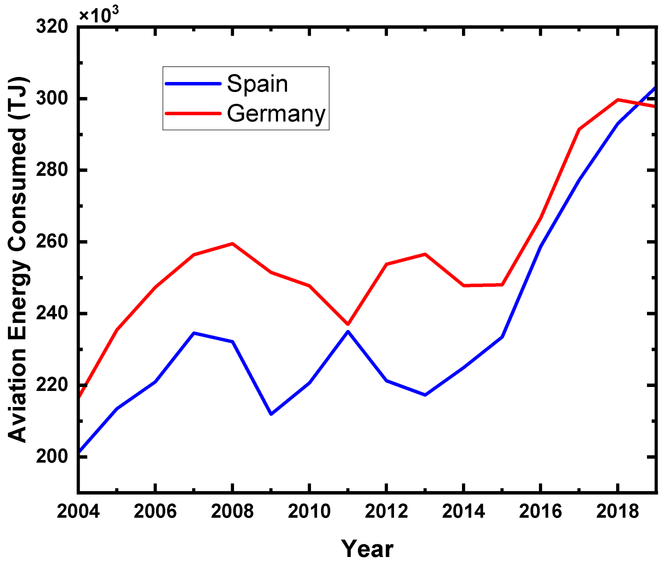

Figure 2: Aviation energy consumed from 2004 to 2019 in Germany and Spain

The faster growth of Spanish aviation is evident when analyzing the Compound Annual Growth Rate (CAGR) for the period from 2004 to 2019. Using the formula $CAGR = (\frac{x_f}{x_i})^{1/n} - 1$, where x_f is the final value, x_i is the initial value, and n is the number of years, it is found that aviation fuel consumption in Spain, which includes aviation fuel, jet fuel, and aviation gasoline, has grown at a CAGR of 2.77%. In 2019, the aviation fuel consumption reached nearly 10.4 million Tn. In comparison, Germany's aviation fuel consumption increased at a CAGR of 2.15%, with 2019 consumption standing at approximately 10.2 million Tn. This certainly indicates a more robust growth trajectory for Spain's aviation sector relative to Germany's.

3.1.3 Data mining process

The aviation energy demand forecast is based on a range of technical and macroeconomic variables. Key factors influencing global air travel demand include disposable income, population growth, economic and business activity, global trade dynamics, airline networks, deregulation, and the cost of air travel. The data mining process employed in the present study includes the following steps:

1. **Identification** of relevant techno-economic **macro-indicators**
2. **Data Collection**: Historical data for most macro-indicators is sourced from the *DataBank World Bank* for the period from 1999 to 2019. *Fuel Efficiency* is computed as described in Section 4.1.1.
3. **Data Preprocessing**: This step involves cleaning the data by addressing missing values, outliers, and anomalies, followed by the preparation of the collected datasets. Datasets with corruption issues are excluded, while valid datasets are indexed to 2010 levels, where the value for 2010 is set to 100, and subsequent and preceding values are scaled accordingly.
4. **Exploratory Data Analysis** (EDA): A cross-correlation analysis is conducted between the predictor variables and the target variable.
5. **Feature Selection and Engineering**: After selecting the predictor variables, a causality test is performed to identify some lagged variables.
6. **Model Selection**: Ridge Regression Analysis is chosen to predict aviation energy demand. While Ridge regression effectively addresses multicollinearity, it has limitations, including the assumption of linear relationships between features and energy demand. This may not fully capture complex, non-linear interactions. Furthermore, the model's predictive capability could be constrained by unforeseen disruptions in the aviation industry.
7. **Model Training and Evaluation**: The regularization parameter α was optimized using 5-fold cross-validation. The final model was evaluated on a holdout test set, with R-squared and mean squared error (MSE) used to assess performance.
8. **Forecasting** of the aviation energy demand: Various CAGRs are considered for the predictor variables under three extreme scenarios. Using the regression equation, aviation energy demand is projected from 2025 to 2050.

9. **Deployment**: The predicted aviation energy demand across the three scenarios is employed for various evaluations, such as comparing the volumes of SAF required against production capacity and available feedstock.

All data analysis for this thesis has been conducted using *Python*, leveraging its powerful data science techniques to manage, analyze, and model the data effectively. The primary library used for data manipulation and analysis is *Pandas*, which facilitates efficient data handling and processing of large datasets. For numerical computations, *NumPy* is utilized, providing support for mathematical functions and array operations. Visualization and plotting of data were achieved through *Matplotlib* and *Seaborn*, which enabled the creation of insightful and publication-quality visualizations. Machine learning models, including Ridge and LASSO regression, are implemented using *scikit-learn*, a comprehensive library that offers various tools for predictive modeling, model evaluation, and cross-validation. These *Python* libraries collectively provided a robust and flexible framework for carrying out all stages of the analysis, from data preprocessing to model development and validation.

3.2 Configuration of scenarios

To develop the aviation energy demand forecast curves, three future scenarios are constructed, each representing different potential pathways for aviation growth and energy consumption. These scenarios are designed to capture a range of possible outcomes based on varying assumptions about economic growth, technological advancements, regulatory environments, and consumer behavior. The same set of scenarios is applied to both Spain and Germany, given the similarities between these countries in terms of economic structure, aviation infrastructure, and energy consumption patterns. Table 3 shows the annual growth (%) considered for the predictors in order to elaborate the three scenarios.

CAGR (%)	Regulatory (S1)	Balanced (S2)	Economic Boom (S3)
GDP per capita	Average of last 4 years	1.5	3.0
Air passengers	-2.0	Average of last 2 years	2.0
Air carrier departures	-2.0	Average of last 2 years	2.0
International Tourism Exp.	-0.5	1.0	3.0
CPI	1.0	2.0	3.0
Fuel Efficiency	2.5	3.0	4.5

Table 3: Annual growth (%) considered for the predictor variables in order to develop the three scenarios

S1) Regulatory Impact scenario In this scenario, stricter regulations are imposed on the aviation industry, leading to higher air travel prices and a subsequent decline in the number of air transport passengers and freight. Adjustments for this scenario include a negative growth rate in *air transport passengers* and *carrier departures*, estimated at a 2% annual decrease. The increased costs within the aviation sector may moderately contribute to overall inflation, affecting the *CPI*, which is expected to rise by 1% annually. *International tourism expenditures* may also decline or see minimal growth, with an annual growth rate of 0-1%, due to higher travel costs and potential restrictions. Similarly, *GDP per capita* growth is expected to stay constant as the average of the years 2016-2019. Despite these regulatory pressures, technological improvements will continue to drive *fuel efficiency*, with a projected annual increase of 2.5%.

S2) Balanced scenario In this scenario, heightened environmental awareness influences consumer behavior and travel choices are evaluated, leading to stable air transport demand and moderate changes in international tourism expenditures. *Air transport passengers* and *carrier departures* are expected to experience no growth, maintaining the mean values of the last two years 2018 and 2019, as consumers opt for more sustainable travel options. *CPI* may see slight increases of 2% annually due to the adoption of environmentally friendly practices and products. *International tourism expenditures* are likely to grow slowly, at a rate of 1-2% annually, as travelers choose destinations closer to home or accessible by sustainable means of transportation. Regardless of these shifts, *fuel efficiency* is expected to continue improving, with a projected annual increase of 3%, driven by ongoing technological advancements.

S3) Economic Boom scenario This scenario assumes a period of economic prosperity, leading to higher disposable incomes and increased demand for air travel for both leisure and business purposes. Even with regulatory measures pushing for reduced air travel, the booming economy results in consumers being willing to pay higher prices and carbon taxes, leading to a 2% annual increase in *air transport passengers* and *carrier departures*. Economic growth is expected to drive up the *CPI* due to increased demand across various sectors, with an annual increase of 3%. *International tourism expenditures* are anticipated to grow significantly, fueled by increased disposable incomes and government investments in tourism infrastructure, with a high annual growth rate of 3%. Fuel efficiency is projected to improve rapidly under this scenario, with a high annual increase of 4-5% due to accelerated technological advancements.

4 Results and discussion

4.1 Forecasting aviation energy demand

By understanding future energy needs, Germany and Spain can better align their SAF production capacities, attract investments, and implement effective policies. This foresight not only reveals potential market sizes and competitive advantages but also guides each country's efforts in becoming a dominant player in the global SAF sector.

In the literature, many global aviation energy demand forecasts can be found. However, to get a better understanding of the dynamics and trends at play and to be able to compare reliably two countries, a forecasting model is developed. Historical data of the aviation energy demand and of various macroeconomic indicators are analysed, modelled, and used to forecast the aviation energy demand for the period from 2025 to 2050, with the help of statistical methods and machine learning techniques.

4.1.1 Predicting variables

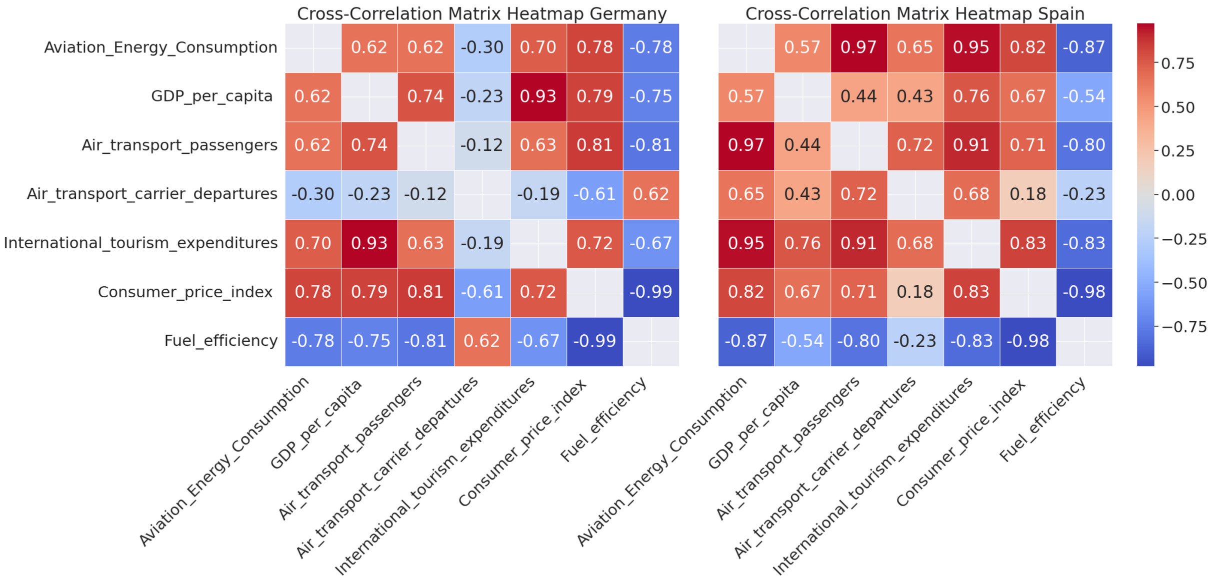

Figure 3: Cross-correlation matrices between the predicted variable and the predictors

After exploring several macroindicators datasets (Annex B), the next six are used as predictors of the aviation energy demand. They all are stationary variables and present clean and complete datasets. Figure 3 shows the cross-correlations matrices between the chosen predictors and the dependent variable. Most of the independent variables present a correlation (Pearson Correlation Coefficient) higher than 0.55 with the *aviation energy* *consumption*, for both Germany and Spain.

Several macroindicators, such as *air pollution* and *fossil fuel energy consumption*, were excluded from the prediction model due to the presence of missing values in their datasets. Additionally, *population growth* was omitted because it is non-stationary.

While incorporating a diverse set of features is typically advantageous, having too many variables—even those with low cross-correlation—can introduce noise into the model. Therefore, careful feature selection and the application of regularization techniques is essential to manage this issue. Including an excessive number of variables can lead to overfitting, particularly in cases where the dataset is small.

GDP per capita As countries and regions become wealthier and more connected to the global economy, the demand for air travel increases. Rising income per capita leads to increasing trips or revenue passenger kilometers per capita: consumers have more disposable income to spend on travel and growing employment and business activity leads to increasing travel. There are many indicators representing the economy capacity of a country. However, *GDP per capita* provides a comprehensive, and readily available metric, making it a preferred choice over *GDP growth* or *disposable income per capita* in modeling and forecasting air travel demand.

The relationship between real GDP per capita and air travel demand can be effectively represented by an S-curve, illustrating how air travel demand evolves with increasing national income. Initially, as countries transition from low to middle-income status, there is a sharp rise in revenue passenger kilometers (RPKs). This phase is marked by a steep slope on the S-curve, reflecting the rapid growth in air travel demand as economies develop and integrate into the global market. However, as economies reach higher levels of income and the transportation sector becomes more mature, the rate of growth in air travel demand moderates, leading to a tapering of the curve. At this point, the demand for air travel increases at a diminishing rate, as basic travel needs are met, and growth is driven more by population and incremental income gains rather than economic development [82].

IATA/ICAO claims that the transition point where the demand elasticity settles down lies at USD 20,000 per capita [82]. Both Germany's and Spain's GDP per capita are higher than this benchmark, the reaction of their aviation demand to a GDP per capita change is expected to be moderate in nature. German GDP per capita in 2019 was USD 47,000, while the Spanish one was USD 30,000. What means that German aviation demand, behaves more moderately to a GDP per capita change than the Spanish. Historically, the GDP per capita in Germany has risen at an average rate of approx. 2%, 2004-2019. GDP per capita in Spain, however, has risen at a 1% in that time frame.

Fuel efficiency The relationship between *fuel efficiency* and *aviation energy consumption* is inverse; as fuel efficiency improves, aviation energy demand decreases for a given level of air travel (Figure 3).

Enhanced fuel efficiency allows aircraft to travel more distance using the same amount or even less fuel, thereby reducing the overall energy consumption required for aviation operations. This can be achieved through technological advancements, such as the development of more aerodynamic aircraft designs, lighter materials, and more efficient engines, as well as operational improvements like optimized flight paths and load management. While increased fuel efficiency can help offset the rise in energy demand driven by growing air travel, especially in expanding markets, the overall impact on aviation energy demand also depends on the rate of air travel growth, technological adoption, and regulatory frameworks. Thus, continuous improvements in fuel efficiency are critical for managing and potentially reducing the environmental footprint of the aviation sector, even as global air travel demand continues to rise.

It has been observed that the overall fuel combustion rate in the airline industry has been on a downward trend since 1960, with a CAGR of -1% recorded between 1960 and 2014 [83], indicating a positive improvement in fuel efficiency. For the forecast model, it is assumed that these long-term historical trends will continue and are applicable to both the German and Spanish markets. Therefore, a curve fitting technique is employed to develop a numerical equation based on long-term data and to project the existing trends through 2050. Power curves, derived from ICAO metric values, were found to provide the best fit, with an R^2 value of 0.951. This power curve equation is then used to forecast fuel consumption over the prediction period (Eq. 4.1).

$$Fuel\_Consumption = (2 \cdot 10^{79}) \cdot x^{-23.47}, \tag{4.1}$$

where x is the year in the range of 1960 to 2050, and fuel consumption obtained is based in ICAO Metric Value – indexed to 1968 = 100. The extrapolated fuel consumption is re-indexed to 2010 = 100 for an easier assessment in relation to aviation energy demand. As this calculated fuel consumption decreases, the fuel efficiency increases.

Consumer Price Index CPI is a measure of inflation and reflects the overall cost of goods and services in an economy. When the CPI is high, it often indicates a period of economic growth, where there is increased spending and higher demand for goods and services. Economic growth typically leads to higher air travel demand for both business and leisure purposes, thus increasing aviation energy consumption.

Correlation does not imply causation. The relationship between aviation energy consumption and CPI may be influenced by other underlying factors such as technological advancements, government policies, and global economic conditions. Nonetheless, indeed there is a high correlation between them in the datasets (Figure 3). Furthermore, the CAGR of the CPI in Germany and in Spain are 1.3% and 1.6% respectively, 2004-2019.

Using the Aviation Consumer Price Index (AvCPI) would be more appropriate than the generic CPI for predicting aviation energy demand, since it specifically captures the changes in prices directly relevant to the aviation industry, such as airfare costs, fuel prices, and related services. This specificity allows for more accurate forecasting and better understanding of how changes in aviation-related costs impact energy consumption in the aviation sector. However, due to data collection issues and the risk of multicollinearity issues during the prediction.

International tourism expenditure By definition from its respective data source, international tourism expenditures are expenditures of international outbound visitors in other countries. The goods and services are purchased by, or on behalf of, the traveller or provided, without a *quid pro quo*, for the traveller to use or give away. These may include expenditures by residents traveling abroad as same-day visitors, except in cases where these are so important as to justify a separate classification. Excluded is the international carriage of travellers, which is covered in passenger travel items.

International tourism expenditure, influenced by purchasing power, directly correlates with *aviation energy consumption* in both Spain and Germany, also presenting a leading power over it. In Spain, this correlation is more evident with the *air transport passenger* due to the country's significant tourism industry. In Germany, the correlation spans both passenger and business travel, reflecting the country's balanced travel patterns and strong economic activities. Furthermore, the behavior of *international tourism expenditure* closely mirrors that of GDP per capita. These two variables are highly correlated in both countries, which could lead to multicollinearity issues in the model.

Air transport Air transport refers to the movement of passengers and cargo by aircrafts across various distances, ranging from short domestic flights to long-haul international routes. In this regard, three indicators are initially explored:

- **Air transport, registered carrier departures worldwide**: Registered carrier departures worldwide are domestic takeoffs and takeoffs abroad of air carriers registered in the country.
- **Air transport, passengers carried**: Air passengers carried include both domestic and international aircraft passengers of air carriers registered in the country.

- **Air transport, freight** (million ton-km): Air freight is the volume of freight, express, and diplomatic bags carried on each flight stage (operation of an aircraft from takeoff to its next landing), measured in metric tons times kilometers traveled.

Observing their cross-correlations (Annex B.2), the differences between the correlations with aviation energy consumption and the types of air transport (freight vs. passengers) in Spain and Germany can be explained by examining the specific economic, geographical, and industrial characteristics of each country.

Spain has a significant export-oriented economy, which rely on air freight for rapid transportation to international markets. Spain's geographical position makes it a strategic hub for air freight between Europe, Africa, and America. This makes its aviation energy consumption more closely tied to the volume of freight transport than for Germany. On the other hand, Germany is a major business and financial hub in Europe, with international hub airports that facilitate significant intercontinental travel. The constant and high volume of passenger traffic leads to a strong correlation between passenger numbers and aviation energy consumption.

Seasonality in aviation Figure 4 represents the monthly historical air traffic in Germany and Spain (2010-2019), where air traffic is quantified as the total number of aircraft movements (number of flights). The raw data is extracted from the *Eurocontrol Data Bank* [84], and shows clear seasonality for both countries. The pattern reflects the typical travel behaviours influenced by holidays, and favourable weather conditions (increases during the warmer months and quenches during the colder months).

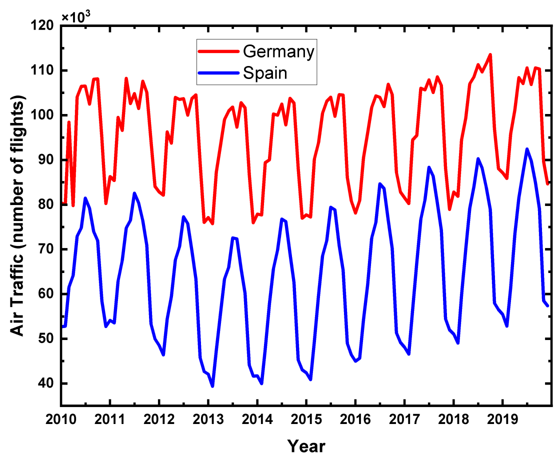

Figure 4: Monthly air traffic in Germany and in Spain, 2010-2019

However, seasonality is more notable for Spain, which has every year a clear peak in July. The increment in Germany from the lowest value to the highest was 24% in

2019, while in Spain was 43%. The larger increase in Spain could be attributed to its popularity as a summer tourist destination, attracting more international and domestic travellers during the summer months. In contrast, Germany, while also experiencing seasonal variations, may have a more evenly distributed air travel pattern throughout the year due to its higher proportion of business travel that is less affected by seasonality. Furthermore, the more seasonal variability for Spain's passenger air transport can strengthen the correlation between *air transport variables* and *aviation energy consumption* (Annex B.2).

This seasonality pattern is assumed to be proportional to the monthly aviation energy consumption. However, due to the lack of data of energy consumption in a monthly basis, it cannot be directly proved. But, with the previous assumption, the seasonality trend of the air traffic data 2010-2019 could be used to transform the annual predicted energy consumption to a monthly forecast.

Lastly, it is important to note that, although aviation energy consumption in 2019 was higher in Spain than in Germany (Figure 2), Germany had a larger volume of air traffic compared to Spain. This discrepancy suggests that the energy efficiency of air traffic in Germany may be higher, or that other factors, such as the average flight distance, aircraft types, or operational practices, might differ significantly between the two countries.

4.1.2 Ridge regression analysis

Based on the nature of the data and objectives, the Ridge regression is chosen as forecasting model. Before, several forecasting models are exhaustively considered, such as, ARIMA, classic regressions with multiple variables, and a LASSO regression.

The results of the Ridge regression model are presented in Tables 4 and 5. Overall, the regression coefficients illustrate that while both countries exhibit similar patterns in how certain factors influence aviation energy demand, the magnitudes of these effects differ considerably. An increase in any predictor, has a higher impact in the aviation energy demand in Spain than in Germany. *Fuel efficiency* is the only variable with negative coefficients for both countries, indicating that improvements in fuel efficiency are associated with lower aviation energy demand.

For both Germany and Spain, the optimal alpha value identified was 10.0, indicating that the same level of regularization was suitable for both countries. An alpha value that is too low could lead to overfitting, while an excessively high alpha would risk underfitting by overly constraining the model's coefficients. In this case, an alpha of 10.0 represents moderate regularization, suggesting that the model strikes a good balance

	Germany	**Spain**
Intercept	102.28 ± 2.13	99.65 ± 1.71
GDP per capita	0.670 ± 0.207	0.880 ± 0.402
Air transport passengers	0.941 ± 0.219	2.869 ± 0.454
Air transport carrier departures	0.319 ± 0.254	1.183 ± 0.097
International Tourism Expenditures	1.392 ± 0.427	2.188 ± 0.547
CPI	0.833 ± 0.249	1.784 ± 0.161
Fuel Efficiency	-0.798 ± 0.271	-1.841 ± 0.174

Table 4: Intercept and coefficients, with their standard errors, of the Ridge regressions

between controlling complexity and preserving predictive accuracy.

	Germany	**Spain**
Best Alpha	10.0	10.0
Training MSE	15.23	12.43
Test MSE	19.82	12.35
Training R-Square	0.5639	0.8657
Test R-Square	0.5898	0.9493

Table 5: Statistical analysis of the Ridge regressions

Spain exhibits a lower training MSE than Germany, indicating a better fit to the training data. Lower MSE values imply that the model's predictions align more closely with the actual values in the training set. Similarly, the test MSE, which reflects the model's ability to generalize to new data, shows that Spain outperforms Germany with a significantly lower error on the test set.

The R^2 values for Spain are particularly high, suggesting that the model explains most of the variance in the data. In comparison, Germany's R^2 values are lower, though still within an acceptable range. This indicates that the chosen alpha value of 10 effectively balances model complexity and predictive performance for both countries, with especially strong results for Spain.

The statistical results are visually illustrated in Figure 5. The model's predictive capability for 2019 shows some deviation from the observed values; however, this discrepancy falls within the range of the standard errors. Notably, the Ridge regression model significantly outperforms the actual aviation energy consumption data for Germany from 2010 to 2016. The model's fit for Spain also reveals limitations, particularly in the earlier years of the training dataset, where it does not align well with the observed data.

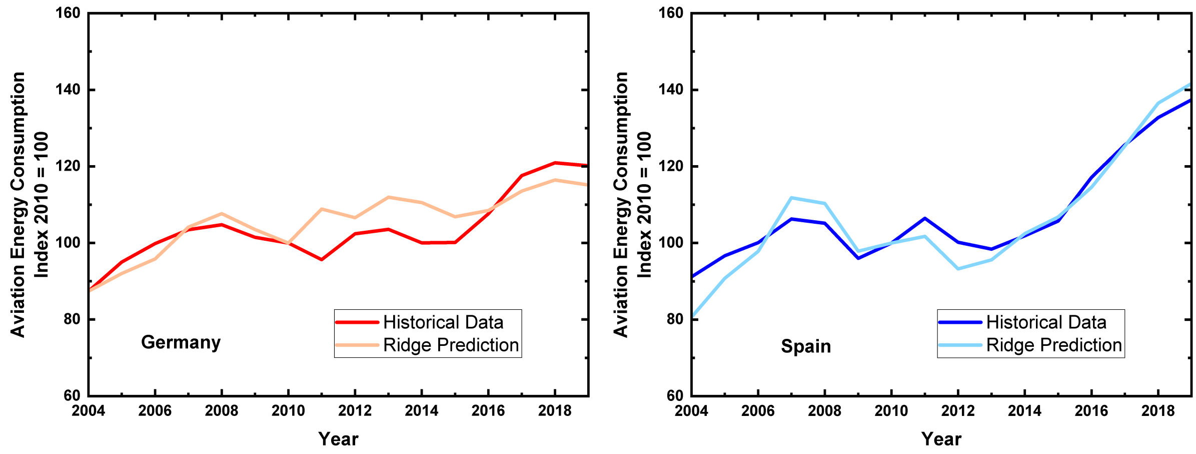

Figure 5: Comparison between the aviation energy consumed historical data and the predicted values from the Ridge Regression Analysis

Part of the error in the regression model arises from the use of non-lagged predictor variables, since the Granger causality analysis does not indicate the need to lag all the variables. Thus, it is assumed that the current values of the non-lagged variables are sufficiently close to their expected values. Moreover, both regression equations are significantly influenced by the variables *air transport passengers* and *international tourism expenditures*. The correlation between these two variables is notably high, suggesting that this strong correlation may contribute to inaccuracies in the model's predictions.

4.1.3 Future aviation demand curves

Using the parameters outlined in Table 3 for the different scenarios and de-indexing from the base year 2010, the aviation energy demand for Germany and Spain is projected for the period from 2025 to 2050 (Figure 6). The forecast indicates that, by 2050, both countries are expected to exhibit similar ranges of aviation energy demand, [500, 200]$\cdot 10^3$ TJ. The actual aviation energy consumed will depend on the actual growth behaviour of the external macroindicators.

Despite this similar range in 2050, the trajectory of energy demand throughout the forecast period differs between the two countries. Over the 25-year timeline, Germany's aviation energy demand is projected to stabilize around 300$\cdot 10^3$ TJ in the balanced scenario, while Spain is forecasted to maintain a slightly higher demand, averaging around 350$\cdot 10^3$ TJ. This suggests that Spain would potentially consume higher aviation energy than Germany over the next 25 years. These differences reflect different growth rates and demand patterns in aviation-related activities, driven by factors such as differences in economic growth, tourism, and air transport infrastructure development.

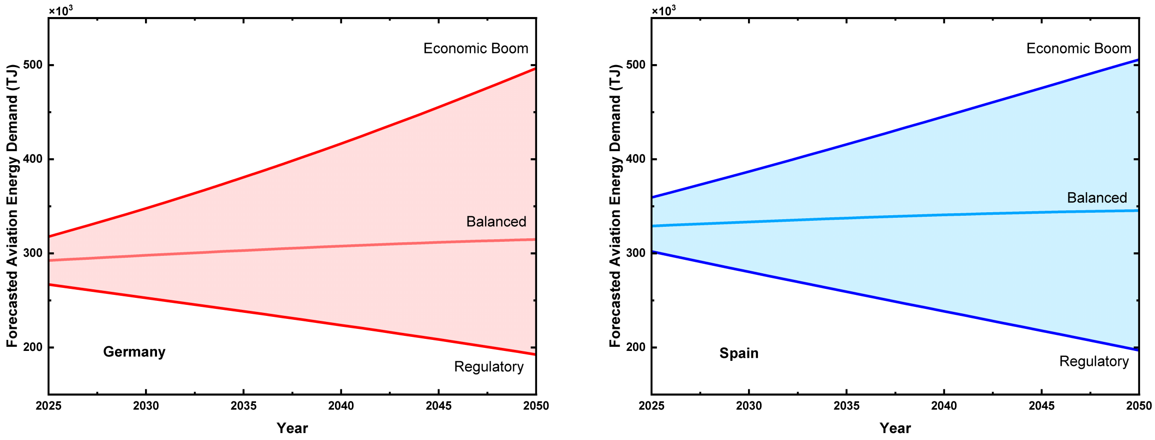

Figure 6: German and Spanish aviation energy demand forecast, 2025-2050

A 2022 study by the Deutsche Energie-Agentur (dena) [85] projects the distribution of aviation fuel shares through 2050. Based on this study, Table 6 presents the expected split between fossil and non-fossil kerosene in the aviation sector. This projection highlights the anticipated shift towards greater reliance on non-fossil alternatives. These fuel shares are useful for graphically representing the forecasted aviation energy demand in Germany (left plots) and Spain (right plots), now broken down by energy type across the three considered scenarios (Figure 7).

Energy Type	**2020**	**2030**	**2035**	**2040**	**2045**	**2050**
Fossil kerosene	99.9%	99.9%	81.1%	41.3%	8.2%	0.0%
Non-fossil fuels	0.1%	0.1%	18.9%	58.7%	91.8%	100.0%

Table 6: Aviation fuel shares assumed throughout the energetic transition to net zero emissions.

The projected fuel shares outlined in Table 6 do not align with the EU, German, and Spanish targets for aviation fuel by 2035 (discussed in Section 2.4.5). This discrepancy suggests that if these countries adhere to the trajectory described in Table 6, they will fall short of meeting their 2035 targets. Nevertheless, it is important to note that Table 6 projects a complete phase-out of fossil kerosene by 2050, which exceeds the ambition of the current targets. Next discussions in this study are based on the projections in Table 6, hence, it is essential to acknowledge this misalignment with the 2035 targets and the potential challenges it presents for meeting near-term goals.

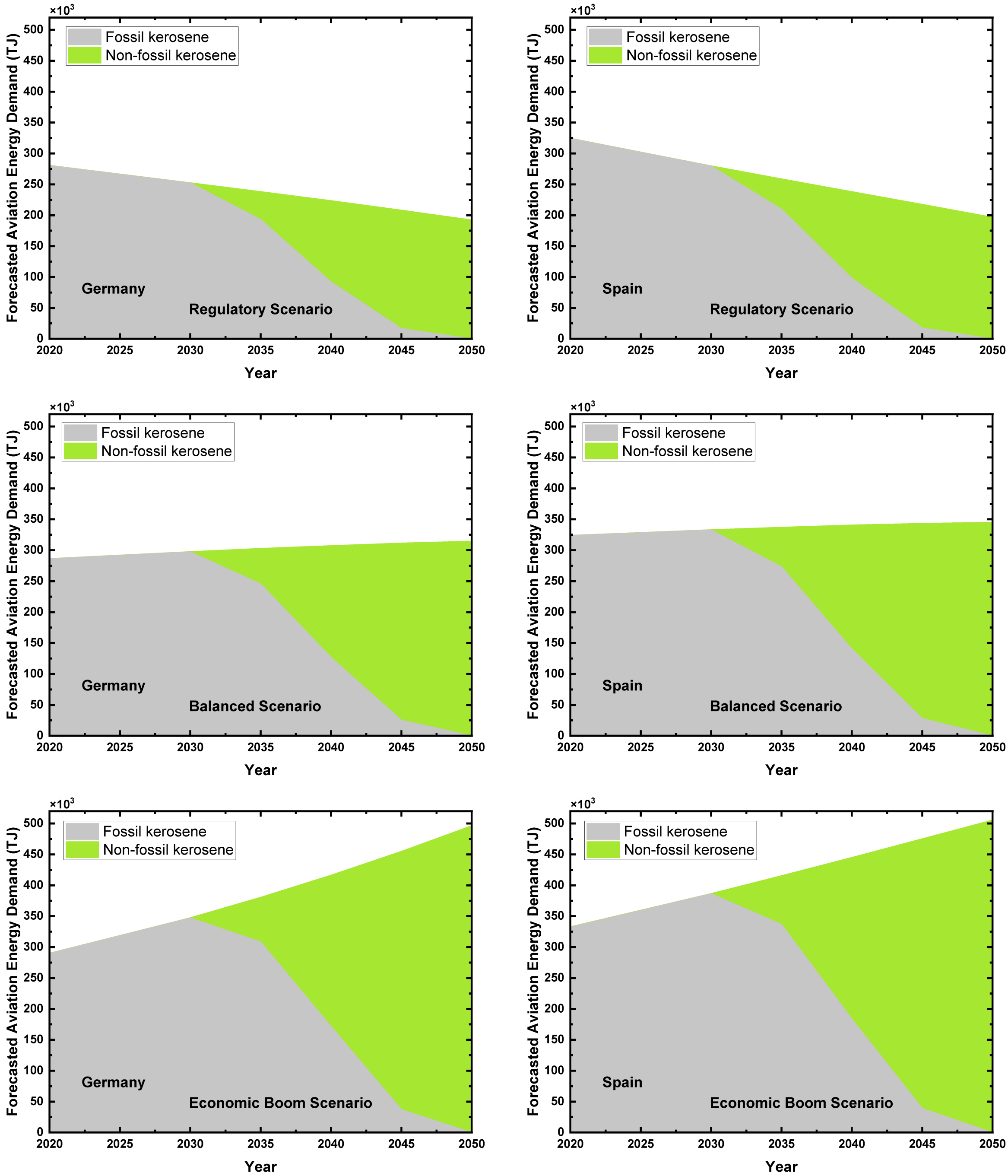

Figure 7: German and Spanish aviation energy demand forecast by energy type and under three future scenarios, 2025-2050

4.1.4 Predicted volumes of fuel

High energy density is a key factor in aviation because it significantly influences aircraft's operational efficiency. Energy density refers to the amount of energy stored per unit mass or volume of fuel. Traditional jet fuels, like kerosene, have a high energy density, which allows aircraft to store large amounts of energy without adding substantial weight. This is critical for long-haul flights, as it ensures sufficient fuel capacity while maintaining optimal performance and fuel efficiency. As the aviation industry shifts towards sustainable fuels, preserving or enhancing energy density is essential.

The energy density of fuels is determined by their chemical composition, particularly by the types of hydrocarbons present, which influence how much energy is released during combustion. For instance, traditional jet fuels like Jet-A or kerosene consist mostly of long-chain hydrocarbons, providing the high energy density required by aviation demands [86]. In contrast, alternative fuels have different molecular structures, which can result in variations in energy content and physical density. Although SAF are designed to mimic fossil kerosene for compatibility with current aircraft engines and infrastructure, their energy density may be slightly lower depending on the production process and feedstock used.

The ongoing challenge for the aviation industry is to develop fuels that offer the right balance between energy density and practical storage and handling, enabling efficient long-range travel while reducing carbon emissions. Table 7 shows the energy density characteristics of the possible aviation fuel options. The values of the fossil kerosene are obtained from [87]; whereas the values of SAF, electricty (littium-ion batteries), and hydrogen (70 MPa compressed) are extracted from [88].

Energy Type	**Fossil Kerosene**	**SAF**	**Li^{+}Battery**	**Hydrogen**
Mass energy density (MJ/kg)	43-48	≈43	<1.8	≈142
Volume energy density (MJ/L)	≈35	≈34.4	<3.7	≈5.6

Table 7: Energetic densities of the aviation fuel options

The volumetric energy densities of fossil kerosene and SAF are used to convert the predicted aviation energy demand in Section 4.1.3 into volume. This conversion provides a concrete measure of the amount of fuel required to meet aviation needs; helping in planning infrastructure, storage, and logistics, and ensuring that production capacities align with demand. It also enables comparison between different fuel types and production strategies, considering local availability of resources, production capabilities, and sustainability targets. Additionally, fuel pricing and sales are often conducted on a volumetric basis, making volume a more consistent measure for economic and operational assessments in the aviation industry.

Therefore, using the assumed shares of fossil and non-fossil fuels from Table 6, the projected volumes of fuel demanded are calculated for Germany and Spain in the three contemplated scenarios (Table 8).

Germany - Fuel Volume (L)

Year	Regulatory		Balanced		Economic Boom	
	Fossil	Non-fossil	Fossil	Non-fossil	Fossil	Non-fossil
2030	7,214,587,393	7,347,771	8,504,996,617	8,662,002	9,929,994,603	10,113,305
2035	5,522,142,208	1,312,775,804	7,019,823,437	1,668,818,732	8,820,032,904	2,096,781,530
2040	2,638,960,603	3,819,344,798	3,629,516,144	5,252,967,242	4,914,102,638	7,112,138,136
2045	489,685,607	5,562,924,639	732,050,632	8,316,238,917	1,069,354,440	12,148,076,397
2050	0	5,595,357,899	0	9,150,791,310	0	14,438,422,238

Spain - Fuel Volume (L)

Year	Regulatory		Balanced		Economic Boom	
	Fossil	Non-fossil	Fossil	Non-fossil	Fossil	Non-fossil
2030	8,001,698,077	8,149,412	9,517,464,151	9,693,160	11,044,685,232	11,248,574
2035	6,003,454,357	1,427,197,874	7,815,085,787	1,857,876,009	9,628,762,974	2,289,040,481
2040	2,812,616,392	4,070,675,315	4,020,533,726	5,818,883,598	5,253,886,480	7,603,904,344
2045	511,623,305	5,812,141,198	807,016,652	9,167,867,621	1,117,192,667	12,691,528,048
2050	0	5,728,496,296	0	10,041,510,315	0	14,706,247,966

Table 8: Volumes of fossil and non-fossil kerosene expected to be required from 2030 to 2050 in Germany and Spain

It is important to note that, although the projected volumes of non-fossil kerosene demanded in both countries are similar, Spain consistently exhibits a higher range of kerosene demand compared to Germany throughout the period from 2030 to 2050. Consequently, Spain would need to produce a greater amount of both fossil and non-fossil kerosene domestically in order to meet its demand and reduce reliance on imports. Under the approach of this study, Germany would need to produce between 7.3 and 10.1 million L of SAF in 2030; whereas Spain, between 8.1 and 11.2 million L. In 2050, Germany would need to produce between 5.6 and 14.4 billion L; whilst Spain, between 5.7 and 14.7 billion L.

4.2 Domestic SAF production capacity

In the following discussion, it is assumed that the previously estimated volumes of non-fossil kerosene will be entirely met by SAF. To satisfy this demand, existing refineries must be transformed, or new SAF refineries need to be constructed. Current estimates suggest that between 5,000 and 7,000 SAF refineries will be required globally by 2050 to achieve the aviation industry's climate goals. Specifically, approximately 1,000 to 1,500 of these refineries will be necessary in Europe [49]. However, as outlined in this section, the SAF production capacity planned for 2030 in both Spain and Germany falls significantly short of the levels required to meet these targets.

4.2.1 Existing SAF production facilities

After a manual search about the now existing and the announced future SAF refineries in Germany and Spain, Table 9 and 10 show how the scene will look in 2030.

Germany

Project/Company	Location	SAF Technology	Entry to Service	Capacity (L/year)
Global Bioenergies GmbH [89]	Leuna	ABtL	2019	125,000
OMV Deutschland GmbH [90]	Burghausen	PtL	2020	62,500,000
Atmosfair gGmbH [91]	Werlte	PtL	2021	456,250
bp Europa SE [92]	Lingen	HEFA	2022	625,000,000
Sunfire GmbH [93]	Dresden	PtL	2022	125,000
KEROSyN100 [94]	Heide	PtL	2023	25,000,000
Ineratec GmbH [95]	Frankfurt	PtL	2024	3,125,000
Caphenia GmbH [96]	Frankfurt	PtL	2024	100,000,000
Shell plc [97]	Wesseling	PtL	2025	125,000,000
HCS Group, Gevo [98]	Speyer	ABtL	2026	75,000,000
Green Fuels Hamburg [99]	Hamburg	PtL	2026	12,500,000
MiRO GmbH [100]	Karlsruhe	PtL	2027	62,500,000
EDL Hykero [101]	Leipzig	PtL	2027	62,500,000
Hy2gen AG [94]	Brandenburg	PtL	2027	42,500,000
Concrete Chemicals [102]	Rüdersdorf	PtL	2028	43,750,000
Synhelion Germany GmbH [94]	Jülich	PtL	2030	4,375,000
HH2E AG [103]	Leipzig	PtL	2030	250,000,000
PCK [104]	Schwedt	PtL	2030	200,000,000

Table 9: Planned SAF production facilities by 2030 in Germany

Spain				
Project/Company	**Location**	**SAF Technology**	**Entry to Service**	**Capacity (L/year)**
Repsol S.A. [105]	Puertollano	HEFA	2020	125,000,000
BP p.l.c. [27]	Castellon	ABtL	2021	1,250,000
Cepsa S.A.U. [89]	San Roque	HEFA	2022	98,425,000
Repsol-Enerkem [89]	Tarragona	ABtL	2022	290,000,000
Repsol S.A. [106]	Cartagena	HEFA	2023	312,500,000
Repsol-Aramco [107]	Bilbao	PtL	2025	2,625,000
Synhelion S.A. [108]	Madrid	PtL	2025	1,250,000
Cepsa S.A.U. [109]	Palos de la Frontera	ABtL	2026	625,000,000
Solarig S.A. [110]	Soria	PtL	2028	75,000,000
HyVal [111]	Castellon	PtL	2030	812,500,000

Table 10: Planned SAF production facilities by 2030 in Spain

As of above, Germany presents a scenario of 18 small-scale projects, while Spain of 10 big-scale projects. Both landscapes have advantages and disadvantages. Large-scale projects benefit from economies of scale, resulting in lower production costs per unit, greater efficiency, and the ability to invest heavily in advanced technologies. They offer stability in supply and are better suited for securing long-term contracts. However, they come with high initial investment costs, feedstock logistics challenges, and risk concentration. In contrast, small-scale projects offer flexibility, adaptability to market changes, and lower initial capital requirements. They can also be set up closer to feedstock sources, reducing transportation costs and emissions, and are ideal for fostering innovation. However, they may face higher per-unit production costs, management complexity, and limited impact individually. A balanced approach combining both large-scale and small-scale projects is often ideal.

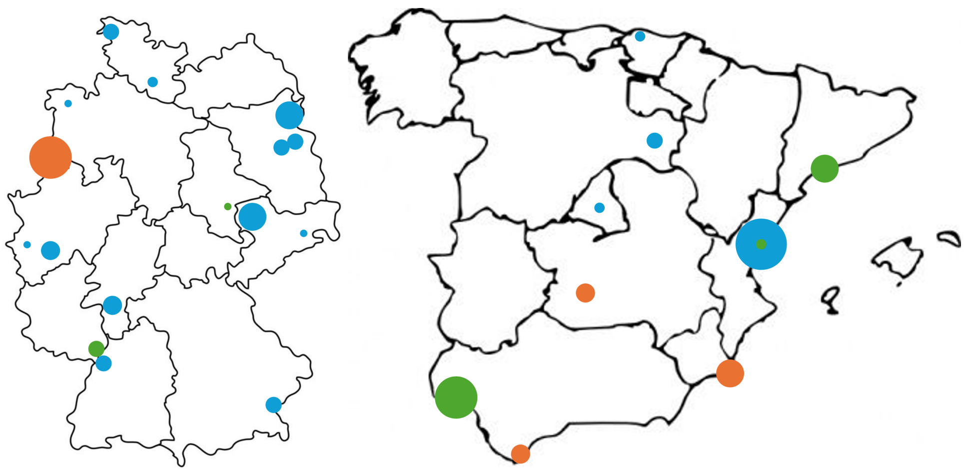

Figure 8: Geographic distribution of the SAF production facilities by 2030 in Germany and Spain

Figure 8 illustrates the projected geographic distribution of SAF refineries in Germany and Spain in 2030. Each colored dot represents a facility, with different colors denoting the SAF technologies used: orange for HEFA, green for ABtL, and blue for PtL. The size of each dot indicates the facility's annual production capacity. By 2030, the distribution of these facilities is expected to align with each country's strategic priorities, availability of feedstocks, and infrastructure capabilities. For instance, in Germany, PtL plants are typically located near PV/wind hybrid power stations. In Spain, where freshwater is scarce, PtL plants would be situated on the coast, where seawater desalination can meet water demands.

In Germany, SAF facilities are likely to be concentrated in regions like North Rhine-Westphalia, where existing refinery infrastructure is present, and near major aviation hubs such as Frankfurt and Berlin. The focus on PtL plants aligns with Germany's emphasis on renewable energy sources. Conversely, in Spain, SAF production will likely be centered in regions with abundant agricultural and waste feedstocks, such as Andalusia (notable for olive oil production) and Castilla-La Mancha. Coastal areas with established petrochemical infrastructure, like Castellon and Tarragona, will also play a significant role, leveraging industrial capabilities and port access for feedstock imports and fuel exports.

Moreover, the evolution of the total SAF production capacity, accumulating the project capacities of Table 9 and 10, is shown graphically in Figure 9. The development between the SAF technologies is notably different in both countries, as it is discussed below.

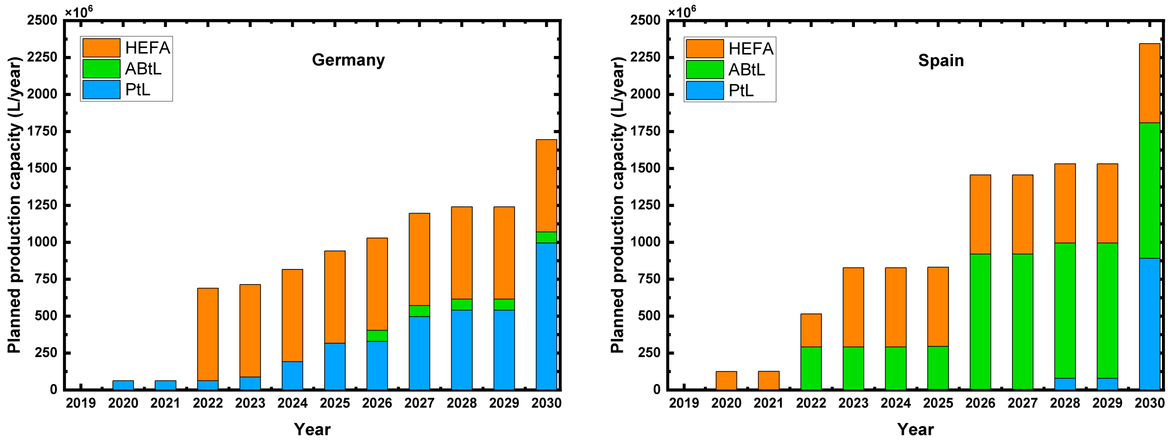

Figure 9: Evolution of the total planned SAF production capacity in Germany and Spain, 2019-2030

Table 11 shows that by 2030, Germany would produce significantly less ABtL-based SAF than Spain, both in absolute and relative terms. This difference is primarily driven by the availability and diversity of biomass resources and the differing policy frameworks

Capacity (L/year)	**Germany**	**Spain**
HEFA	625,000,000 (36.9%)	535,925,000 (22.9%)
ABtL	75,125,000 (4.4%)	916,250,000 (39.1%)
PtL	994,331,250 (58.7%)	891,375,000 (38.0%)
Grand Total	1,694,456,250	2,343,550,000

Table 11: Planned total SAF production capacity of Germany and Spain in 2030, split by SAF technologies

in each country. Spain's warm Mediterranean climate supports a wide variety of biomass crops, with longer growing seasons and higher yields contributing to a larger biomass supply for SAF production. Resilient energy crops that withstand drought conditions provide a reliable biomass source, even under climate stress. Spain's diverse agricultural sector, including residues from olive production, vineyards, and cereal crops, along with extensive forested areas, creates an abundant biomass supply. This has attracted strategic investments from Spanish energy companies like Repsol and Cepsa into ABtL technology. In contrast, Germany's biomass resources are less diverse and abundant.

Germany's energy strategy, *Energiewende*, has historically emphasized wind, solar, and hydrogen technologies over biomass, favoring non-biomass pathways that avoid competition with food production and land use. Restrictive environmental regulations and high competition for land use, given Germany's dense population and industrial activities, further limit the potential for large-scale biomass production. As a result, ABtL production in Germany (starting mainly in 2026) remains lower than in Spain.

Germany's production of PtL-based SAF is projected to account for 57.8% of total SAF production by 2030, compared to 38.0% in Spain. Furthermore, the Spanish PtL production becomes significant with a large-scale project in 2030, while German PtL production increases progressively along the timeframe. This aligns with Germany's focus on renewable electricity and its strengths in chemical engineering and process optimization. Significant government support through subsidies and incentives has further driven investment in PtL technology, and numerous pilot projects are underway to scale up PtL production.

HEFA-based SAF is expected to represent 36.9% of production in Germany and 22.9% in Spain. While Spain benefits from local feedstock availability, Germany's industrial capacity and technological expertise have made it a leader in HEFA production. Germany has converted fossil fuel refineries to process biofuels, and although it imports a large portion of its feedstocks, it compensates with efficient logistics and supply chains for collecting waste oils and fats across Europe and beyond.

4.2.2 SAF production capacity vs. SAF required

In this subsection, it is examined whether the planned SAF production capacity in Germany and in Spain is enough to meet the SAF requirement calculated in Section 4.1.4.

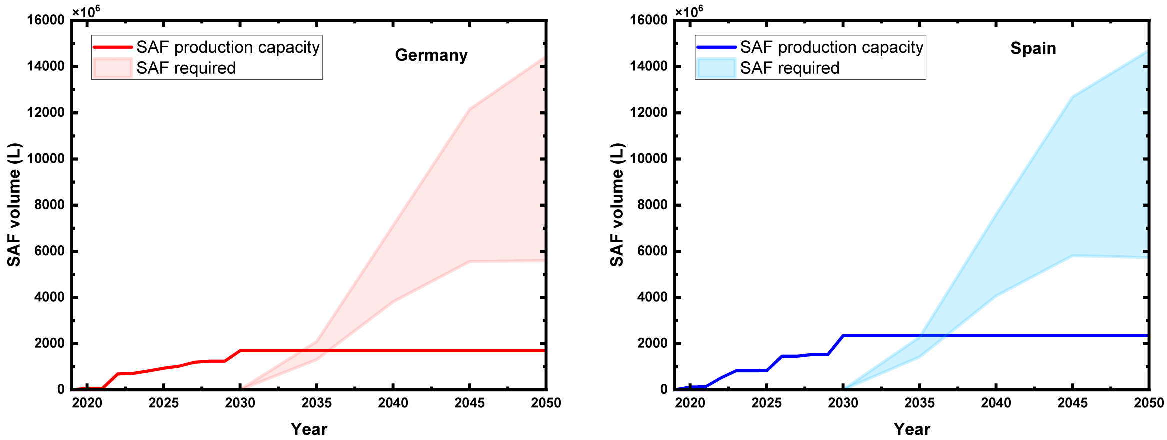

Figure 10: Comparison of the SAF production capacity and the domestic requirement in Germany and in Spain, 2019-2050

Figure 10 shows that both Germany and Spain are projected to meet their SAF volume requirements with planned production capacity until around 2035. The colored area represents the range of non-fossil kerosene volumes required under the two extreme scenarios outlined in Table 8, while the bold line indicates the planned domestic production capacity. SAF needs are met domestically when the bold line is above or within the colored area. However, beyond 2035, domestic production capacity is expected to fall short. To avoid reliance on imports, they will need to expand their SAF production by constructing new SAF refineries, converting existing fossil fuel refineries, or adopting other alternative non-fossil propulsion technologies such as hydrogen or electricity.

According to the premises of this study, Spain is expected to have sufficient domestic SAF production until around 2037, while Germany's capacity is projected to fall short shortly after 2035. However, this time difference may not be significant in reality, considering the assumptions taken during the calculations.

Furthermore, with the planned production capacities, Spain is expected to successfully meet its SAF and PtL targets (Section 2.4.5) under all scenarios until 2035. In contrast, Germany may barely meet the RefuelEU targets by 2035 but will not achieve its own SAF and PtL targets under any future scenario, unless it increases production capacity or relies on imports. Such analysis is easily performed by comparing the total projected kerosene volume required in Table 8 and the total planned production capacity split by SAF technology in Table 11.

4.3 Domestic feedstock availability

The production of some biofuels, specially based on grown feedstocks raises several concerns, including potential changes in the use of agricultural land, water use, the possible effect on food prices, and the impact of irrigation, pesticides, and fertilisers on local environments. Nevertheless, SAF are demonstrated to meet strong sustainability requirements and standards [16]. Moreover, Section 4.4 also points out that feedstock costs are generally a big proportion of the production costs.

CORSIA encourages countries to implement climate policies that prioritize the use of domestic biofuel feedstocks. Many nations outside the EU have set ambitious climate targets and introduced incentives to optimize the use of their own waste and residue resources. As a result, relying on biofuel imports, particularly from outside the EU, may become increasingly challenging for European climate policy. For example, the EU currently imports significant quantities of UCO from Asian markets. However, as Asian countries increasingly prioritize their own climate objectives, competition for UCO is expected to intensify, making imports less reliable [22]. This highlights the need for Germany and Spain to develop a robust biofuel production industry that is based on domestic feedstocks, reducing dependence on unpredictable imports.

4.3.1 Feedstock present in Germany and Spain

This section explores the present availability of feedstocks in both nations per SAF technology. For a better understanding, Annex D further explains land usage and climate conditions in Germany and Spain.

HEFA feedstocks The HEFA pathway for producing SAF relies on FOG feedstocks, such as UCO, animal fats, and vegetable oils. Their domestic availability is critical for scaling up HEFA SAF production. Spain has a robust agricultural and food processing industry, offering significant potential for HEFA feedstocks. Germany also has significant resources for HEFA SAF production, though its focus is more on waste-based feedstocks.

Spain has a well-established collection system for UCO, where around 322,000 Tn[2] are generated per year [112]. Similarly, Germany has a potential of collection 350,000 Tn/year of UCO [113]. As countries like China and India intensify their own biofuel programs, the competition for UCO is expected to increase, making domestic collection even more important.

[2]Density factor for cooking oil used of 0.92 g/mL

The potential for HEFA fuels is limited by the availability of vegetable oil and animal fat resources, and by the cost of these resources. Animal fats are byproducts of the meat and livestock industries and are categorized based on their suitability for human consumption or other uses. The focus is on Category 1 and 2 fats, which are considered unsuitable for human consumption, and then minimize competition with food and feed uses, aligning with sustainability goals under the EU RED II. Spain was the largest producers of animal fats in Europe in 2020, largely due to its significant meat and livestock industry, followed by Germany. Both countries approached the 500,000 Tn of Category 3 animal fats produced in 2020, however, a fewer amount of around 110,000 Tn of Category 1 and 2 animal fats. Furthermore, Spain produced 120,000 Tn of biofuel from animal fats in 2021; while, Germany, 48,000 Tn [114]. Additionally, Germany does not support the use of animal fat in its biofuel mandate due to the risk of indirect emission caused by displacement from existing uses [49].

Both Spain and Germany have significant potential for the use of vegetable oils in HEFA SAF production, particularly through the cultivation of rapeseed and sunflower. However, sustainability policies, such as EU RED II, prioritize waste-based and non-food feedstocks, limiting the role of virgin vegetable oils in SAF. While the ILUC emissions for other vegetable oils such as soy, sunflower and rapeseed are expected to be lower than those for palm oil, they are still high enough to eliminate or significantly reduce any net climate benefit from their use in biofuel production [27].

Rapeseed oil is the dominant vegetable oil used for biofuel production in Germany [115][116]. Germany is expected to be the biggest rapeseed producer in 2024, with 4.2 million Tn of rapeseed produced in 2023 [117]. However, the domestic demand is also high, and the potential for expansion is limited due to land use restrictions and competition with food production [118]. Other vegetable oils, such as soybean oil, are less produced but contribute to biofuel supply [119]. According to the German Federal Statistical Office, around 104,000 Tn of soybeans were harvested in Germany in 2021.

The average cultivated area of the main oilseeds (sunflower, rapeseed and soybean) in Spain is estimated at over 820,000 Ha, with an average production of over 1 million Tn [120]. Spain's climate allows for diverse feedstock sources, including sunflower oil and olive oil by-products, though rapeseed oil is less prominent than in Germany. Spain the major olive oil producer worldwide (45% of the total olive oil production is in Spain), with 664,000 Tn in the campaign 2022/2023 [121]. The Spanish sunflower harvest is usually 830,500 Tn/year [120], producing around 300 million L of sunflower oil annually [122]. However, the biofuel production cannot rely on sunflower oil in Spain, as half of the sunflower industry in Spain depends on imports. The rapeseed production in Spain rounds about 202,400 Tn/year [120]. Soybean oil production in Spain for biofuel purposes is relatively limited compared, as its domestic production is minimal due to its climate. Spain produced 4,769 Tn of soybean in 2021 [123].

Palm oil remains one of the most widely used feedstock for biofuel production in certain EU countries like Spain, being the major vegetable oil feedstock used for the production of biofuel in Spain. More than 98% of Spanish HVO produced in each year from 2015 to 2019 was palm oil based [27], a situation which should be stopped due to its environmental concerns. In contrast, from January 2023 onwards, Germany effectively banned the use of palm oil biofuels.

Both in Germany and Spain, the production of non-food oils, such as camelina, jatropha, and algae oils, is still at a relatively small scale, with a focus on research and development rather than large-scale commercial production. Camelina could be a promising non-food oilseed crop that grows well in Spain's semi-arid regions.

Lastly, the feedstocks used in HEFA are also used for the road sector biodiesel production, which has a simpler and less costly production process, and may therefore be a more attractive option for producers. Competition for feedstock between the road and aviation sector is expected to increase as more ambitious policy measures to decarbonise the transport sector are adopted.

ABtL feedstocks Three main feedstocks can be distinguished for the SAF production via ABtL: MSW, forest residues, and agricultural residues.

Germany has one of the most advanced waste management systems in the world, with high recycling rates and well-developed infrastructure for MSW. According to the European Environment Agency (UBA), Germany generated around 52.6 million Tn of MSW in 2020 [124], with a significant portion suitable for waste-to-energy processes, including SAF production, although competing uses may limit availability. Spain produces slightly less MSW per capita compared to Germany, generating approximately 22 million Tn annually [124]. However, Spain's recycling rates are lower, and landfilling remains more common, meaning that a larger portion of MSW could be diverted for biofuel production.

Germany has a significant forest coverage, with forests occupying around 11.4 million Ha (32% of the country's land area) [125]. Germany's well-managed and highly regulated forestry industry generates approximately 2 million tonnes of forest residues available annually [126]. However, most of this is already used for biomass energy, leaving a limited amount for SAF production. In parallel, Spain's forest area covers around 18.6 million Ha (about 37% of its land area) [125]. However, the availability of forest residues for biofuel production is lower due to less intensive forest management and limited infrastructure for residue collection. Spain produces around 0.5 million Tn of available forest biomass annually [126]. This suggests that Spain may have more untapped potential to use forest residues for SAF production.

Germany, as a leading agricultural producer in Europe, generates substantial agricultural residues, primarily from wheat, barley, and maize production. With 16.5 million Ha of agricultural land (47% of its total land area), Germany produces approximately 12 million Tn of agricultural residue annually [125, 126]. Spain, with 52% of its land dedicated to agriculture (26.2 million Ha), also generates significant agricultural residues, especially from cereal crops, olive groves, and vineyards. It is estimated that Spain produces around 2.5 million Tn of agricultural residues per year [126], with olive by-products being extensively utilized for biofuel production [127]. The potential availability of raw material from olive groves and vineyards in Spain is estimated at 4.2 million Tn per year [128]. In summary, while Germany produces a larger quantity of agricultural residues, particularly from cereal crops, Spain has a notable reserve of underutilized residues, especially from olive groves and vineyards.

The agricultural residues are transformed into ethanol and isobutanol, through the AtJ pathway. Corn is one of the key crops for producing ethanol through fermentation, which can then be converted into SAF. Corn (maize) is cultivated in Germany (2.7 million Ha in 2020), producing 3.84 million Tn of maize in 2022 [129], but is mainly used for animal feed and biogas production [130], leaving limited quantities available for biofuel. Spain is also one of the largest maize producers in the EU, with an annual production of 3.59 million Tn [129]. Corn is a promising feedstock in Spain with opportunities to expand its use in ethanol-based SAF. On the other hand, neither Germany nor Spain produce sugarcane due to their temperate climates, which means it does not contribute to ethanol production in either country. Instead, both nations cultivate sugar beet, although this crop is primarily used for sugar production rather than for ethanol.

PtL feedstocks The availability of key inputs like renewable electricity (mainly solar and wind) and CO_2 is crucial for the PtL technology. Comparing Germany and Spain, distinct differences in their potential for PtL production are observed.

PtL technology requires vast amounts of renewable energy for the electrolysis process, which splits H_2O into H_2 and O_2. H_2 is then combined with CO_2 to produce SAF. Germany's strong wind energy sector, especially in the northern regions, positions it well for PtL production. However, the availability of solar energy is limited due to the country's temperate climate. On the other side, Spain has excellent potential for renewable electricity, particularly in solar energy, thanks to its sunny climate. Spain is among Europe's top producers of solar power, and also has ample land resources for further expansion of renewable infrastructure, making it well-positioned to scale up PtL production. Further information in Section 2.4.7.1.

In PtL processes, CO_2 can be sourced from industrial emissions through CCS or directly from the air via DAC. An abundant and consistent supply of CO_2 is crucial for scaling up SAF production. Germany, with its extensive industrial infrastructure, generates large amounts of point-source CO_2 from heavy industries such as steel, cement, and chemical manufacturing. These sectors provide a reliable near-term source for CO_2 capture, making Germany well-positioned to leverage its industrial emissions for PtL applications. However, DAC technology might be less efficient in Germany, as its climate and high vegetation density lead to relatively lower atmospheric CO_2 concentrations.

In contrast, Spain, with its strong industrial sector, especially in regions like Catalonia and Andalusia, also offers significant industrial CO_2 from cement, steel, and petrochemical industries. This ensures Spain's capacity for industrial CO_2 utilization for PtL is comparable to Germany. Moreover, Spain's arid climate and higher solar radiation levels make it an ideal candidate for more efficient DAC, as lower humidity and more stable sunshine conditions enhance the process of atmospheric CO_2 extraction.

4.3.2 Domestic feedstock required

Next, it is investigated if the national planned SAF production capacity is able to rely only on domestic feedstocks. The expected annual production volumes of SAF (in L) for 2030, as presented in Table 11, are converted into the corresponding quantity (in Tn), using the density of SAF, which is $0.8 \cdot 10^{-3}$ Tn/L. The amount of feedstock required to produce a given quantity of SAF distillate (the final SAF product) is calculated based on the yield factors provided by the ICAO [43], and outlined in Table 1.

As discussed in Section 8, although Germany's SAF production from HEFA is less diversified than Spain's, it remains higher. Based on the volume estimates in Table 11, Germany would require 415,000 Tn of FOGs to satisfy its internal SAF production, while Spain would need 355,854 Tn of FOGs for its HEFA production. However, following the previously highlighted discussion on UCO availability, neither country has sufficient UCO to allocate exclusively for HEFA production. As a result, both would need to rely on non-food vegetable oils to meet their planned HEFA production targets.

Besides, all Spanish ABtL SAF is produced via the FT process, using organic waste as feedstock. The projected annual production of 916,250,000 L of ABtL SAF translates into feedstock requirements of either 227,230 Tn of MSW, 131,940 Tn of forest residues, or

102,620 Tn of agricultural residues. In Germany, two ABtL SAF refineries are planned for operation by 2030. The facility in Leuna, operated by Global Bioenergies GmbH, will use the AtJ technology, with bio-isobutene as its primary feedstock. Its production capacity of 125,000 L/year will require 45,075 Tn of alcohol as feedstock. The second refinery, located in Speyer and operated by HCS Group and Gevo, is scheduled to begin producing SAF in 2026 using the FT process. Its expected capacity of 75,000,000 L/year would require either 18,600 Tn of MSW, 10,800 Tn of forest residues, or 8,400 Tn of agricultural residues as feedstock. It is evident that Spain would require a significantly higher amount of feedstock for its ABtL SAF production compared to Germany. However, despite this, both countries possess sufficient domestic feedstock to meet the demands of their planned ABtL production capacities.

It is estimated that 190,998 Tn of CO_2/H_2 will be required to meet Germany's planned SAF PtL production in 2030, while Spain would need 171,144 Tn. However, these figures are not directly comparable to the previous discussions on feedstock requirements. In some cases, CCS or DAC units may be integrated directly into the PtL refinery, enabling CO_2 capture from nearby industrial processes or direct air capture on-site. This integration offers logistical and efficiency benefits by reducing transportation and storage costs. In other instances, CO_2 may be sourced from external CCS or DAC facilities, requiring transport to the refinery. Therefore, it can be concluded that both Germany and Spain will rely on their domestic resources to produce the synthetic SAF required for their planned PtL production.

Lastly, it is important to consider not only the availability of feedstock, but also the environmental impact of SAF production in each specific country. Different SAF production pathways have varying environmental consequences depending on the local conditions. For instance, a master's thesis from Utrecht University [131] illustrates that, except for the HEFA pathway, most SAF production methods involve a higher land-use footprint in Poland than in Spain. If it is assumed that Poland and Germany exhibit similar environmental consequences in terms of land use for SAF production, producing SAF in Germany damages more the environment than in Spain. Evaluating the environmental effects of SAF production in each country is crucial for making informed decisions about sustainable aviation fuel deployment.

4.4 Production costs

With a potential future demand of about 325 million Tn of SAF to achieve net zero by 2050, up to EUR 1,000 billion in capital expenditure will be needed simply to establish SAF refineries [11]. This is a huge investment, especially considering that currently the SAF industry is still in a stage of uncertainty.

The low production and use of SAF is attributed to diverse barriers. One major barrier to demand for SAF is its cost, with the price ranging from approximately two to eight times that of conventional aviation fuel [20]. Production processes can be complex, depending on the pathway, and the cost of feedstock may be high, while existing policy measures, such as the EU ETS, do not appear to be sufficient incentives to drive up demand.

4.4.1 Analysis of the different SAF technologies

Many techno-economic studies compare the production costs of SAF, considering a wide range of feedstocks and production types. Utilizing the available cost breakdown from several techno-economic studies, Detsios et al. (2023) set a general range regarding the CAPEX (capital expenditures), OPEX (operational expenditures), and feedstock contributions to the production costs of each technology (Table 12) [21]. It must be noted that H_2 associated costs are considered in CAPEX and OPEX costs whitin HEFA process, while considered feedstock costs for PtL. The average values from Table 12 are used for the cost allocation of each technology, presented in Figure 11.

	HEFA	**ABtL-AtJ**	**ABtL-FT**	**PtL**
CAPEX range (%)	22-40	45-75	54-81	5-20
OPEX range (%)	8-10	2-14	12-21	5-15
Feedstock range (%)	51-69	20-44	0-32	70-85

Table 12: CAPEX, OPEX, and feedstock range of contribution to the production costs of the SAF technologies

HEFA pathways are seen to have low investment costs [20] with relatively simple production processes. However, they have been associated with concerns over availability and cost of feedstock, including current and future restrictions on use of food-based feedstock. The high feedstock cost range is in accordance with Table 1, where the most expensive feedstocks are the HEFA ones. The most expensive feedstock is the jatropha oil, whilst the most cost-competitive HEFA options are UCOs [132]. On the other hand, ABtL pathways benefit from a lower costly and abundant feedstock, but a complicated

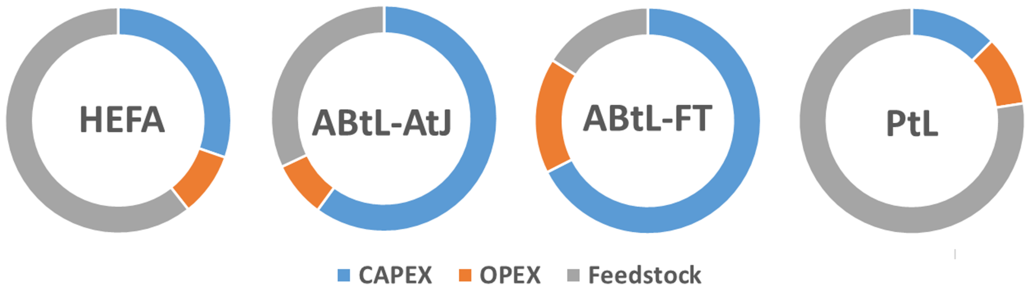

Figure 11: Average CAPEX, OPEX, and feedstock range of contribution to the production costs of the SAF technologies

production process entails higher capital costs (CAPEX). Alcohols are generally more expensive that generic biomass [132], that is why AtJ presents higher shares of feedstock costs than the FT synthesis. Concerning PtL, the securement of green hydrogen, its feedstock, is clearly the most influential cost parameter and is driven by renewable electricity prices and the electrolyzer hardware used.

	HEFA	**ABtL-AtJ**	**ABtL-FT**	**PtL**
Production costs range (EUR/L)	0.66-1.94	0.64-2.68	0.85-1.94	2.93-3.23

Table 13: Range of production costs of the SAF technologies

For a better interpretation of Table 13, production costs are converted to euros, using the exchange rate EUR 1=USD 1.18 [132]. HEFA and ABtL present a high flexibility in the feedstock selection, what results in a relatively wide range of production costs. Contrarily, production costs of PtL presents a narrower range and its boundaries are considerably higher.

In general, the variations in existing PtL fuel cost estimations rely on different assumptions for the plant setup, its geographical location, the operation of the plants, as well as capital and operational expenditures (CAPEX and OPEX) of individual components. With many of these factors hard to predict due to the yet-to-be-scaled nature of individual components [133]. The production process of PtL is currently very expensive, with estimations of three to six times more expensive than kerosene, due to high conversion losses and high transportation and distribution costs. Further developments to specific production steps (high-temperature electrolysis, direct CO_2 capture from air), declining renewable electricity and electrolyzer costs, and economies of scale could enhance the efficiency and, hence, aid to bring down cost. This phenomenon is already foreseen and quantified in some studies [11].

4.4.2 Jet fuel price

Jet fuel prices are highly susceptible to external factors and can fluctuate significantly. Key drivers include fluctuations in crude oil prices, geopolitical tensions, currency exchange rates, seasonal demand shifts, global economic conditions, and government policies. Additionally, natural disasters or disruptions in refinery operations can cause significant price changes, making jet fuel costs unpredictable and challenging for stakeholders to manage. As for fossil kerosene, SAF prices are also constantly fluctuating and are influenced by the country and region. This makes difficult to make a current analysis and a forecast about the evolution of SAF prices, even though many studies perform it naming it minimum jet selling price (MJSP) [21][34][65][132][133][134].

Within this research, SAF prices are calculated based on average production costs (data from [26]) and a 10% markup including e.g. administrative or transportation costs [11]. Besides, the average price of the kerosene in Europe for the week ending 30 August 2024 is USD 745.35/Tn, which with the proper conversions[3] equals to EUR 0.537/L [135]. Next, a yearly CAGR of 1% is applied to it to simulate a slow but steady price increase to the fossil kerosene. Furthermore, a second scenario is considered for the fossil kerosene price, where the CO_2 cost is added up to it. In this study, a carbon price of EUR 0.24/L from the EU ETS (Section 2.4.4.2) is summed to the predicted fossil jet fuel price. The final exact numbers are shown in Table 14.

To advance in the SAF market, regulatory and economic incentives such as quotas or voluntary markets are commonly employed. However, carbon pricing mechanisms offer another viable option. These mechanisms increase the cost of fossil kerosene by incorporating a price based on the CO_2 emissions of the energy source, applied through either a tax or an ETS. This approach effectively adds a carbon cost to the base price of fossil fuels, enabling a more equitable comparison between fossil kerosene and SAF. By reflecting the true environmental cost of fossil fuels, carbon pricing enhances the competitiveness of renewable energy sources. Globally, 65 carbon pricing initiatives [11] have been established, though they vary in their application to the aviation sector, and a unified global approach has yet to be achieved.

Carbon credits and carbon pricing are crucial for promoting SAF adoption by incentivizing reductions in carbon emissions. Under schemes such as the EU ETS and CORSIA, airlines can purchase carbon credits to offset their emissions. SAF is particularly attractive for earning credits due to its lower lifecycle emissions compared to conventional jet fuel. The carbon intensity of SAF can lead to substantial savings, as each metric ton

[3]The 30th August 2024, there was an exchange rate of 0.9 EUR=1 USD, and the density of jet fuel is considered as 0.8 kg/L.

of CO_2 avoided through SAF use can be traded in carbon markets. For aviation fuel, the emission factor is around 3.16 Tn of CO_2 per Tn [11]. Nevertheless, the economic viability of SAF hinges on the balance between production costs, market incentives, and evolving carbon pricing frameworks as part of global decarbonization efforts in aviation.

Price (EUR/L)	**HEFA**	**ABtL-AtJ**	**ABtL-FT**	**PtL**	**Fossil Kerosene**	**Carbon price**
2030	1.050	1.694	1.540	1.738	0.564	0.804
2040	1.012	1.584	1.298	1.188	0.623	0.863
2050	0.968	1.496	1.320	0.977	0.689	0.929

Table 14: SAF and fossil kerosene price projection until 2050

As previously noted, the figures in Table 14 should not be interpreted quantitatively, as prices are subject to fluctuations and vary by region. However, the table provides a qualitative overview that can be analyzed for general insights.

The modest cost-reduction potential of HEFA is reflected in the forecasted price decrease of only up to 8% over a 20-year period. This limited reduction is primarily attributable to high feedstock costs and associated environmental concerns. In contrast, FT technology, which relies heavily on capital expenditures due to gasification and extensive gas-cleaning requirements, shows a forecasted price reduction of 14% over the same period. While ABtL-FT technology offers extended feedstock flexibility and significant greenhouse gas (GHG) reduction capabilities, its cost reductions are constrained by the high initial investment and operational complexities. For ABtL-AtJ routes instead, greater feedstock flexibility does not translate into a significantly larger forecasted price reduction, with projections indicating only up to a 12% decrease over 20 years. In comparison, PtL technologies are forecasted to achieve up to a 44% price reduction over the same period, driven by optimistic expectations for decreasing green electricity costs.

Additionally, while the scale effects for ABtL-FT, ABtL-AtJ, and PtL are expected to be beneficial, their exact impact is challenging to predict as these technologies have not yet reached full-scale deployment. Conversely, HEFA technology, being more mature, has lower technology risk but does not exhibit the same level of potential for dramatic cost reductions. Overall, forecasting for the next decade is fraught with uncertainties, and predicting trends over a 30-year horizon is even more complex.

Even though none of the SAF technologies are projected to reach price parity with baseline fossil kerosene, or fossil kerosene with the added carbon price, before 2050 (based on the figures in Table 14), rising carbon prices are expected to narrow this gap. While estimates for future carbon prices vary significantly [49], it is likely that price parity could be achieved between 2040 and 2050. However, this timeframe remains distant, underscoring the need for strong incentives to accelerate this process and make fossil kerosene considerably more expensive than current predictions suggest.

4.4.3 Comparison between Germany and Spain

Germany and Spain have similar SAF production cost ranges across different technologies, but future costs are likely to decrease as renewable energy capacity expands and technological improvements occur. While Germany's strong industrial base and renewable energy investments may lower costs in PtL and FT over time, Spain's renewable energy potential could also make it competitive, particularly for solar-based SAF production.

Production costs for HEFA-based SAF would be similar for both countries. Their feedstock availability (Section 4.3) will determine their production costs. ABtL-FT SAF technology is more complex than HEFA but benefits from Germany and Spain's advanced capabilities in gasification and forestry and agricultural waste feedstocks required. On the other hand, ethanol-based AtJ pathways benefit from Germany's strong bioethanol industry, but ABtL-AtJ commercialization is still developing. Although Spain's ethanol industry is not as large as Germany's, it could potentially leverage agricultural waste and biofuels for this technology. All in all, no big differences in the production costs of HEFA, ABtL-FT, and ABtL-AtJ are expected between Germany and Spain.

However, in Spain, the production costs for PtL are expected to be lower than in Germany, largely due to the high renewable energy intensity required for the process. Although Germany boasts a well-established renewable energy infrastructure, Spain's greater potential for generating renewable electricity at more competitive prices gives it an advantage. According to data from the German Environment Agency, near-term production costs for PtL, including both FT and Direct Air Capture (DAC) technologies, are projected to be EUR 2,885/Tn in Germany, compared to EUR 2,284/Tn in Spain. Looking to the long term, these costs are expected to decrease to EUR 2,186/Tn in Germany and EUR 1,762/Tn in Spain [23].

Furthermore, Germany is expected to have higher SAF prices than Spain, like its historically higher gasoline prices. This can be attributed to Germany's higher energy costs, taxes, and regulatory factors, despite its advanced renewable energy infrastructure. In contrast, Spain benefits from cheaper renewable electricity, leading to lower SAF production costs [136].

5 Limitations and further research

This study has several limitations that should be considered when interpreting the results. First, the availability and quality of the data used in forecasting aviation energy demand, particularly the calculation for fuel efficiency, may introduce inaccuracies. The Ridge regression model, while suitable for this analysis, relies on certain assumptions which may not fully capture the complexity of real-world dynamics.

Another limitation arises from the scenario-based approach used to forecast aviation energy demand in Germany and Spain. The same conditions on the scenarios are applied for both countries, however their particular dynamics and historic trends might suggest different growth of their external macroindicators. some data might have been overlooked during the manual research process, particularly regarding the project production capacities and the quantities of feedstock available.

Despite these limitations, the study provides valuable insights into the potential for Germany and Spain to meet their future aviation energy demands and lead the global SAF market. However, these projections should be viewed as indicative rather than definitive.

This study highlights several areas where further research could deepen. First, further research could focus on evaluating the environmental impacts of SAF production in each country. Uncovering the differences in terms of carbon emissions, water usage, and land requirements for feedstock and SAF production in Germany and in Spain, would allow to take more sustainable decisions.

Additionally, researching the price dynamics of various feedstocks in each country could help identify the most cost-effective options for SAF production. Such analysis could inform more efficient allocation of resources and enhance the economic viability of SAF production in both countries. Lastly, further quantitative exploration into the differences in SAF production costs between Germany and Spain is also needed. Investigating the specific cost drivers in each country, including energy input costs, technology deployment, and feedstock logistics, would provide a clearer picture of the financial barriers and opportunities unique to each nation.

In conclusion, future research in these areas would not only refine the current understanding of SAF production but also provide valuable insights for policymakers and industry leaders aiming to scale SAF in a sustainable and economically viable manner. By addressing these knowledge gaps, Germany and Spain would advance their leadership in the global SAF market while making informed decisions that support long-term decarbonization in aviation.

6 Conclusions

The global demand for sustainable aviation fuels positions them as a leading solution for achieving net-zero emissions in the aviation sector by 2050. While SAF provides a promising pathway, significant challenges remain, including supply constraints and high production costs. These hurdles underscore the urgent need for robust policy measures to accelerate SAF's commercial adoption. Europe plays a pivotal role in this decarbonization of aviation, with Germany and Spain emerging as strong candidates to lead SAF production efforts.

Historically, Germany has boasted a stronger aviation industry, with higher air traffic than Spain. However, the post-COVID-19 landscape has shifted these dynamics, as the decline in business travel and Spain's rise as a global tourist destination led to it surpassing Germany in air traffic in 2023, aided by its strategic geographical location.

Spain's dense solar and wind power infrastructure, crucial for SAF production, combined with its significant agricultural sector, positions it as an ideal site for developing and processing this fuel. In contrast, while Germany possesses a strong renewable energy framework and policies promoting green hydrogen and synthetic fuels, its focus has leaned more toward industrial applications and technological innovations rather than optimizing resources for SAF production. This strategic advantage allows Spain to enhance its role in the emerging SAF market in the near-term.

This thesis employs Ridge regression to forecast aviation energy demand in Germany and Spain, utilizing six external indicators: *GDP per capita, air transport passengers, air transport carrier departures, international tourism expenditures, Consumer Price Index, and fuel efficiency.* Although the regression results are comparable for both countries, the predictors have a more pronounced effect on aviation demand in Spain. Several assumptions made in the model may introduce inaccuracies in the results. Nevertheless, the developed model offers reliable qualitative insights, projecting higher overall aviation energy demand for Spain compared to Germany until 2050.

Under three scenarios, projected aviation energy demand is categorized into fossil and non-fossil kerosene. From 2030 to 2050, Spain shows higher projected demand for non-fossil kerosene (SAF) compared to Germany. Ideally, the energy needs of the aviation sector should be met entirely through domestic production to reduce reliance on SAF imports or feedstocks. However, current planned internal SAF supply for both countries is insufficient to meet forecasted demand from approx. 2035; concretely, Germany would need to increase its SAF production efforts slightly more than Spain to meet domestic demand.

The availability of feedstocks for SAF production in Germany and Spain varies considerably, reflecting each country's unique agricultural and industrial strengths. Spain benefits from a robust agricultural sector that provides substantial quantities of HEFA feedstocks, particularly UCO and animal fats. However, EU sustainability regulations limit the use of vegetable oils, and neither country has an abundance of sustainable options, although camelina oil shows potential for production in Spain. Conversely, Germany emphasizes waste-based feedstocks, benefiting from larger quantities of MSW and forest and agricultural residues. Despite these differences, both countries could achieve their planned SAF production targets through bio-based domestic feedstocks, although substantial investments in collection and processing infrastructure are crucial to optimize their potential. Additionally, it has to be recognized that available feedstocks must be shared across various industries and cannot be exclusively allocated for SAF production.

Regarding PtL technology, Spain may hold a comparative advantage over Germany due to its abundant renewable resources, particularly solar energy, and its potential for DAC. This allows Spain to scale up PtL production more cost-effectively, thanks to favorable climate conditions and lower renewable electricity costs. However, Germany has a well-established renewable energy infrastructure and is actively investing in SAF, with several pilot projects focused on PtL technology. With ambitious targets for expanding its PtL capabilities, Germany is poised to become a key player in the global PtL production landscape.

Germany and Spain have similar SAF production cost ranges across different technologies, but future costs are likely to decrease as renewable energy capacity expands and technological improvements occur. Overall, Spain is expected to produce SAF at a lower cost; however, SAF production will continue to be more expensive than refining fossil jet fuel for the next 20 years unless strong carbon pricing policies are implemented.

In summary, policymakers and industry leaders should prioritize investments in domestic feedstock production and processing infrastructure to meet the growing aviation energy demands in Germany and Spain. By leveraging Germany's robust R&D investments and policy framework alongside Spain's abundant biofuel resources and cost-effectiveness, both countries can significantly advance decarbonization in aviation and establish themselves as leaders in the global SAF market, potentially even exporting their production. Substantial economic investments are essential for both countries to meet this rising demand and achieve regulatory targets.

Declaration of Authorship

I hereby declare that the master thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references.

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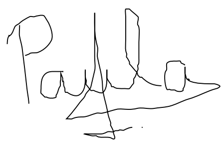


A Chemical reactions SAF processes

A chemical understanding of how the HEFA, AtJ, and FT processes work is crucial for conducting an accurate techno-economic assessment and for gaining a deeper comprehension of their efficiency, feasibility, and cost implications and environmental trade-offs associated with each SAF production pathway.

A.1 HEFA

During hydrotreatment, the glycerides and FFA's are converted into alkanes in a few steps (Figure 12). First, triglycerides are hydrotreated to saturate the natural occurring double bonds. In the case of triolein, 3 moles of H_2 are required to form stearine, a saturated triglyceride. The saturated triglyceride is hydrotreated again to remove the glycerol backbone which breaks up the triglyceride into three FFA's. In the case of stearine, 3 moles of H_2 are needed to end up with 3 moles of stearic acid with propane as byproduct. The last step necessary to create alkanes is to remove the oxygen content from the FFA's, which can be with decarbonylation (removal of CO), decarboxylation (removal of CO_2) or hydro-deoxygenation (removal of H_2O). Hydro-deoxygenation is preferred, as this ensures the highest carbon efficiency and no carbon is emitted into the atmosphere. A range of C_{15}-C_{18} alkanes is produced.

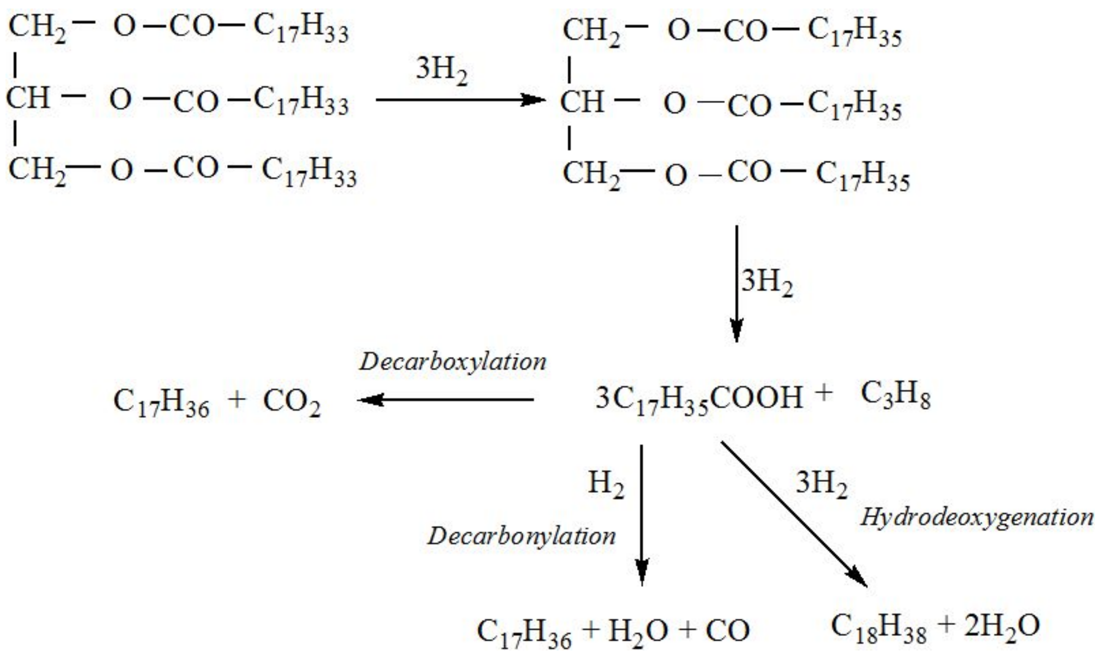


Figure 12: Molecular reactions occurring in the hydroconversion of a triglyceride [1]

The obtained mix of alkanes (also called linear paraffins) needs to be isomerized and hydrocracked as final step, requiring hydrogen and catalysts. Isomerization turns the long chain hydrocarbons (linear paraffins) into branched hydrocarbons (iso-paraffins) to reduce the freeze point, necessary to meet jet fuel A1 standards.

A.2 AtJ

As an example, the fermentation reaction of ethanol is shown in equation A.1:

$$C_2H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 \tag{A.1}$$

Next, the ethanol is dehydrated next, which removes the water, creating a double bond between carbon atoms and converting ethanol into ethylene, the shortest chain alkene. Ethanol dehydration (equation A.2) is sped up with catalysts and requires a temperature of ± 180 ℃ [2].

$$C_2H_5OH \longrightarrow C_2H_4 + H_2O \tag{A.2}$$

Ethylene is then converted into longer chain alkenes (linear α-olefins, with a carbon number between 8 and 16) with oligomerization:

$$n[C_2H_4] \longrightarrow C_{2n}H_{4n} \tag{A.3}$$

Oligomerization also produces a variety of shorter chain olefins (unsaturated hydrocarbons), which are not usable as jet fuel, due to their instability. The mixture is distilled to remove the short chain olefins, which are reused in the oligomerization process to end up with a higher share of jet fuel range olefins. The alkene mixture is hydrogenated to convert them into alkenes, with the use of catalyst at ambient temperature and pressure (Figure 13). Finally, the alkane mixture is distilled and fractionated to end up with usable jet fuel.

$$C_nH_{2n} + H_2 \longrightarrow C_nH_{2n+2} \tag{A.4}$$

Figure 13: Hydrogenation of an alkene [2]

A.3 FT

After pre-treatment, the biomass enters the gasifier where it is pressurized and gasified with a mixture of pure oxygen and steam. The oxygen is obtained by feeding ambient air through an air separation unit, which splits the oxygen from the air mixture by using electricity. Steam is generated by heating water in a boiler, powered by produced syngas or additional biomass. During gasification, a mixture of CO, CO_2, H_2O, H_2, CH_4 and other CH molecules is formed by thermo-chemically breaking down (hemi)cellulose and lignin structures:

$$Biomass + O_2 + H_2O(g) \longrightarrow CO, CO_2, H_2O, H_2, CH_4 + otherCHs \tag{A.5}$$

The specific composition of the syngas is dependent on multiple factors, such as the feedstock composition, moisture content of the feedstock and gasifier operation conditions. The gas contains multiple impurities after gasification which need to be removed. Next, the H_2/CO ratio is adjusted to the optimal FT ratio with the water gas shift reaction (equation A.6), and fed into the FT reactor, where they are combined to form a wide range of hydrocarbons (alkenes/olefins, alkanes/paraffins, alcohols,...). The selectivity of products is highly dependent on the catalyst used, which is generally cobalt or iron. Unconverted syngas is recycled back into the FT reactor to increase desired product yield, the remaining gas can also be used for electricity generation necessary for the air separation unit [2].

$$nCO + (2n+1)H_2 \longrightarrow C_nH_{2n+2} + n(H_2O) \tag{A.6}$$

The initial share of kerosene/jet fuel range hydrocarbons can be increased by hydro-treatment, such as hydrogenation and hydro-cracking. During hydro-treatment, hydrogen reacts with longer hydrocarbons to split them into shorter chain alkanes. As final step, the mixture is distilled to end up with a mixture which fits the desired kerosene output profile.

B Macroindicators selection analysis

Various time series datasets of macroindicators are analyzed to identify the appropriate variables for inclusion in the regression analysis aimed at forecasting aviation energy demand.

B.1 ADF stationarity test

The Augmented Dickey-Fuller (ADF) test is used to check the stationarity of a time series. A stationary time series has properties that do not depend on the time at which the series is observed. The following parameters are studied to conclude the stationarity of the variables: *ADF Statistic* is compared against the *critical values* to determine stationarity, and the *p-value* is compared against a chosen significance level (commonly 0.05) to conclude whether the null hypothesis is rejected.

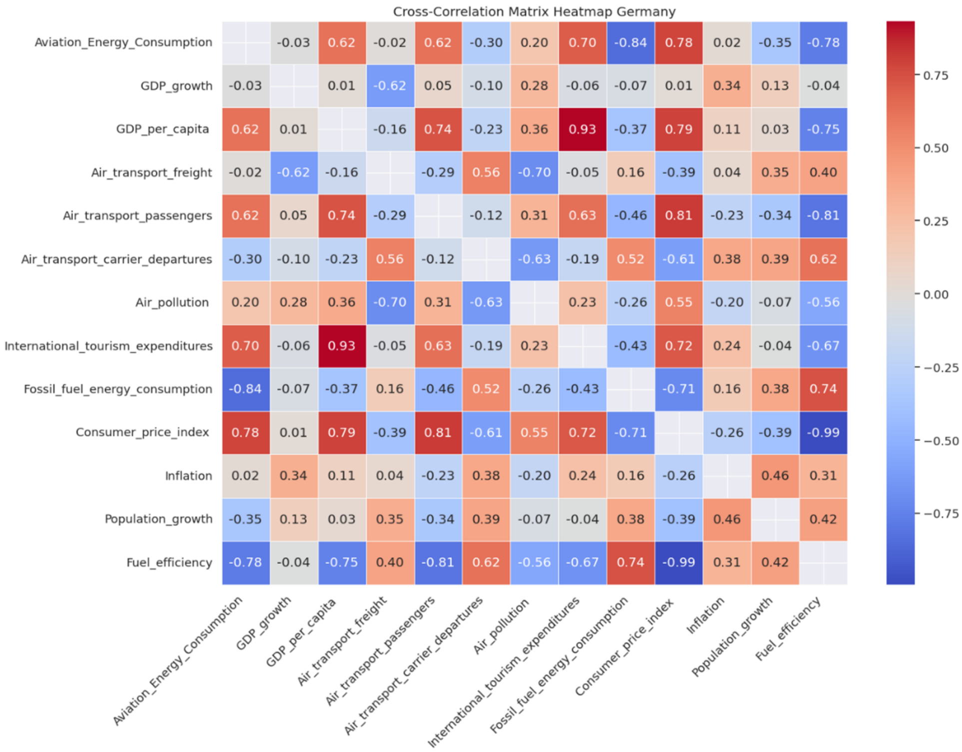
	Germany	**Spain**
GDP growth	Non-stationary	Stationary
GDP per capita	Stationary	Stationary
Air transport passengers	Stationary	Stationary
Air transport freight	Stationary	Non-stationary
Air transport carrier departures	Stationary	Stationary
Air pollution	Stationary	Stationary
Fossil fuel energy consumption	Non-stationary	Non-stationary
International tourism expenditures	Stationary	Stationary
CPI	Stationary	Stationary
Inflation	Stationary	Non-stationary
Population growth	Non-stationary	Non-stationary
Fuel efficiency	Stationary	Stationary

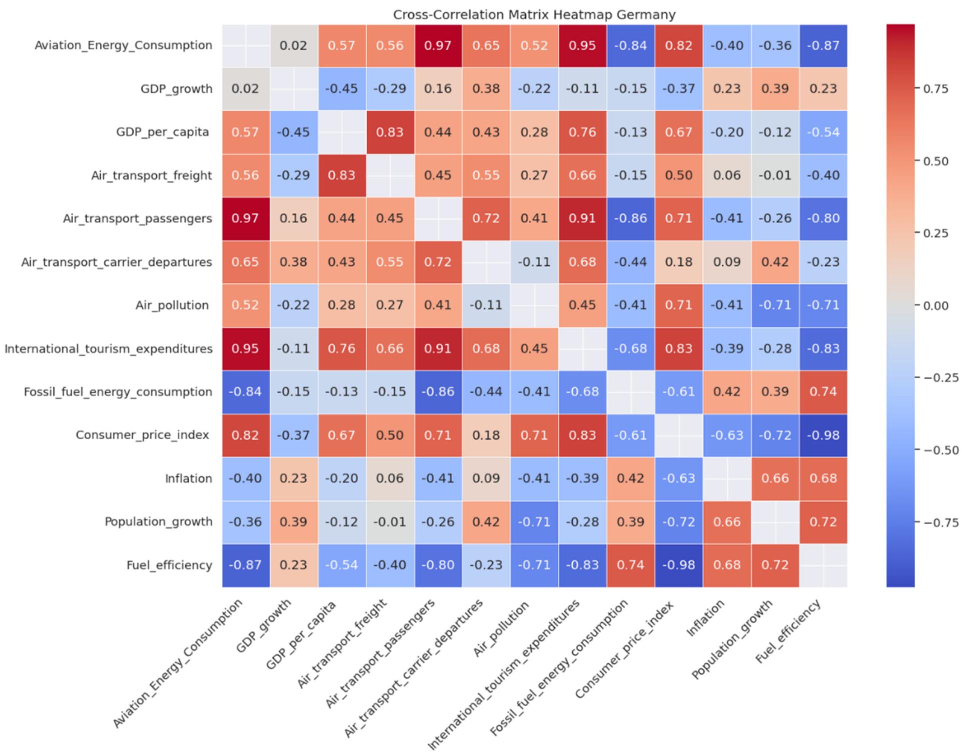
Table 15: Intercept and coefficients, with their standard errors, of the LASSO regression for Spain

Based on the results from the python code in Table 15, non-stationary variables cannot be included in subsequent regression analyses. By ensuring that a time series is stationary, it can be used in further time series analysis and modeling, including the Granger causality tests.

B.2 Cross-correlation matrices

The Pearson correlations between all the initially considered indicators, with no time-lags, are shown in the next heatmap matrices:





B.3 Granger causality test

A Granger causality test was conducted to assess the relationship between the predictor variables and the target variable. Granger causality indicates that if past values of a predictor provide valuable information for forecasting the target variable, the predictor is said to "Granger-cause" the target. When this occurs, it becomes essential to incorporate the appropriate lags of such variables into the regression model.

The results of the Granger causality test can be interpreted through the p-values obtained. These p-values indicate whether the null hypothesis—that past values of one variable do not aid in predicting the current value of another variable—can be rejected. A p-value below the significance level, typically set at 0.05, suggests that the null hypothesis can be rejected for that specific lag, providing evidence that the predictor variable Granger-causes the target variable. If certain variables Granger-cause the target variable, it is essential to include the relevant lags of these variables in the regression model. Granger causality indicates that the historical values of a predictor contain valuable information for forecasting the target variable.

Hence, the datasets are analysed with *Python Pandas* and the results are as follow

For the German datasets:

- *GDP per capita* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.0156
- *Air transport carrier departures* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.012
- *International tourism expenditures* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.0009
- *International tourism expenditures* Granger-causes *Aviation Energy Consumption* at lag 2 with p-value 0.0059
- *Fuel efficiency* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.0291
- *Fuel efficiency* Granger-causes *Aviation Energy Consumption* at lag 2 with p-value 0.0019

For the Spanish datasets:

- *International tourism expenditures* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.004
- *International tourism expenditures* Granger-causes *Aviation Energy Consumption* at lag 2 with p-value 0.0074
- *Fuel efficiency* Granger-causes *Aviation Energy Consumption* at lag 1 with p-value 0.0204
- *Fuel efficiency* Granger-causes *Aviation Energy Consumption* at lag 2 with p-value 0.0156

Based on the leading power of some variables over the before described *Aviation Energy Consumption*, some lags are applied in the Ridge regression. For Germany, *GDP per capita* and *International tourism expenditures* are lagged by 1 time frame, while *Fuel efficiency* is lagged by 2. For Spain, *International tourism expenditures* is lagged by 1 time frame, while *Fuel efficiency* is lagged by 2.

C LASSO regression

As an example, the LASSO regression results for Spain are presented in Table 16 and 17. Overall, the LASSO regression results for Spain indicate a well-performing model, characterized by a suitable level of regularization and strong predictive power. The combination of low MSE and high R-squared values suggests that the model effectively captures the dynamics of the data while maintaining generalizability. The choice of alpha = 1.649 demonstrates that the regularization technique has been effectively utilized to enhance model performance while preventing overfitting. Despite this, the LASSO regression excludes from the model *GDP per capita* and *fuel efficiency.* This is due to multicollinearity between the predictors. LASSO zero out the correlated predictors to handle redundancy and simplify the model.

	Spain
Intercept	28.42 ± 0.708
GDP per capita	0.0000 ± 0.0152
Air transport passengers	0.4302 ± 0.0514
Air transport carrier departures	-0.0038 ± 0.0582
International tourism expenditures	0.1187 ± 0.0468
CPI	0.1824 ± 0.0966
Fuel efficiency	0 ± 0

Table 16: Intercept and coefficients, with their standard errors, of the LASSO regression for Spain

	Spain
Best Alpha	1.649
Training MSE	5.203
Test MSE	3.817
Training R-Square	0.9762
Test R-Square	0.9630

Table 17: Statistical analysis of the LASSO regression for Spain

D Land usage and climate conditions in Germany and Spain

Germany, with a total land area of approximately 357,022 square kilometers, exhibits a diverse land usage pattern shaped by its geographical and economic factors. Approximately 36% of the land is devoted to agriculture, which includes crop cultivation and livestock farming, contributing significantly to the country's economy and food security. Forests and natural areas cover about 32% of Germany, playing a crucial role in biodiversity, carbon sequestration, and recreation. Urban areas, which account for approximately 12% of the land, include major cities such as Berlin, Munich, Hamburg, and Frankfurt, serving as cultural and economic hubs. The remaining land is used for various purposes, including industrial activities, infrastructure, and transportation networks. Germany's land usage reflects a commitment to sustainable practices, balancing economic development with environmental conservation.

Spain, covering an area of approximately 505,990 square kilometers, has diverse land usage that reflects its varied geography, climate, and economic activities. Approximately 48% of the country is devoted to agriculture, making Spain one of Europe's largest agricultural producers, renowned for its olive oil, wine, fruits, and vegetables. Around 38% of the land is covered by forests and natural areas, including woodlands, mountains, and national parks, which are vital for biodiversity and conservation. Urban areas comprise about 7% of the land, encompassing cities, towns, and infrastructure, with major urban centers such as Madrid, Barcelona, Valencia, and Seville. The remaining land is utilized for various purposes, including industrial areas, transportation networks, and water bodies. Overall, Spain's land usage reflects a balance between agricultural production, urban development, and natural conservation, shaped by its cultural and economic context. As a result, Spain possesses a larger land area dedicated to agriculture, forests, and natural spaces, making it a significant source of sustainable fuel feedstock.

Furthermore, Krasuska et al. (2010) made a projection of the surplus land share to the total agricultural land [3]. This refers to the proportion of agricultural land that is not currently being used for active agricultural production, but could potentially be utilized for other purposes. In the context of SAF, this surplus land could be used to grow feedstocks for biofuels without directly competing with food production. Figure 14 depicts that large regions with the highest percentage of land potentially available for energy crops (over 20%) are located in central and eastern Spain, and in central and eastern Germany, in scenario 2030.

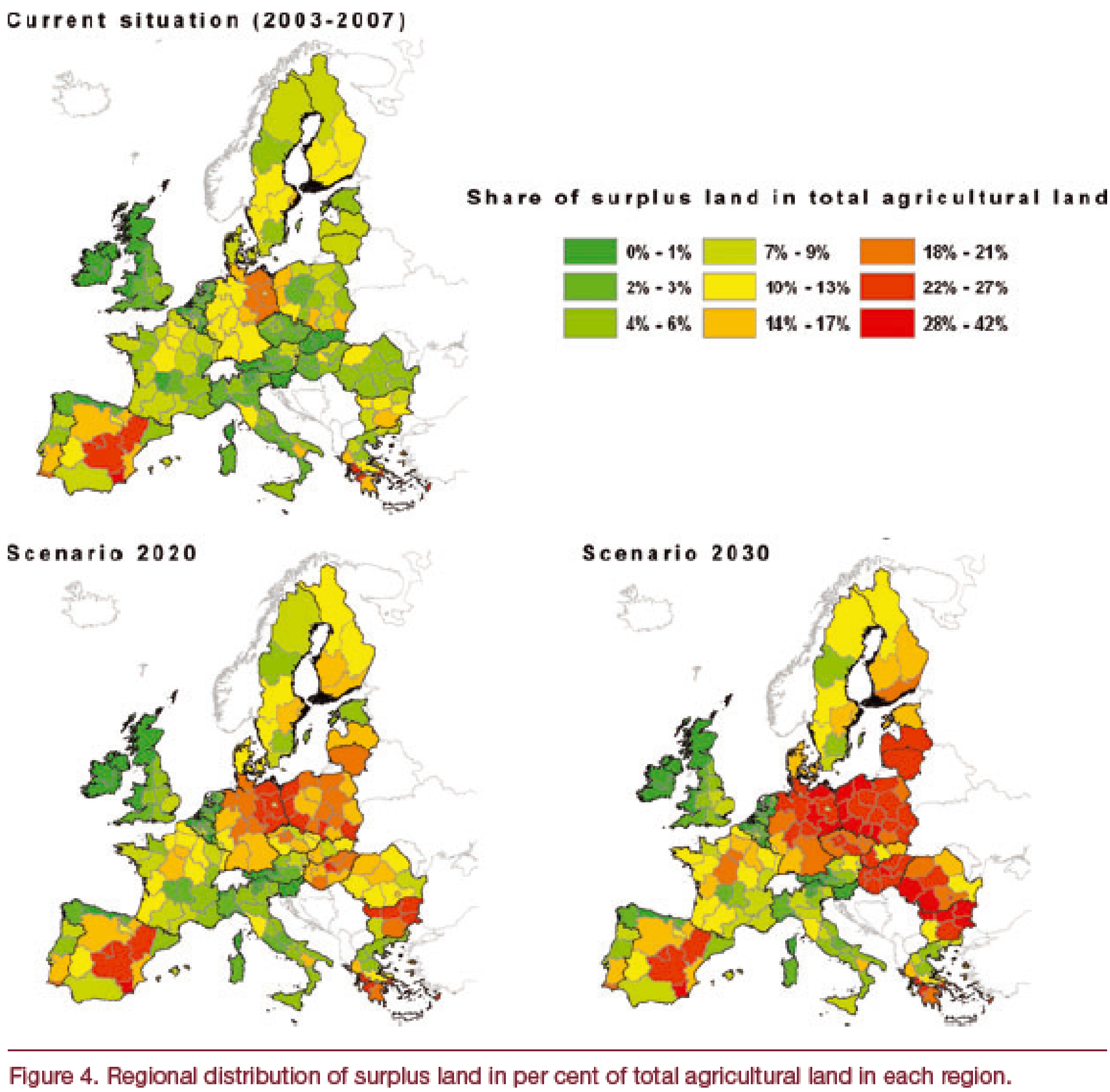


Figure 14: Surplus land share of total agricultural lands in the EU [3]

In addition to surplus agricultural lands, Fischer et al. (2010) highlight that 2nd generation feedstocks for biofuel production can also be cultivated on pastures [4]. The study (Figure 15) identifies regions with high potential for 2nd generation biofuels, such as parts of Germany. Hence, these areas have favorable conditions for the cultivation of energy crops or the use of agricultural residues. The study does not include marginal lands for biomass cultivation, like in Spain. Marginal lands are typically low-productivity lands not suitable for food production due to poor soil quality, low water availability, or other factors.

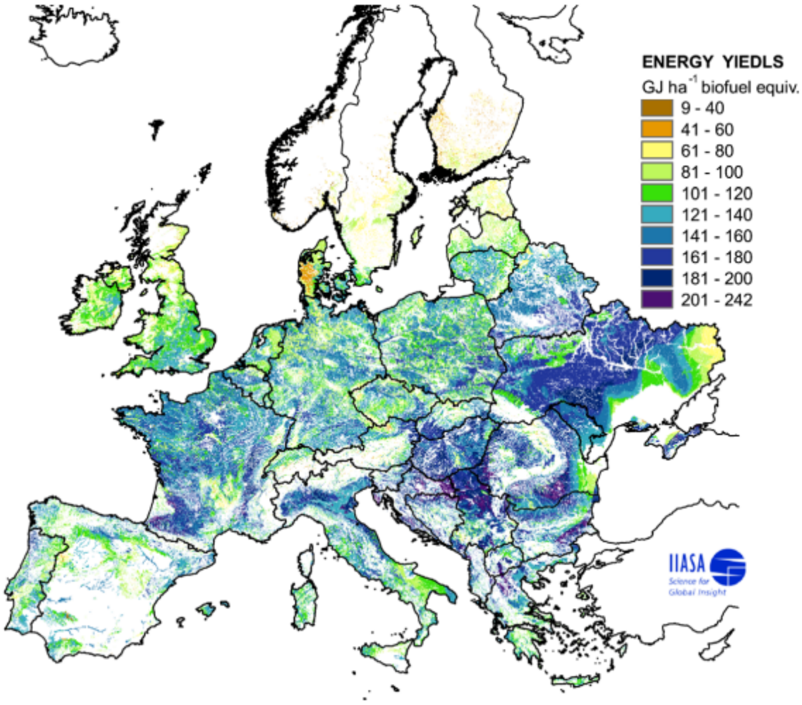


Figure 15: Potential energy yields of 2nd generation biofuels from feedstocks cultivated on pastures and surplus agricultural land [4]

Moreover, Figure 16 illustrates that Spain benefits from significantly higher solar radiation compared to Germany. In contrast, Figure 17 indicates that Germany has greater wind resources than Spain, which can be harnessed for wind electricity generation.

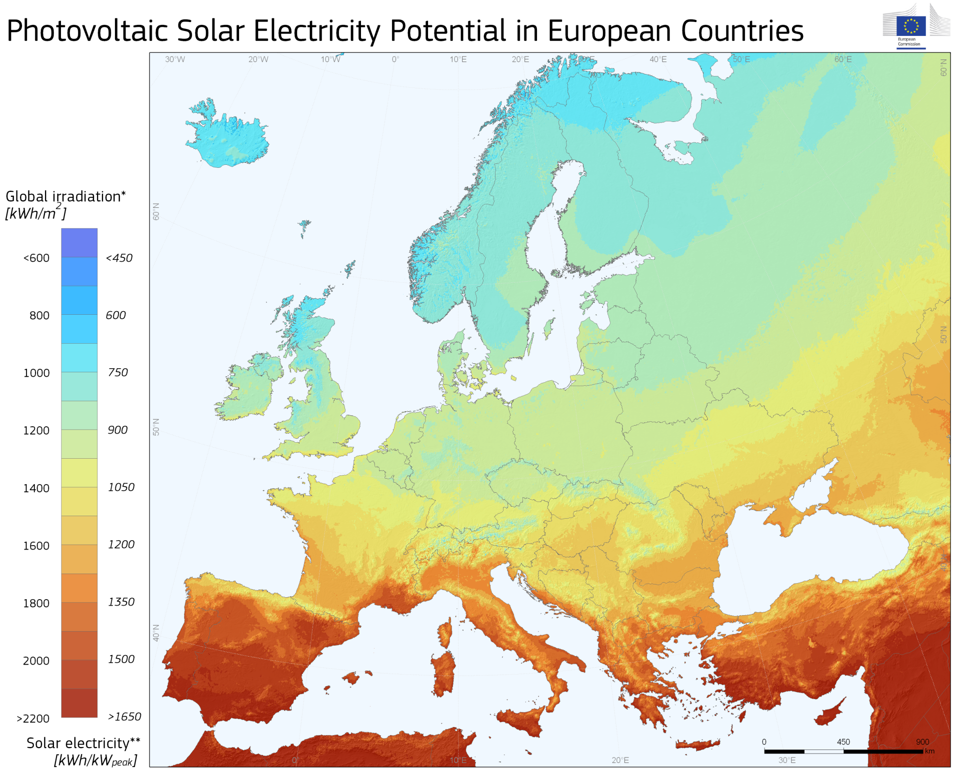


Figure 16: Yearly sum of global radiation in Europe [5]

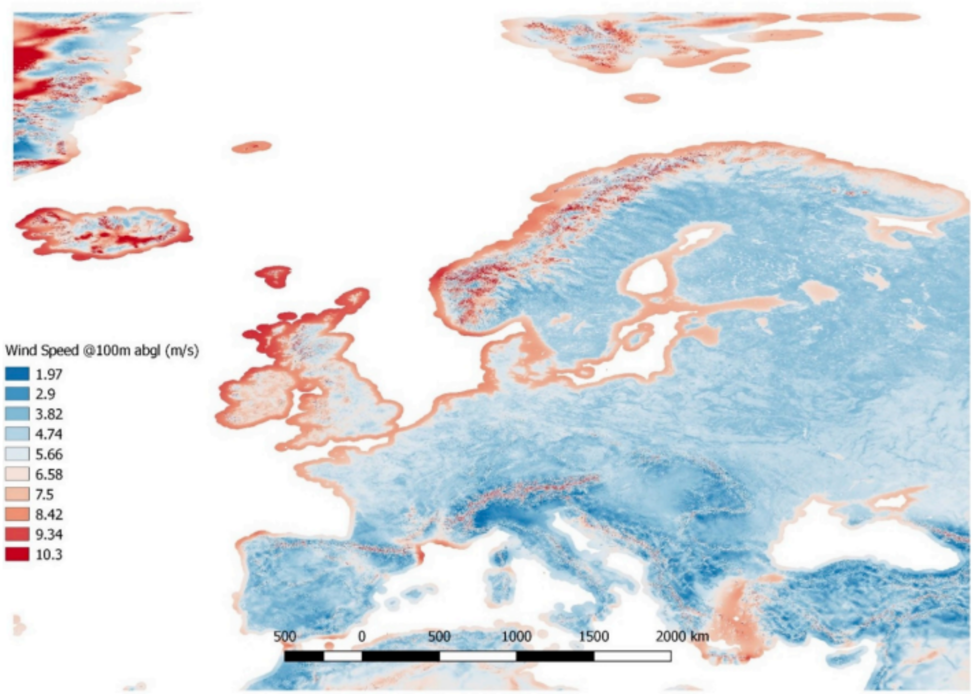


Figure 17: Annual mean wind speeds at 100 m above ground level in Europe [6]

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