

HYDROGEN SUPPLY NETWORKS' EVOLUTION FOR AIR TRANSPORT – SUPPLEMENTARY REPORT

June 2026



Imprint

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Recommended citation

HyNEAT Project, Hydrogen Supply Networks' Evolution
for Air Transport – Supplementary Report, (2026).
<https://doi.org/10.15488/21176>

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Funding

The project HyNEAT – Hydrogen Supply Networks' Evolution for Air Transport is funded by the German Federal Ministry of Research, Technology and Space (BMFTR) in the field of energy research programme. The project is supervised by Project Management Jülich (PtJ).

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With funding from the:



Federal Ministry
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Executive summary

This supplementary report extends the scope of the HyNEAT final project report by integrating the hydrogen (H₂) demand for H₂-based Sustainable Aviation Fuels (eSAF) into the assessment of liquid hydrogen (LH₂) supply infrastructure. While the main study focused exclusively on the infrastructure for direct H₂ propulsion, this analysis extends that perspective by providing a comprehensive evaluation of a European airport network that accounts for the significant H₂ demand associated with eSAF production. To comply with ReFuelEU Aviation

mandates and overcome the scalability constraints of biogenic fuels, the sector must rely on eSAF for long-haul decarbonisation. Unlike biofuels, the power-to-liquid pathway creates a substantial demand for renewable H₂. Consequently, this study determines the future for eSAF and LH₂ demand and models the parallel supply chains for LH₂ and eSAF to determine their aggregated impact on the European energy system, infrastructure optimisation, and macroeconomic landscape across varying uptake scenarios.

What we have found

- » The inclusion of eSAF as specified in the ReFuelEU aviation regulation significantly increases the total H₂ demand of the aviation sector, as eSAF production generates a massive indirect H₂ demand that exceeds the demand of direct LH₂ propulsion by a factor of nine, even in the Moonshot scenario.
- » In a cost-optimised parallel supply network, LH₂ is predominantly imported via vessels from regions with low production costs, such as Chile. Conversely, gaseous H₂ for European eSAF refineries is primarily supplied via pipelines from Europe and Morocco.
- » The additional H₂ demands for domestic eSAF production also drive up the overall LH₂ costs, as the increased demand means production can no longer be limited to the most cost-effective regions in Europe.
- » Meeting the European aviation demand with a 60% eSAF import share requires a massive expansion of the European energy system, including a 76% increase in solar photovoltaic capacity and a 90% increase in electrolyser capacity.
- » From a macroeconomic perspective, the production of eSAF and LH₂ offers significant value-creation in potential export countries. Countries like Morocco and South Africa show pronounced employment multipliers due to labour-intensive supply chain phases, while Australia and Canada exhibit high household income and gross domestic product multipliers.

What we recommend

- » Infrastructure planning must proactively account for the parallel development of LH₂ and eSAF supply chains to avoid resource competition and supply bottlenecks.
- » A rapid and coordinated expansion of renewable energy generation, particularly solar photovoltaics, alongside electrolysis capacities is critical to meet future H₂ demands without disrupting the broader European energy transition.
- » Europe should establish strategic and diversified international trade partnerships to import a significant share of its eSAF and LH₂ demand. This mitigates the extreme pressure on the domestic energy system while fostering global macroeconomic benefits and supply security.



Advisory board



The representations in this document do not necessarily reflect the opinions of the companies on the Advisory Board.

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INTRODUCTION

1 Introduction

This document serves as a supplementary report to the HyNEAT final project report, extending the initial scope of the investigation [1]. While the main study evaluated the liquid hydrogen (LH₂) supply infrastructure specifically for H₂-powered aviation, it excluded the H₂ demands associated with the production of H₂-based sustainable aviation fuels (eSAF). Consequently, this analysis integrates the H₂ supply requirements for both direct H₂-propulsion and eSAF-powered aviation across a European airport network.

The transition to a climate-neutral aviation sector by 2050 requires a multifaceted approach to fuel supply, as reflected in the ReFuelEU Aviation regulation [2]. This policy framework mandates a progressive increase in the share of Sustainable Aviation Fuels (SAF) at European airports, increasing from 2% in 2025 to 70% by 2050. While the regulation includes specific sub-mandates for synthetic aviation fuels, biofuels currently constitute the most technologically mature and commercially viable option. Biofuels are pivotal for near-term decarbonisation, functioning as drop-in solutions that leverage existing aircraft fleets and refueling infrastructure with minimal modification. However, the long-term scalability of biofuels is constrained by several critical factors. The availability of sustainable biomass is limited, and its production often faces intense competition for land use with food and feed production, as well as biodiversity conservation [3]. Due to these sustainability limits and land availability issues, biofuels alone cannot meet the total projected energy demand of the aviation sector.

Consequently, eSAF produced via the power-to-liquid pathway is a critical component for the holistic decarbonisation of the aviation sector, as also reflected in the ReFuelEU regulation. While direct H₂ combustion and

fuel cell technologies offer promising solutions for short-to-medium-range segments, the high energy density requirements of long-haul aviation necessitate the continued use of liquid hydrocarbons for the foreseeable future [4]. eSAF offers a carbon-neutral drop-in replacement for conventional kerosene, utilising captured CO₂ and green H₂. Since biofuel production typically does not require external H₂, it is not included in the technical infrastructure analysis in this report. Instead, this report provides a more comprehensive assessment of the total H₂ demand and the resulting impact on infrastructure and energy resources by addressing both LH₂ and eSAF pathways simultaneously.

Building upon the airport network established in the main HyNEAT report, this study incorporates the additional H₂ demand necessitated by eSAF production. This integrated approach allows for a rigorous analysis of the influence on LH₂ supply infrastructure at individual airport nodes, the configuration and scaling of the overarching LH₂ supply network, the broader European energy system, and the associated macroeconomic implications.

The report is structured as follows. First, the methodology of this work is discussed in Chapter 2, including the overall design of the study and the specific methodologies employed in the individual thematic analyses. Following this, further developed scenarios from the HyNEAT project are presented in Chapter 3, including the resulting fuel demands for both LH₂ and eSAF. Chapter 4 analyses the parallel H₂ and eSAF supply chains, with a focused evaluation of their impact on the LH₂ supply network, the energy system, and the macroeconomic landscape. The report concludes with a summary and a discussion of the final conclusions.

METHODOLOGY

2 Methodology

To provide context for the study results, this chapter first outlines the current regulatory framework regarding eSAF. Following on this, the eSAF supply routes and components considered in this study are introduced. It also introduces the overall study design and model framework. Given the wide range of models and methodologies applied in this interdisciplinary project, the specific methodology of each model is briefly discussed in this chapter to support a clearer understanding of the results. As this report serves as a supplementary report to the HyNEAT final project report, only the adjustments and special features of the methodology relevant for this study are presented. A detailed description of the complete methodology, including model equations and assumptions, is provided in Appendix A and the main report [1].

2.1 Regulatory framework

In this section, the regulatory framework regarding eSAF is discussed. There are four relevant policies to incentivise the uptake of SAF on a multinational level, which are detailed below. It is important to note that these international and EU-wide frameworks often coexist with national policies; individual Member States may implement more stringent domestic regulations, such as higher blending mandates or specific sub-quotas for certain feedstocks, to accelerate their local decarbonisation trajectories.

CORSIA

Under the International Civil Aviation Organization (ICAO), two primary climate targets have been established, which are the goal of “carbon-neutral growth” from 2020 onwards and the long-term aspirational goal of net-zero CO₂ emissions by 2050 [5]. CORSIA mandates the offsetting of international aviation CO₂ emissions exceeding a baseline that transitioned from 2019 levels during the pilot phase (resulting in zero requirements through 2023) to 85% of 2019 levels for the 2024–2035 period [6]. Compliance is managed through the procurement of ICAO-certified emission units that satisfy rigorous environmental criteria, such as permanence and the avoidance of double counting, or by utilising eligible SAFs to directly reduce total offsetting obligations. As of 2026, 130 states participate in the voluntary phase of CORSIA [7].

EU ETS

The EU Emissions Trading System (EU ETS) is a market-based mechanism that caps total greenhouse gas emissions from regulated sectors, requiring aircraft operators to surrender allowances for their CO₂ emissions on flights within the European Economic Area (EEA) and to the UK or Switzerland [8]. From 2024, the scope extends to outermost regions, and as of 2025, operators are also required to monitor and report non-CO₂ environmental effects. While international flights involving CORSIA-participating third countries are currently managed via the global offsetting scheme, the European Commission is scheduled to evaluate CORSIA's environmental integrity by July 2026 to decide if the EU ETS should be expanded to further align with the Paris Agreement and Union climate goals. Exemptions remain in place for domestic flights in non-EEA states and routes serving least developed countries or small island nations. This dual-track approach ensures that European aviation contributes to regional targets while bridging the transition toward international climate frameworks.

EU Renewable Energy Directive (RED)

The Renewable Energy Directive III (RED III) mandates an EU-wide renewable energy share of 42.5% by 2030, requiring the transport sector to achieve either a 14.5% greenhouse gas intensity reduction or a 29% renewable energy share [9]. While the directive does not set aviation-specific mandates, the sector is expected to fulfil a significant portion of the 5.5% combined sub-target for advanced biofuels and Renewable Fuels of Non-Biological Origin (RFNBOs) through the quotas established by the ReFuelEU Aviation regulation.

Stakeholders warn that inconsistent national transposition of feedstock rules and uncertainty regarding eSAF obligations may obstruct uptake, as industry investment cycles for new fuel technologies often exceed seven years [6]. To maintain transparency and environmental integrity across these targets, Article 30(1) establishes a mass balance chain-of-custody system for all renewable energy carriers. Harmonising these national implementations is essential to prevent regulatory fragmentation from undermining the inherently international nature of the aviation market.

ReFuelEU Aviation

ReFuelEU Aviation is a regulation that mandates fuel suppliers at EU airports to provide increasing shares of SAF, scaling from 2% in 2025 to 70% by 2050, covering all commercial flights including international departures. This includes a specific sub-quota for synthetic fuels (RFNBOs) starting at an average of 1.2% in 2030 (0.7% minimum) and rising to 35% by 2050, alongside advanced biofuels and recycled carbon fuels that meet a 70% emissions-savings threshold. Notably, suppliers may also fulfil these mandates – including the synthetic sub-quota – by providing renewable or low-carbon H₂ for direct use in aircraft, provided it meets a 70% lifecycle emission savings threshold. To prevent economic distortion and carbon leakage, the regulation includes an anti-tankering provision requiring airlines to uplift at least 90% of their annual fuel needs at Union airports. Furthermore, a transitional flexibility mechanism, active until 2034 allows suppliers to meet blending targets through weighted averages across airports, supporting efficient logistics at major hubs and pipeline-connected facilities. This framework aims to provide long-term investment certainty while accommodating the initial technical and logistical challenges of SAF distribution. [2]

Chain of Custody Systems

Chain of custody systems are essential tracking mechanisms used to verify environmental claims by documenting the movement of SAF through the supply chain [10]. The first and most rigid model is physical segregation, which requires keeping the SAF entirely separate from conventional jet fuel from production until it is loaded into the aircraft. While this allows for direct molecule-to-claim traceability, it is often considered economically and environmentally inefficient because SAF is a drop-in fuel fully compatible with existing infrastructure; building separate tanks and pipelines would significantly increase costs and the carbon footprint of logistics [11].

The second model, mass-balance, allows sustainable and conventional fuels to be mixed within a shared, closed infrastructure. Under this system, any supplier who introduces a specific volume of SAF into the network can claim the associated environmental benefits, even if the physical molecules they withdraw elsewhere are not the original ones. This approach significantly reduces logistical overhead while maintaining a verifiable link to a

physical supply system, ensuring that for every unit of fuel claimed as sustainable, a corresponding unit was actually produced and injected into the infrastructure [10].

The third and most flexible option is the book-and-claim system, which decouples the environmental attributes from the physical fuel and converts them into tradable certificates managed through a central registry. This model allows airlines and suppliers to purchase and claim the benefits of sustainable fuels even if they lack direct access to physical distribution sites, facilitating a global market and greater scalability [11]. By redeeming these certificates, the environmental benefits are linked back to an equivalent volume of physical fuel sold. European legislation already utilizes similar mechanisms for biomethane and renewable energy units, suggesting that existing administrative frameworks could be adapted to support a centralized registry for aviation fuels, ensuring integrity and preventing issues like double-counting [12].

Currently, regulatory frameworks such as RED III and ReFuelEU Aviation rely on a mass balance chain of custody system [2,8]. This ensures that while SAF molecules are mixed with fossil kerosene in existing infrastructure, the environmental benefits remain linked to the physical fuel supply. ReFuelEU Aviation currently allows a transitional flexibility mechanism where fuel suppliers can meet their blending mandates as a weighted average across multiple airports. This flexibility is scheduled to end in 2034. From 2035 onward, the regulation requires that the minimum SAF shares be met at each individual Union airport [2]. This requires that the mass balance has to be achieved specifically within the fuel supply of each individual airport

In contrast, the book and claim model is the standard for the voluntary market, used by organizations like the Sustainable Aviation Buyers Alliance to allow for global scalability regardless of geographic location [13]. Looking forward, the European Commission is developing the Union Database to improve transparency and traceability of these certificates [14]. While there is significant industry pressure to adopt a standardized book and claim framework for regulatory compliance after 2035 to reduce logistical costs, the current legislative path focuses on localized mass balance to maintain regional environmental integrity [6].

2.2 eSAF supply routes and components

In this section, the available SAF production methods, the eSAF supply chains and the components required for them are presented.

There are different SAF production pathways available. For every new production pathway, the fuel must undergo extensive testing to define the maximum blend ratio with conventional jet-fuel and to ensure these novel fuels meet performance and safety standards for civil aviation. Currently, there are eight SAF production pathways accepted by the American Society for Testing and Materials (ASTM).

- » Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)
- » Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)
- » Synthetic Iso-Paraffin (SIP)
- » Fischer Tropsch Synthetic Kerosene with Aromatics (FT-SKA)
- » Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)
- » Catalytic Hydrothermolysis Jet fuel (CHJ)
- » Hydroprocessed Hydrocarbons-HEFA (HHC-HEFA)
- » Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)

The Fischer-Tropsch pathway is widely regarded as the most promising pathway for the large-scale production of eSAF due to its technical maturity, feedstock versatility, and the quality of the resulting fuel. As a mature, ASTM-certified drop-in solution, FT technology enables immediate industrial scaling without necessitating modifications to existing aviation infrastructure or

propulsion systems. By leveraging theoretically unlimited renewable H₂ and captured CO₂, this pathway bypasses the resource constraints of bio-based fuels to satisfy long-term synthetic fuel mandates. Additionally, its high chemical selectivity and feedstock flexibility ensure the production of hydrocarbons that reliably meet the required 70% lifecycle emission reduction thresholds. This is why, in this study only eSAF production using Fischer-Tropsch technology is considered.

Supply routes

Figure 1 illustrates the supply pathways for eSAF considered in this study. Two primary scenarios are evaluated: domestic eSAF production within Europe and eSAF import to Europe. In both pathways, H₂ is produced via electrolysis powered by renewable energy sources (RES), with gaseous hydrogen (GH₂) storage utilised to mitigate the intermittency of renewable generation. Regarding the carbon feedstock, while CO₂ could theoretically be obtained from biogenic or industrial point sources (e.g., the cement industry), the anticipated sector-wide decarbonisation limits the long-term reliability of these streams. Consequently, this study assumes that CO₂ is sourced via Direct Air Capture (DAC) powered by RES. In the downstream process, H₂ and CO₂ are converted into synthesis gas (syngas) via the Reverse Water Gas Shift (RWGS) reaction. Subsequently, the syngas undergoes Fischer-Tropsch synthesis to produce synthetic crude (syncrude), which is fractionated into final fuel cuts. While various configurations exist for the Fischer-Tropsch synthesis, this study assumes a configuration optimised for eSAF, yielding naphtha and Liquefied Petroleum Gas (LPG) as co-products. The eSAF could then be blended either directly with kerosene or alternatively transported and blended at a later point. The utilisation of SAF as a drop-in fuel eliminates the necessity for dedicated transport, storage and refuelling infrastructure.

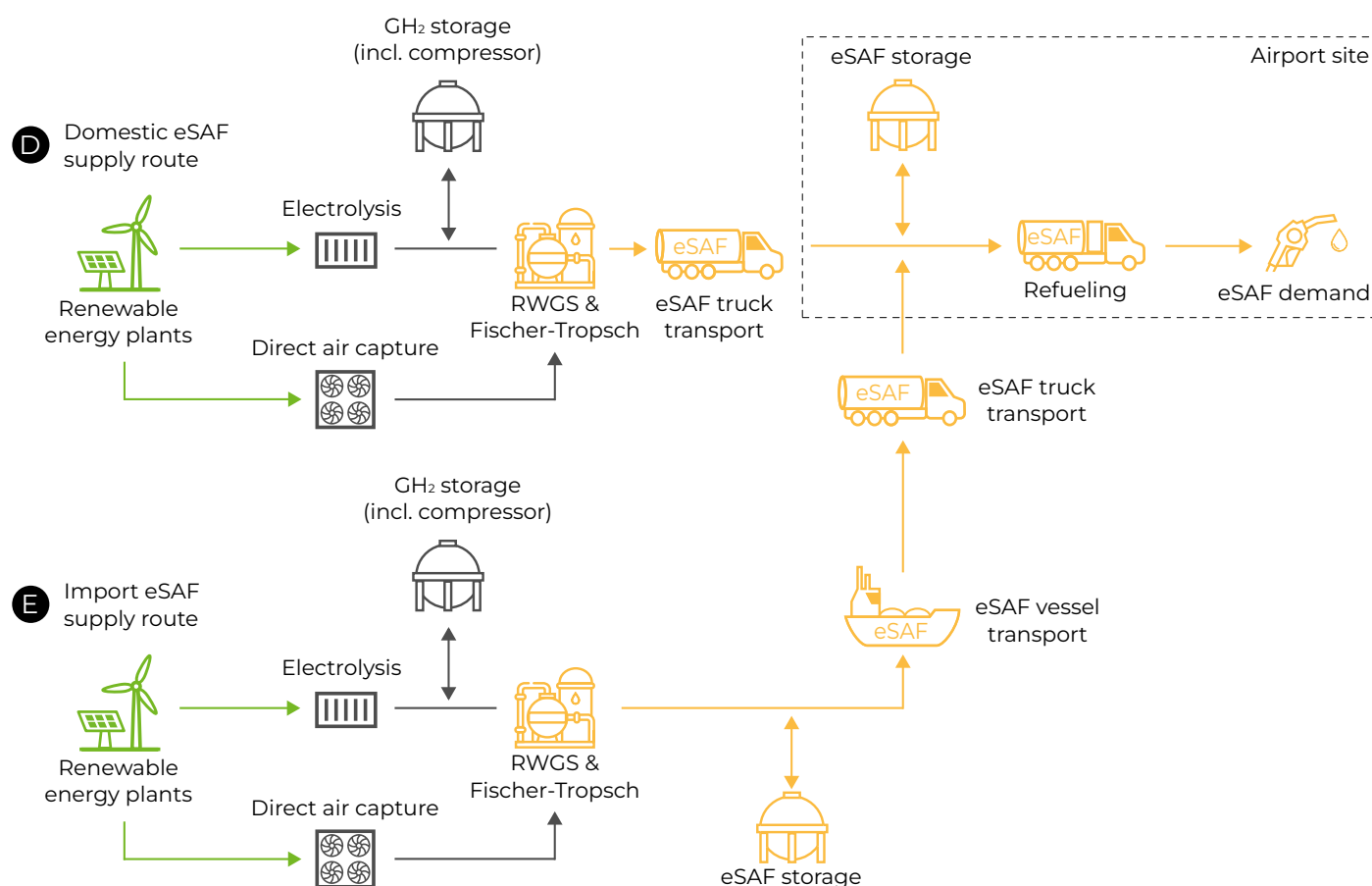


Figure 1: eSAF supply routes considered in this study: D: Domestic eSAF supply route, E: Import eSAF supply route

2.3 Study design and model framework

This section outlines the study design for the analysis of the H₂ supply network for eSAF and LH₂. The methodology aligns with the main report to ensure consistency and comparability of results. All evaluations are grounded in the overarching scenarios detailed in Chapter 3. Subsequently, Chapter 4 analyses the H₂ supply chain, focusing on how the eSAF supply influences the LH₂ supply network, the broader energy system, and macroeconomic indicators. The analysis utilises the airport network established in the main report. The eSAF production and blending are assumed to occur centrally at large blending hubs to leverage existing kerosene infrastructure and logistics. These hubs are identified as either crude oil refineries or import seaports. The supply network model considers 93 potential refinery locations and five import seaports. Figure 2 illustrates the selected airports and available refinery locations. To optimise computational efficiency, eSAF demand at airports is allocated to refineries prior to the primary network optimization. Since the distribution of eSAF blends utilises existing transport modalities, a detailed techno-economic analysis of this specific transport leg is excluded. Instead, demand allocation is modelled as a discrete facility location problem, minimizing total transport work in ton-kilometres (tkm). To benchmark the constraints of using existing infrastructure, this allocation method was also applied to a greenfield scenario, examining an equivalent

number of locations without fixed geographic constraints. The greenfield approach leads to similar eSAF production locations compared to the existing refinery locations, which confirms that these locations are suitable for eSAF production not only because of their existing infrastructure but also because of their geographical location. The detailed methodology and results of the demand allocation are shown in Appendix A.

From a global economic perspective, importing the majority of eSAF to Europe could theoretically minimise overall supply costs, primarily due to the comparatively low transport costs associated with liquid fuels and the comparably lower potential for low-cost renewable energy in Europe. However, escalating geopolitical tensions and market volatility have elevated supply security to a critical priority. To account for these uncertainties, this study examines scenarios with varying eSAF import share (60%, 70%, 80% and 90%). The allocation of imported eSAF to specific airports is determined based on the results of the European energy system analysis. Airports located in regions characterised by low H₂ availability or high domestic production costs—particularly those in proximity to import seaports—are prioritised for supply via imported eSAF blended directly at the import terminal. The remaining demand is allocated to domestic refinery locations as defined in the methodology above.

● Airports
● Refineries

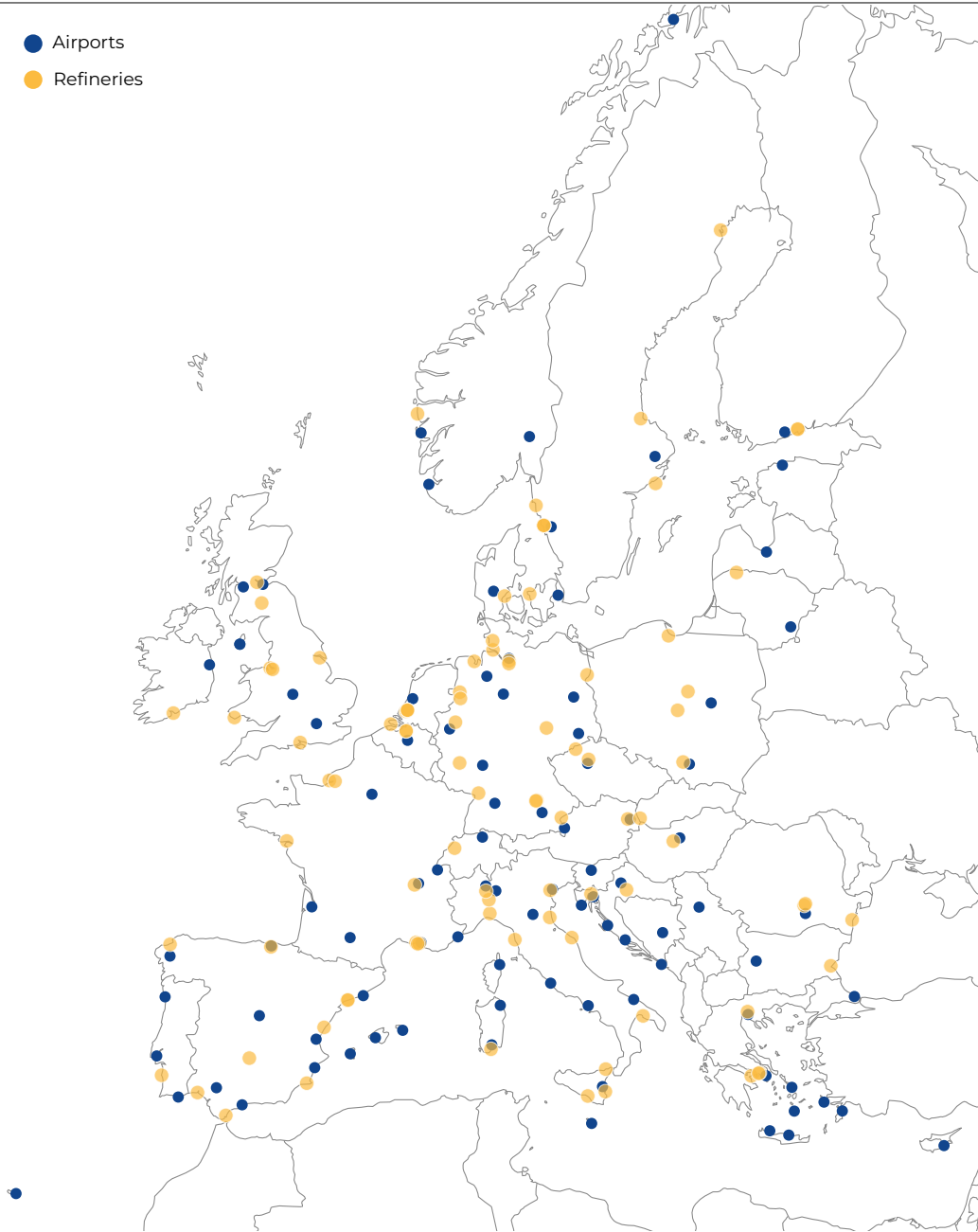


Figure 2: Airport network and refinery locations under consideration

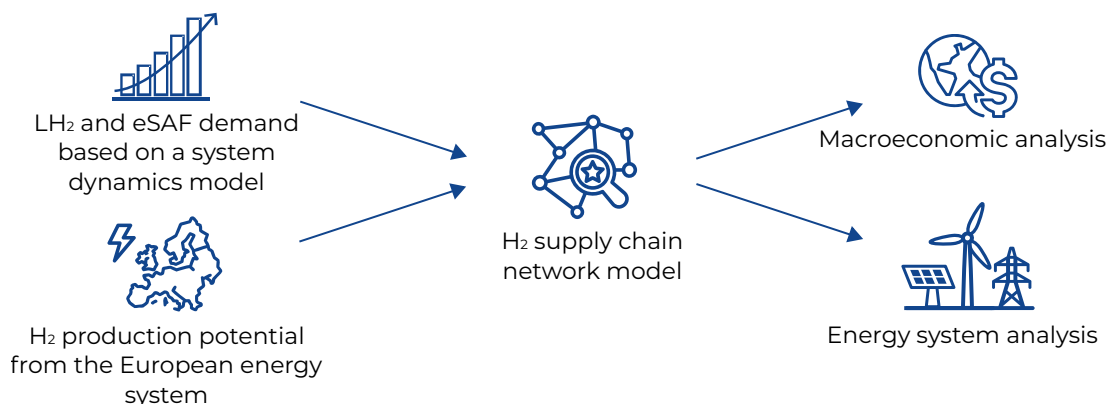


Figure 3: Model framework for this report

2.4 Methodology for the individual studies

In the following, the applied models in this study are briefly introduced. All costs in this report are stated in USD2023, with literature values corrected to USD using a conversion factor of 1.09 EUR/USD. The inflation effects are considered using the Chemical Engineering Plant Cost Index (CEPCI) to convert the assumptions to USD2023 [15]. The techno-economic assumptions in this study are shown in Appendix A. It is important to note that, the cost

assumptions used in this study represent only one possible development path. A more robust assessment of future costs would require a comprehensive sensitivity analysis. However, due to the high computational effort and long runtimes of the applied models, such an analysis is not feasible within this study. As the main source of emissions, only commercial aviation is included in this study.

2.4.1 System dynamics model for the hydrogen and eSAF demand scenarios

The methodological basis is the System Dynamics model introduced in the main project report [1]. System Dynamics is well-suited for modelling, simulating, and analysing complex socio-technical systems, as it explicitly represents interdependencies, feedback loops, and time delays between different actors [16]. In aviation, this is particularly relevant because the transition towards alternative energy carriers depends on the interaction among aircraft manufacturers, airlines, airports, fuel suppliers, and policymakers over time [17].

The original model focused on estimating future LH₂ demand resulting from the market introduction and diffusion of H₂-powered aircraft. It captured fleet renewal decisions, aircraft production capacities, delivery backlogs, and the availability of H₂ infrastructure. Airline investment decisions were modelled based on the total cost of ownership (TCO), including acquisition, maintenance, and energy carrier costs. This core structure is retained in the present extension.

The project top-up broadens the model scope by integrating sustainable aviation fuels (SAF) as additional fuel options. This is necessary because the direct use of H₂ in aircraft is expected to be most relevant for regional, short-haul, and medium-haul operations, while long-haul aviation remains difficult to address due to range and aircraft design constraints. By contrast, SAF can be used in existing aircraft and infrastructure and is therefore relevant for all route segments, including long-haul aviation.

Within the extended model, airline decisions are represented in two stages. First, the airline decides whether to procure hydrogen-powered or conventional aircraft when additional capacity is required. This decision follows the original TCO-based logic and depends on aircraft availability, purchase and maintenance costs, fuel costs, and policy-related cost components. Second, the airline determines the fuel mix for its conventional fleet. Existing and newly acquired conventional aircraft can be operated with kerosene, eSAF, or bio-based SAF. Fuel selection is primarily cost-driven, while ensuring compliance with regulatory requirements, particularly the blending mandates under RefuelEU aviation [2].

The extended model, therefore, captures H₂ demand through two pathways: direct LH₂ demand for H₂-powered aircraft and indirect H₂ demand as an input for eSAF production. This distinction is important because both pathways may develop in parallel, compete for renewable H₂ supply, and address different aviation market segments.

The extension also incorporates long-range passenger demand more explicitly. This enables a more complete representation of future aviation fuel demand and allows the H₂ requirements associated with eSAF production to be quantified across the full aviation network. Overall, the extended System Dynamics model preserves the core feedback structure of the original model while accounting for complementary decarbonisation pathways and their implications for future H₂ supply planning.

2.4.2 Energy system transformation model (ESTRAM)

To assess the potential H₂ production volumes and costs, an energy system transformation model from the main report has been used. As part of the defossilization of the energy system, many sectors currently supplied with fossil fuels will be electrified. However, certain sectors remain particularly challenging to electrify. These so-called hard-to-abate sectors include not only specific processes in the industry but also transportation, with aviation standing out as a critical example.

The key challenge, therefore, lies in the transition of today's energy system in a way that ensures that future energy demands across all sectors can be met while adhering to the remaining carbon emission budget. To address this, the energy system transformation model (ESTRAM) is developed, which optimises transition pathways from the present energy system to a highly renewable one under macroeconomic considerations. The objective of ESTRAM is to identify and evaluate possible pathways for the energy transition, thereby providing insights into feasible strategies for achieving climate targets. The optimisation framework ESTRAM is based on a spatial and temporal discretisation of the European energy system. For the spatial representation, the NUTS (European Union Nomenclature of territorial units for statistics) classification down to the NUTS-1 level is used, corresponding to distinct European regions. Temporally, the model operates with a five hourly resolution, capturing the evolution of the energy system from the present up to 2050.

As a first step, data on the current energy system are collected, including existing power plants and the installed capacities of RES such as photovoltaics and wind power. Each spatial node, representing a NUTS-1 region, is modelled to exchange energy with neighbouring nodes. This is enabled through the integration of existing European transmission grids, as well as the inclusion of planned future grid expansions. In addition to supply-side data, sector specific energy demand profiles are compiled. These demands are projected into the future by

accounting for factors such as demographic developments and renovation rates of the building stock. Coupling of sectors is performed via the introduction of sector coupling technologies such as battery-electric vehicles or heat pumps.

The collected data form the basis for the optimisation problem, which is formulated as a linear programming (LP) model. Subsequently, ESTRAM determines the cost-optimal dimensioning of energy sources, converters, storages and consumers. A variety of constraints are incorporated into the LP to ensure realistic and policy-consistent outcomes. These include the energy balance at each individual node and at all times, annual limits on the expansion rate of renewable energy technologies, and the remaining lifetimes of existing power plants. Furthermore, the optimisation is constrained by an annual carbon emission limit, with explicit consideration of national climate strategies and regulatory frameworks where such information is available.

The LP model is solved with the objective of minimising the total energy system costs. For this, techno-economic assumptions have been made for all relevant system components, including RES, storage technologies, consumer, and converters such as electrolyzers. These assumptions (shown in Appendix A) include values for the capital expenditures (CAPEX), operational expenditures (OPEX), component lifetimes and technical parameters such as conversion efficiencies for each step of the transition path. This approach enables ESTRAM to identify least-cost transition pathways while remaining consistent with both system limitations and political targets. The result contains both dimensioning and dispatch of all components for all nodes and timesteps of the model. On a global scale, ESTRAM is used to calculate import costs of green H₂ from production sites around the world. To this end, global island energy systems are modelled consisting of electrolyzers coupled with photovoltaics and wind power and determine the marginal costs of the produced H₂.

2.4.3 Hydrogen supply network model

To determine cost-optimal H₂ supply chain networks (HSCNs) for aviation, a mixed-integer linear programming (MILP) model is developed that captures strategic infrastructure decisions and operational H₂ flow planning across a spatially and temporally resolved network. The model minimizes the total cost of the H₂ network, including capital expenditures, operational costs, and maintenance for all facilities and transport infrastructure.

Strategic decisions in the model include where and when to invest in H₂ production, import terminals, liquefaction plants, storage facilities, and transportation modes, along with their respective capacity levels. At the operational level, the model determines the amount of H₂ to be produced, transported, stored, and delivered. It accounts for spatial and temporal variation in H₂ supply and demand, the resulting variations in H₂ production costs, and specific H₂ handling characteristics such as losses during transport and storage.

The model includes constraints to ensure that airport LH₂ and refinery GH₂ demands are met, supply limits are respected, and all H₂ flows are balanced throughout the network. It enforces capacity limits for facilities and transport assets, ensures stock consistency over time at storage locations, and incorporates handling losses. All decisions are subject to logical and technical feasibility requirements, including investment timing and minimum deployment thresholds. The model was implemented in Python and solved using the Gurobi Optimizer. The model is tested in case studies and results provide valuable

2.4.4 Macroeconomic analysis

The macroeconomic analysis builds on the Social Accounting Matrix (SAM)-based multiplier model described in detail in the main project report and its Appendix [1]. For consistency with the main report scope, all SAMs are constructed for the base year 2019. As the modelling framework remains unchanged, this supplementary report primarily differs in its study design, which is outlined below.

Country selection

The main project report focused on Europe and the Middle East and Northern Africa (MENA). In contrast to the original scope, the supplementary analysis does not incorporate dedicated analyses on European countries. Given the expected relevance of eSAF imports for Europe, this supplementary adopts a more global perspective and focuses on potential export countries with favourable production conditions.

As in the main report, Morocco and Saudi Arabia are also key export markets for eSAF within the MENA region. The selection of additional export countries follows a structured suitability assessment based on economic and political indicators and the eSAF export potential. Key criteria include (1) Green H₂ production potential exceeding projected domestic demand, (2) Coastal access for maritime transport, (3) Macroeconomic and political stability, and (4) Regional diversification to reduce dependency on a single continent. Based on these criteria, four additional countries are included: Australia, Canada, Chile, and South Africa. All selected countries offer favourable conditions for renewable H₂ production and are widely discussed as potential exporters of green derivatives such as eSAF [18,19].

Australia benefits from vast land availability and high potential for solar PV and wind power [18], combined with

insights into the optimal structure and cost of H₂ supply for aviation. The results of the H₂ supply network model describe which airports and refineries are supplied by specific production hubs, the transport modes employed under the varying conditions, the roles of storage and liquefaction, and the resulting LH₂ supply costs at each airport. They also comprise a detailed cost breakdown across all supply chain components, supporting data-driven infrastructure planning and policy decisions. Details of the H₂ supply network optimization model are provided in the main report [1].

strong economic and political stability and explicit ambitions to become a major exporter of green derivatives [20,21]. Canada provides favourable wind conditions for H₂ production [22,23] and has already established strategic H₂ partnerships with European countries [24]. Chile represents South America and is among the most politically stable countries in the region [25]. Its long coastline and great RES conditions, particularly for wind power, provide strong preconditions for large-scale H₂ production and export [18,26]. South Africa is included to represent Sub-Saharan Africa (SSA), being the most industrialised and economically mature country in the region [27,28]. It combines comparatively favourable institutional conditions with strong renewable energy potential and access to maritime transport [29,30]. An overview of the selected countries with relevant economic indicators is shown in Figure 4.

Supply chain analysis

The eSAF supply chain largely builds upon the LH₂ supply chain analysed in the main project report. Technologies such as renewable energy, electrolysis, and gaseous H₂ storage remain central elements. The main difference is the downstream conversion stage. Compared to LH₂, eSAF production requires two additional technological components: Direct Air Capture (DAC) for the provision of circular CO₂ and an integrated synthesis plant comprising Reverse Water Gas Shift (RWGS) and Fischer-Tropsch (FT) synthesis [33,34]. In addition, a storage tank for eSAF is incorporated into the supply chain design. As eSAF is assumed to be blended with and transported alongside conventional kerosene within existing fuel infrastructure, downstream blending and distribution processes are not explicitly modelled in the macroeconomic assessment. A detailed overview of all technologies and key components included in this supplementary analysis is provided in Appendix A.1.

Economic scenario design

The main project report assessed multiple economic scenarios reflecting different structural trajectories and development pathways. Given the adjusted focus of this supplementary, the economic base scenario is applied consistently across all countries. The base scenario reflects a country-specific status-quo projection and is defined along three structural dimensions: (1) Degree of self-supply for key components, (2) Domestic shares in installation and operation phases, and (3) Origin of

investment. In line with the original methodology, the degree of self-supply for key components is derived from country-specific trade balances using UN Comtrade data [35]. Domestic shares for installation and operation are calculated based on the respective SAM structures. The share of foreign investment is determined using foreign direct investment (FDI) stock data [32]. A detailed country-level overview of all underlying data and assumptions is provided in Appendix A.3.

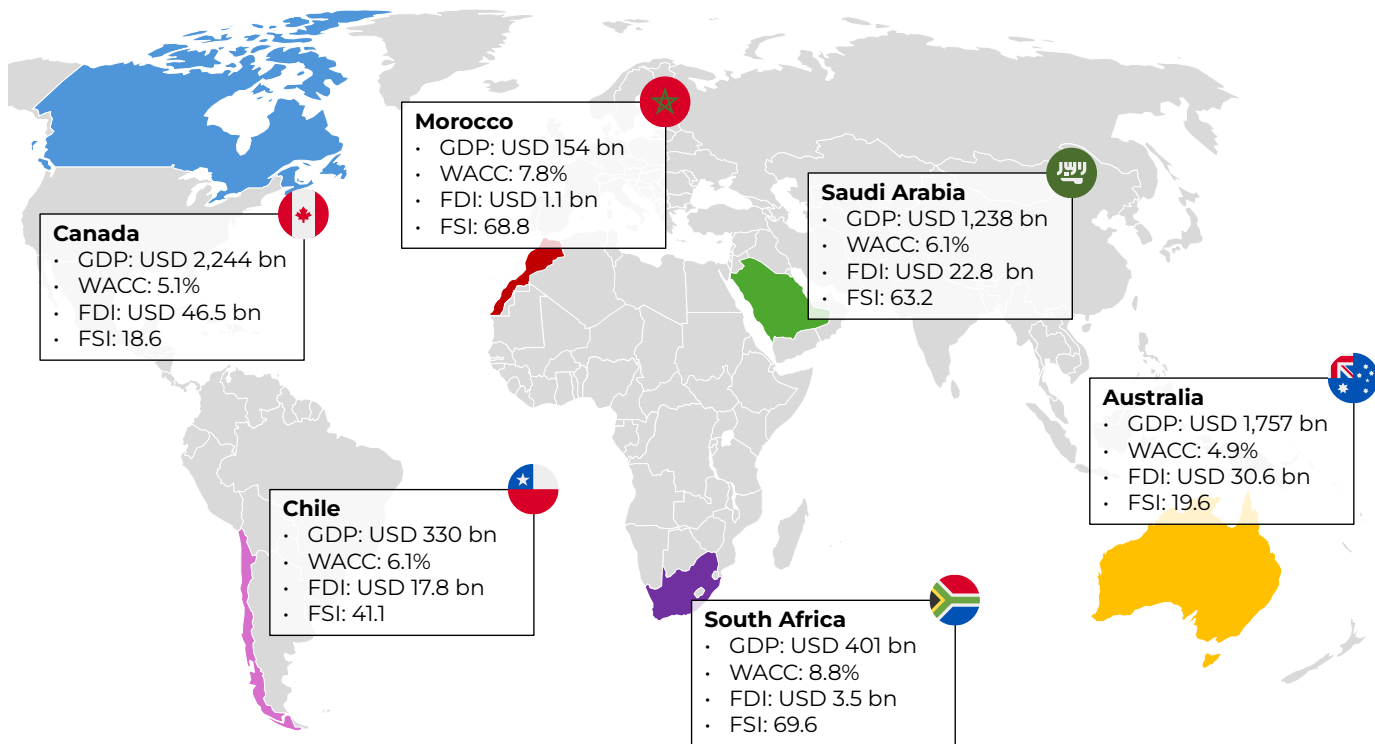


Figure 4: Overview of the selected countries/regions with economic indicators. GDP data is given for 2024 [31]. WACC data are obtained from project-internal estimations for LH2 infrastructure. Foreign direct investment (FDI) reflects the inflows into the respective country in 2023 [32]. The Fragile States Index (FSI) is shown for 2024 [25].

SCENARIO DEFINITION AND FUEL DEMANDS

3 Scenario definition and fuel demands

This section presents the extended scenario framework and the resulting fuel demand developments. Building on the model from the main HyNEAT report, the project top-up integrates bio-based SAF and eSAF as additional fuel options for conventional aircraft. This allows the analysis to

capture both direct LH₂ demand from H₂-powered aircraft and indirect H₂ demand from eSAF production. Afterward, the resulting fuel demand structures across the three HyNEAT scenarios are compared.

3.1 Extension of the main HyNEAT model

The original model focused on estimating future LH₂ demand resulting from the market introduction and diffusion of H₂-powered aircraft. The corresponding demand trajectories were derived using a System Dynamics model that captures interactions between aircraft manufacturers, airlines, and airports over time. These interactions determine the pace of fleet renewal, the availability of H₂-powered aircraft, and the resulting LH₂ demand at the airport and European level.

The extension developed in the project top-up broadens this perspective by integrating additional aviation fuel options into the existing modelling framework. Besides the direct use of LH₂ in H₂-powered aircraft, the model now also considers bio-based SAFs and eSAF besides fossil kerosene for the conventional aircraft fleet. This

allows future aviation fuel demand to be assessed more comprehensively, particularly because SAFs can be used in existing aircraft and infrastructure, making them relevant to all route segments, including long-range aviation.

The extended model preserves the core structure of the original System Dynamics model. Airline fleet development, aircraft acquisition decisions, passenger demand growth, and the market diffusion of H₂-powered aircraft remain central elements of the analysis. The main methodological extension lies in the explicit representation of fuel allocation decisions for the conventional fleet and in the quantification of the indirect H₂ demand associated with eSAF production.

3.2 Fuel choice logic and main assumptions

The analysed scenarios differ primarily with respect to fuel allocation decisions, fuel price developments, regulatory requirements, and the resulting fuel demand structures. The comparison focuses on how airlines adapt their fuel choices under varying economic and regulatory conditions.

In the model, airline fuel selection is assumed to be cost-driven. Airlines choose between the available fuel options according to their relative costs while complying with mandatory regulatory requirements. In particular, the RefuelEU Aviation quota requirements are implemented as binding constraints that must be fulfilled independently of market price developments.

For conventional aircraft, the existing model logic is extended by allowing the use of kerosene, bio-based SAF, and eSAF. H₂-powered aircraft, by contrast, continue to generate direct LH₂ demand. The model therefore distinguishes between two H₂ demand pathways: direct

demand for LH₂ used in H₂-powered aircraft and indirect demand for H₂ used as an input for eSAF production.

A central assumption of the analysis is that no production constraints are imposed on the availability of eSAF, bio-based SAF, or H₂. All fuels are assumed to be available in sufficient quantities to meet the modelled demand. As a result, differences between the scenarios arise from economic conditions, fuel prices, and policy assumptions rather than from supply limitations. This allows the analysis to isolate the effects of cost developments and regulatory requirements on airline fuel choices.

To quantify the H₂ demand associated with eSAF production, a conversion factor is applied within the model [36]. This factor links eSAF output to the corresponding hydrogen input required for its production. The price assumptions for bio-based SAF are based on EASA (2025) [37].

3.3 Scenario comparison and resulting fuel demands

Across the analysed scenarios, clear structural shifts in aviation fuel demand become visible. Under the defined assumptions, SAF and eSAF can reach substantial demand levels and increasingly substitute conventional kerosene. This indicates that SAFs can become an important component of future aviation decarbonisation, particularly in those market segments where direct H₂ use remains technologically constrained. The role of eSAF depends strongly on its relative cost position compared with kerosene and bio-based SAF. Once eSAF becomes cost-competitive, it will increasingly replace other fuel options in the conventional aircraft fleet. This transition represents a central driver of the future fuel demand structure, as eSAF provides a drop-in fuel option while simultaneously creating additional H₂ demand through its production process.

The comparison of scenarios, therefore, shows that the interaction among fuel costs, regulatory quotas, and the availability of aircraft technology shapes future fuel demands. While the HyNEAT scenarios in the main report mainly differentiated the market uptake of H₂-powered aircraft through varying levels of political support and market introduction dates, the extended analysis additionally captures how airlines allocate fuel types within the conventional fleet under the same scenario logic.

Figure 5 shows the resulting H₂ demand regarding eSAF production and direct use in H₂-powered aircraft for the three scenarios analysed in the main report.

In the **Moonshot scenario**, a significant increase in eSAF deployment occurs in 2042. This pronounced shift is

driven by a substantial decline in H₂ prices, which reduces eSAF production costs to levels below those of kerosene and biofuels. Prior to this cost crossover, airlines adopt eSAF only to the extent required to comply with mandated blending quotas. Once eSAF becomes the economically preferred option, consumption expands rapidly. This results in overall H₂ demand of 115.5 MtH₂ (102.9 MtH₂ for eSAF) in 2050 and cumulative demand of 989 MtH₂ (977 MtH₂ for eSAF)

In the **Ambitious Policy scenario**, eSAF achieves cost competitiveness considerably later. eSAF prices fall below those of kerosene and biofuels in 2049. Consequently, until this point, airlines again limit eSAF adoption to the fulfilment of regulatory quota requirements, with substantial market-driven uptake occurring only after the cost advantage emerges. This results in overall H₂ demand of 120.1 MtH₂ (117.4 MtH₂ for eSAF) in 2050 and cumulative demand of 389 MtH₂ (386 MtH₂ for eSAF). Figure 6 shows the airport specific H₂ demands for eSAF and LH₂. As discussed in Section 2.3, the H₂ demand for eSAF production occurs at refineries, where eSAF is produced and then transported to airports.

In contrast, the **Baseline scenario** shows no economic transition toward large-scale eSAF adoption. Throughout the entire modelling horizon, eSAF remains more expensive than both kerosene and biofuels. As a result, airlines consistently meet only the minimum quota obligations, and no additional substitution toward eSAF takes place. This results in overall H₂ demand of 42.52 MtH₂ (42.515 MtH₂ for eSAF) in 2050 and cumulative demand of 207.68 MtH₂ (207.66 MtH₂ for eSAF).

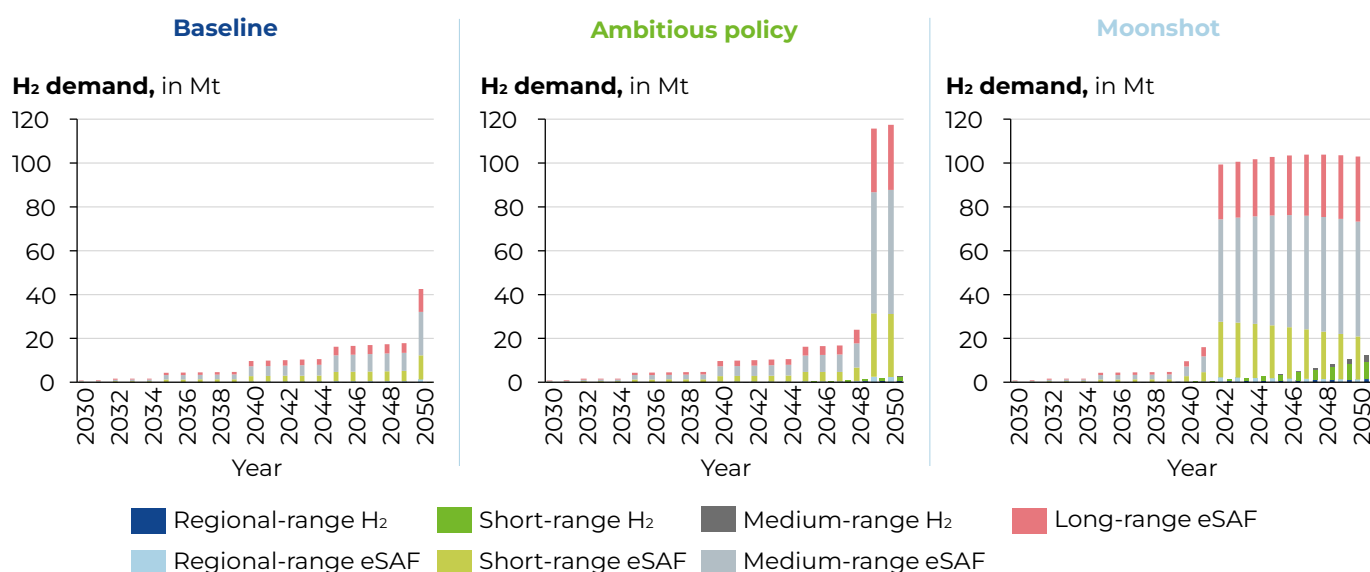


Figure 5: H₂ demand in the three HyNEAT scenarios for eSAF and direct use

3.4 Implications for hydrogen demand

The extension substantially broadens the perspective on H₂ demand in aviation. H₂ is no longer required only where H₂-powered aircraft are operated, but also indirectly wherever eSAF is used in conventional aircraft. This distinction is particularly relevant for long-range aviation, where direct H₂ use remains limited by aircraft design and range constraints, while eSAF can be used with existing aircraft and infrastructure.

H₂ price developments, therefore, influence aviation fuel demand through two channels. They affect the competitiveness of H₂-powered aircraft via direct LH₂ costs and simultaneously determine the cost position of eSAF,

since H₂ is a key input for its production. Consequently, H₂ costs represent a decisive factor for long-term fuel adoption patterns across the analysed scenarios.

Overall, the results show that the inclusion of eSAF changes the interpretation of future H₂ demand in aviation. The total H₂ requirement may be significantly higher than suggested by direct H₂ aircraft demand alone, because synthetic fuels create an additional indirect H₂ demand. This finding is important for the planning of future H₂ supply networks, as infrastructure and production capacities must account for both direct aircraft use and H₂-based fuel production.

PARALLEL HYDROGEN SUPPLY CHAIN FOR eSAF AND LIQUID HYDROGEN

4 Parallel hydrogen supply chain for eSAF and liquid hydrogen

In the following section, the impact of the parallel H₂ supply for eSAF and LH₂ on the LH₂ supply networks, the European energy system and macroeconomics is

discussed. The H₂ supply network exclusively for H₂-powered aviation is discussed in the main report [1].

4.1 Impact on the LH₂ supply network

To design a cost-optimal parallel H₂ supply network for eSAF and LH₂ for the target year 2050, the optimization model is applied to a comprehensive case study involving 68 European airports, 18 clustered European NUTS-1 production hubs, 93 potential refinery locations and two intercontinental low-cost H₂ production hubs Chile and Morocco similarly to the main project report. The H₂ supply network is evaluated under the Ambitious policy demand scenario for the 60%/70%/80%/90% eSAF import scenarios (see Section 2.3 of the main report). The average network supply cost of LH₂ at the airports for 60% eSAF import scenario, including production, storage, liquefaction, and transportation, are 4.80 USD/kgH₂,

compared to 4.82 USD/kgH₂ (70% eSAF import), 4.75 USD/kgH₂ (80% eSAF import) and 4.66 USD/kgH₂ (90% eSAF import). Furthermore, the average network supply cost of GH₂ at the refineries for 60% eSAF import scenario, including production, storage and transportation, are 5.24 USD/kgH₂, compared to 4.71 USD/kgH₂ (70% eSAF import), 4.20 USD/kgH₂ (80% eSAF import) and 3.95 USD/kgH₂ (90% eSAF import). The breakdown of the average network costs is shown in Figure 7, where a large share of the cost is incurred by H₂ production, and the shares are slightly changing depending on the eSAF import scenario.

Average GH₂ network supply costs at refineries and LH₂ supply costs at the airport, in USD/kgH₂

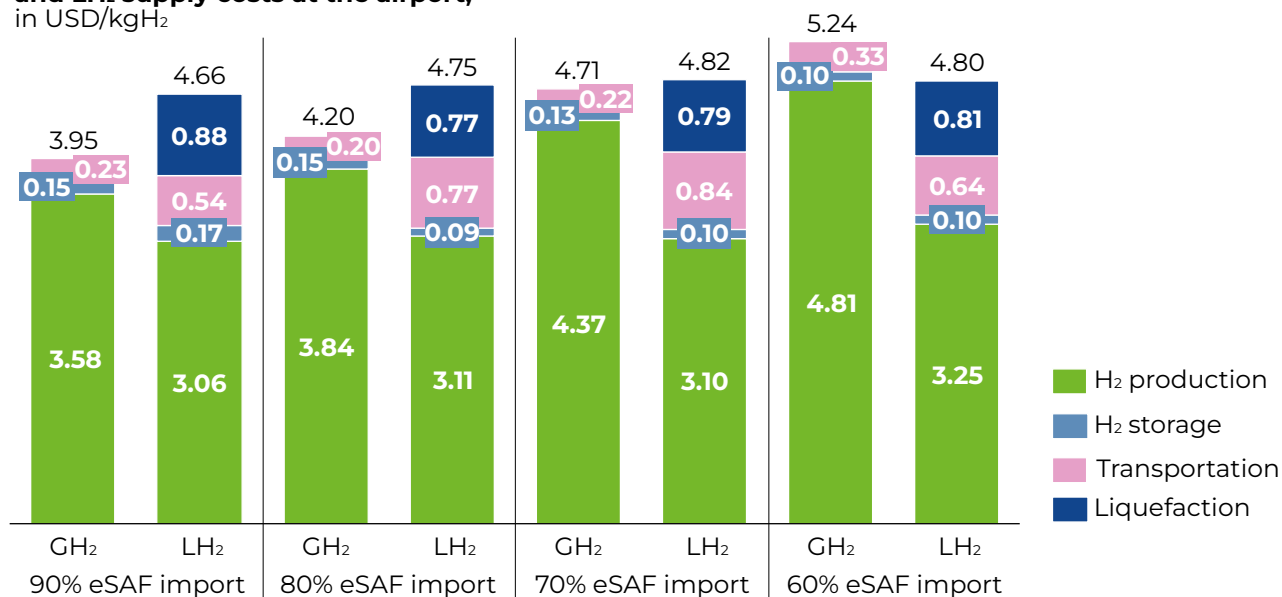


Figure 7: Average network GH₂ costs at the refineries and LH₂ at the airports for different import scenarios with cost component breakdown

In most eSAF import scenarios, the average GH₂ supply costs at the refinery are lower compared to the LH₂ supply costs at the airports although the H₂ production costs are significantly higher for the GH₂ supply. This is due to the production location and transport mode. As the share of domestic H₂ production for eSAF is fixed in the import through the import scenarios, comparably high-cost H₂ is produced in Europe and Morocco and transported through GH₂ pipelines to the refineries. For the LH₂ supply in contrast, almost in all scenarios the LH₂ is imported with an LH₂ vessel and transported to the airports by

truck. This allocation leads to the lowest overall supply network cost, as the low-cost H₂ is allocated to the refineries and imported LH₂ can reach lower cost compared to additional domestic H₂ production and transport. In Figure 8 the share of H₂ transported by the available transport mode is shown for the eSAF import scenarios. In these scenarios LH₂ is imported from Chile and further transported by truck to the airports. For higher eSAF import shares – and therefore lower domestic H₂ demands – H₂ is also produced in Europe for LH₂ demands and transported by GH₂ pipelines, either

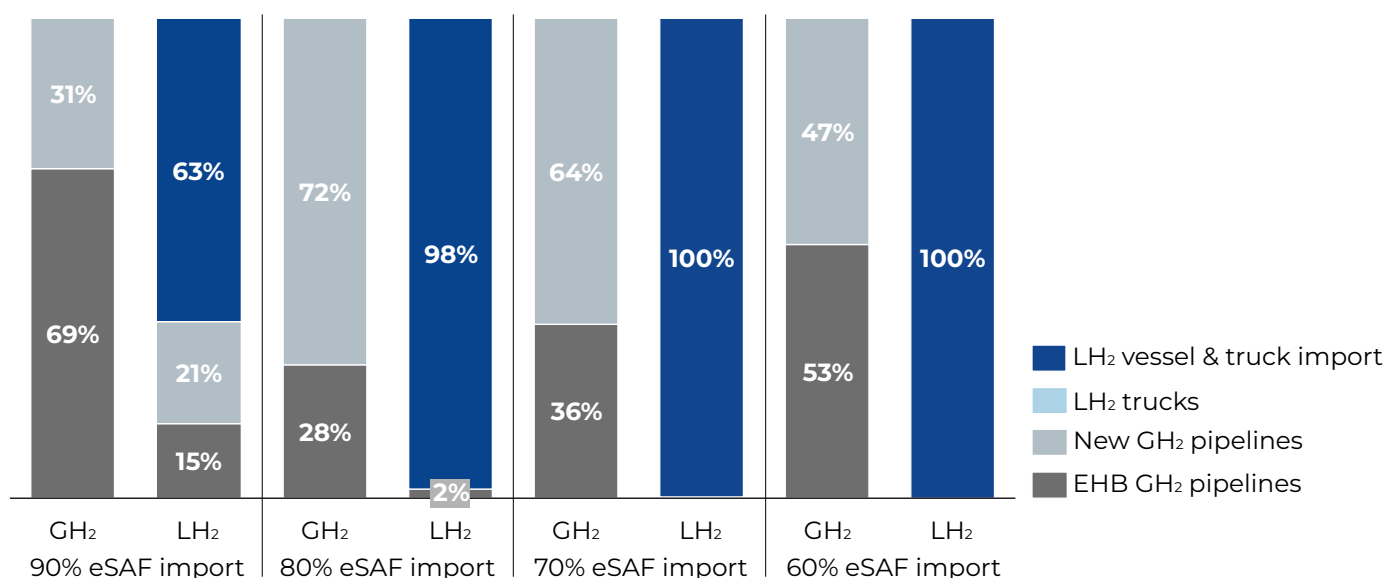


Figure 8: Share of H₂ transported by different transportation modes to the refineries and airport for different eSAF import shares.

through the European Hydrogen Backbone (EHB) or newly built GH₂ pipelines. The GH₂ for eSAF production at the refinery locations is exclusively transported through GH₂ pipelines. Depending on the specific combination of production hubs and refineries, the share of existing pipeline usage ranges between 28% and 69%. These findings are consistent with those reported in the main analysis and underline the important role of EHB infrastructure in enabling a future large-scale H₂ economy.

Figure 9 shows the optimal H₂ supply network configuration connecting the H₂ production potentials with the airports and refineries for the Ambitious policy and 60% eSAF import scenario. This map illustrates the supply relationships within the network, indicating which production regions supply which airports and refineries. It also highlights the major production regions under cost-

optimal conditions, assuming that regional H₂ production capacity constraints are not exceeded. As mentioned above, the LH₂ supply originates from Chile, driven by the limited availability of low-cost production capacity within Europe. The imported LH₂ is distributed to airports via major European seaports. In contrast, H₂ produced locally within Europe supplies GH₂ to the refineries, together with GH₂ imports from Morocco.

It is also observed that the average network LH₂ supply cost at the airports, as calculated in the main report (without eSAF inclusion), increased from 4.33 USD/kgH₂ to the range 4.66-4.82 USD/kgH₂ for the parallel H₂ supply chains for LH₂ and eSAF. This is due to the additional GH₂ demand at the refineries which leads to a higher H₂ production in Europe. This capacity expansion is associated with higher costs, particularly for European production hubs. Therefore, while cheaper European

4.2 Impact on the energy system

In this section, both the import options and the domestic supply options for eSAF in the European energy system are investigated. Similar to the main report, the analysis first focuses on global energy island calculations to estimate the production costs for different quantities of H₂ and eSAF outside of Europe. These energy islands produce H₂ from local renewable energy resources, which is eventually converted into eSAF. The resulting cost and quantity data then serve as the basis for the second step, in which the domestic production potentials and costs of H₂ for covering aviation demand within the European energy system are calculated. For the domestic pathway, only the H₂ demand is considered within the energy system model, as the H₂ is subsequently transported to refineries where it is converted into eSAF as shown in Section 2.2. Finally, the impact of European aviation on the energy system is analysed by comparing a European energy transition scenario without aviation energy demand to a scenario that includes aviation energy demand. Figure 10 shows the schematic of the energy islands which are evaluated globally. Global capacity factors for solar PV and wind power are calculated using the same ERA5 weather data as in the main report. The main difference is the addition of eSAF synthesis and storage components to the calculation. The techno-economic assumptions for each component are listed in

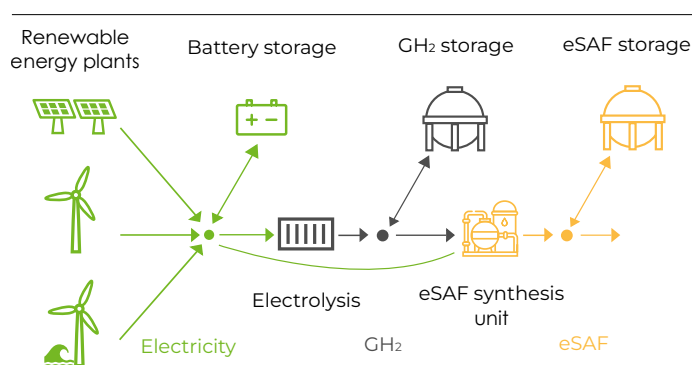


Figure 10: Schematics of the components of the energy island systems for the production of eSAF. Components are similar to those in the main report, but the hydrogen is used in an eSAF synthesis unit rather than in a liquefaction plant. The eSAF synthesis unit is a container for several processes and components including direct air capturing of carbon dioxide, reverse water gas shift and a Fischer-Tropsch-synthesis.

the appendix. With these assumptions, both the production costs as well as the transport costs to Europe are calculated. Figure 11 plots the total costs, that is production plus transport costs, versus the cumulated technical eSAF potential. As can be seen, the minimum import costs around 1.75 USD/kg eSAF can be achieved with production sites in Chile. There is a potential for about 7,500 MteSAF of annual eSAF import for costs up to 2.20 USD/kg eSAF. With increasing eSAF import quantity, this price slowly increases up to around 4 USD/kg eSAF for annual import quantities of up to 40,000 MteSAF.

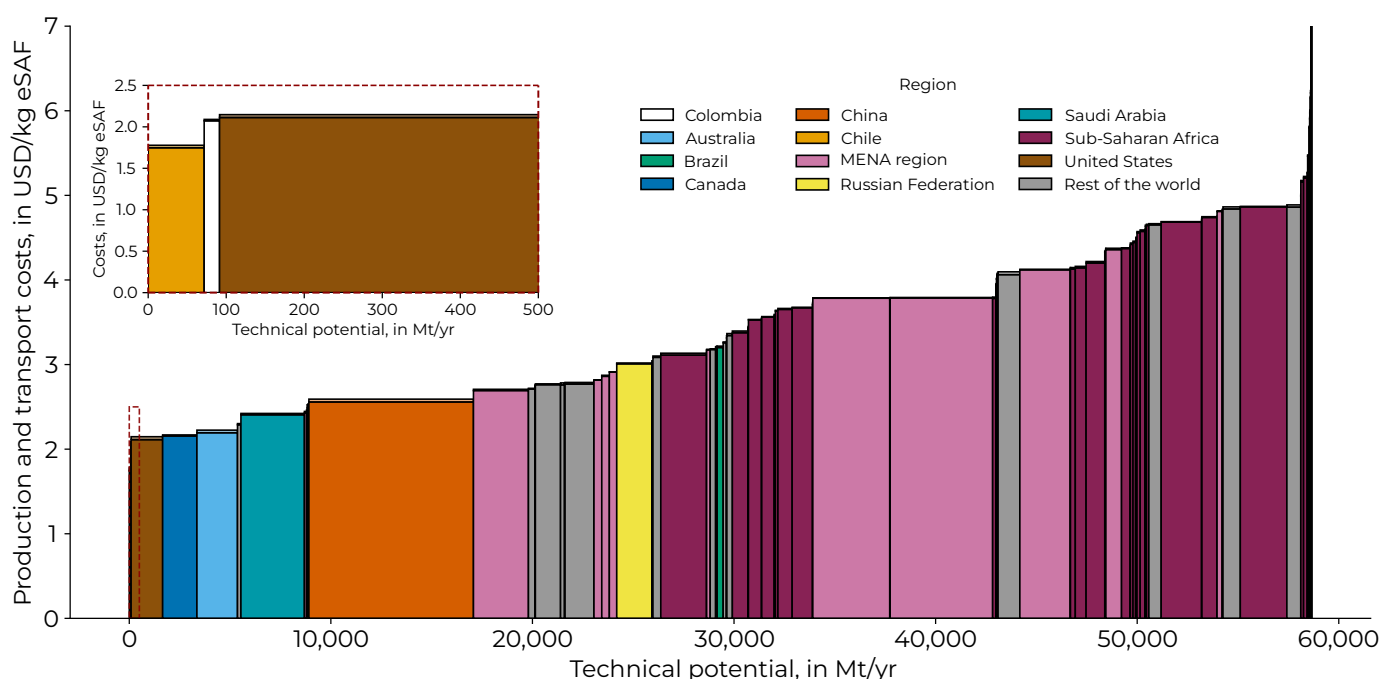


Figure 11: Import costs for eSAF plotted versus the technical annual potential.

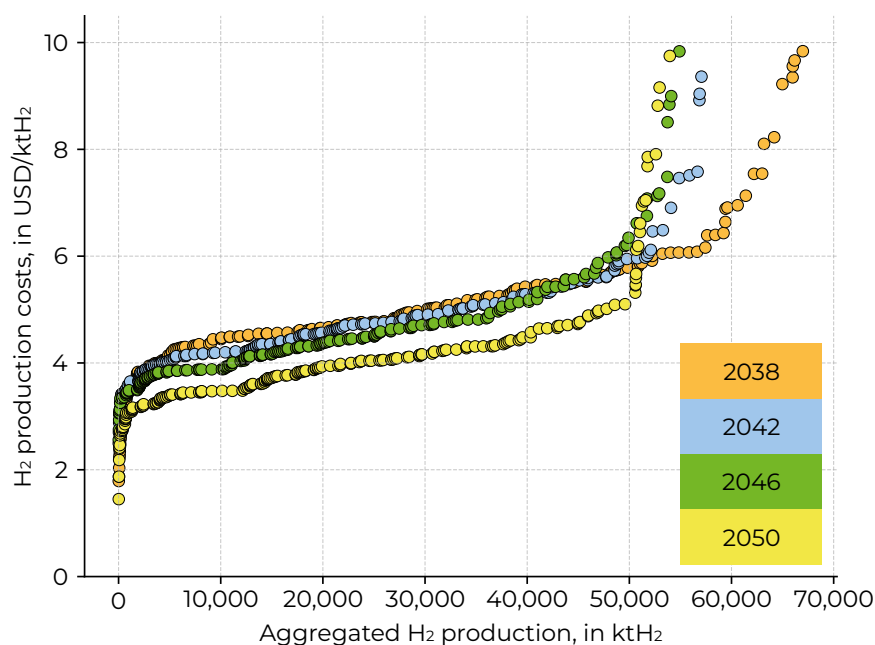


Figure 10: Schematics of the components of the energy islands systems for the production of eSAF. Components are similar to those in the main report, but the H₂ is used in an eSAF synthesis unit rather than in a liquefaction plant. The eSAF synthesis unit is a container for several processes and components including direct air capturing of carbon dioxide, reverse water gas shift and a Fischer-Tropsch-synthesis.

For the domestic production, the same hierarchical calculation method as applied in the main report is used. However, as described in the previous sections, the production of eSAF takes place in refineries at fixed locations. These refineries are partly fuelled with the domestically produced H₂ whose quantity-cost relationship is depicted in Figure 12. In contrast to the main report, the import of green oils for non-aviation demand is allowed. As a result, some non-aviation demands switch towards imported green oils freeing up some previously used renewable energy potentials. Because of this, the H₂ cost at low to medium quantities stays the same. However, there is a pronounced increase in the maximum quantity which can be supplied by the European energy system. This applies in particular to the end of the transition path, where because of climate neutrality the utilization of renewable energy potentials is highest.

In the next step, the impact of the ambitious policy scenario for the European aviation development on the European energy system is evaluated. Further, it is assumed that 60% of the eSAF demand is met by imports from outside of the European energy system as shown in Section 4.1. The analysis shows that an import share of 60% and thus a domestic eSAF production of 40% of the total demand is close to the maximum which can be supplied by the European energy system.

Figure 13 shows the regional demands for both green H₂ as well as electricity to meet the European aviation demand in 2050. In this case, electricity demand consists solely of the refineries' electricity needs. In the scenario analysed, no electricity is used for H₂ liquefaction, as all LH₂ demand at European airports is met through imports

from non-European countries. Almost every region contributes to the European H₂ production. In the regions with low additional H₂ demand the available renewable energy potentials are already completely utilised or not cost competitive. This applies in particular to Switzerland and Italy as well as the Baltic states.

Bar scaling

200 TWh

Additional energy requirements

- Refinery electricity
- Regional H₂ production

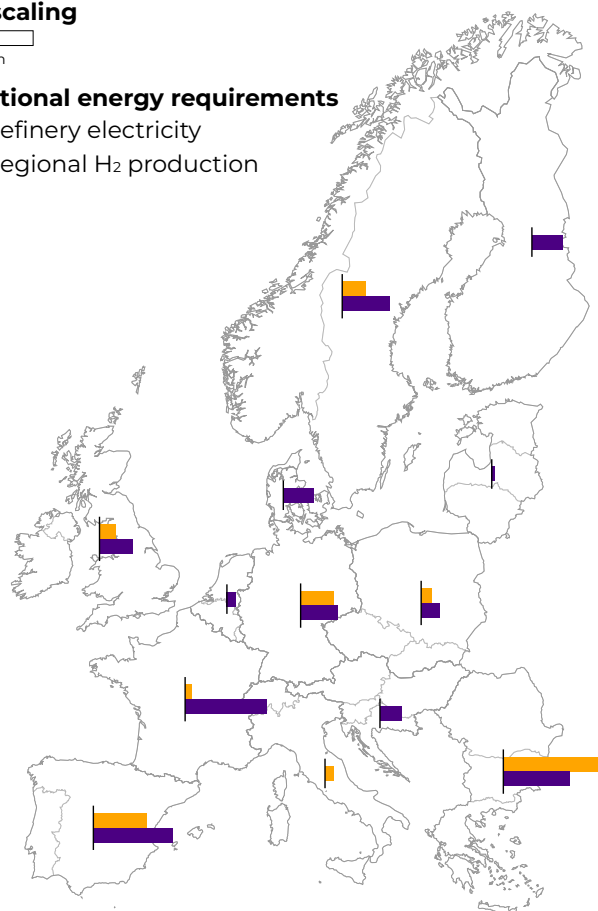


Figure 13: Regional H₂ and electricity demands to meet the European aviation demand in 2050.

Figure 14 displays the additionally installed power of components which are being built to meet the European aviation demand in 2050. Please note, that the scaling refers to the output power of the components. There is a pronounced increase in solar PV utilisation in particular in the South. Additionally, there is a modest increase in wind power utilisation which is more pronounced in the North. This underlines that solar PV because of its abundant availability and low costs of electricity will become a cornerstone of the European energy system. This increase in renewable energy generation comes with additional demands for flexibility and sector coupling. Therefore, there is an increase in storage components, e.g. battery systems and H₂ storages which is particular pronounced where the increase in renewable energy utilisation is largest. In order to convert the additional electricity into H₂, a significant amount of additional electrolyser capacity will also need to be added.

In conclusion, the European aviation demand in the ambitious policy scenario with an eSAF import share of 60% has a pronounced impact on the energy system. Over all regions there is an increase in solar PV capacity of 76%, in wind power capacity of 22%, in electrolyser capacity of 90%, of battery storages of 68% and of H₂ storages of 70%. The aviation demand in the final step of the transition path shows a steep increase which results in a sharp increase in necessary expansion rates. This highlights the importance of incorporating detailed aviation data in energy system analysis and emphasises the value of a forward-looking energy system planning to prevent disruptive and costly changes in the energy system. When viewed at the regional level, this problem becomes even more pronounced. Since the potential for renewable energy is unevenly distributed, renewable energy expansion is highly concentrated in certain areas. As a result, some regions may be particularly affected, while others will see relatively little expansion of renewable energy infrastructure.

Bar scaling

250 GW

Components

- Battery storage
- Electrolysis
- H₂ AG storage
- H₂ storage
- Heat pump
- Solar power
- Wind offshore

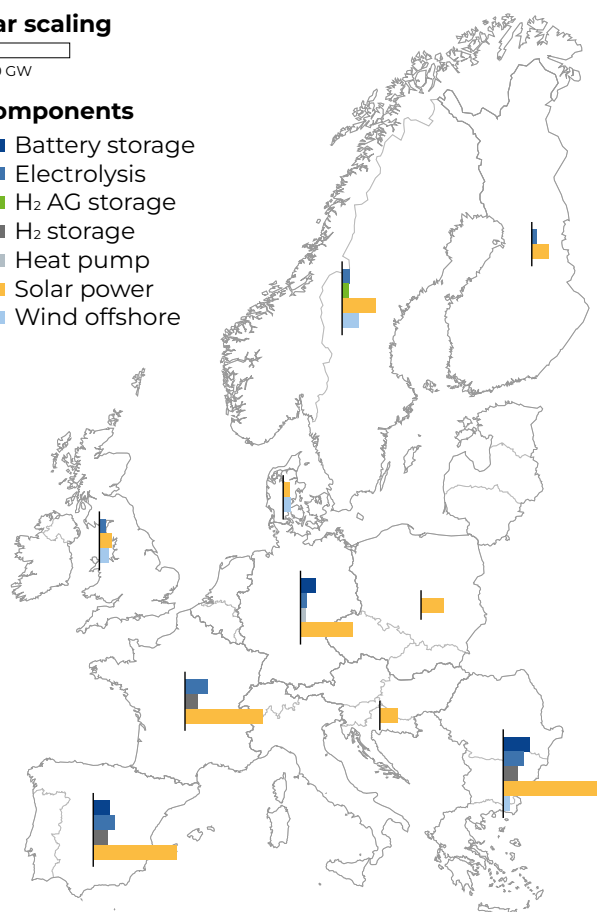


Figure 14: Additional installed power for components of the future energy system to meet the modelled European aviation demand in 2050.

4.2 Macroeconomic impact

This chapter presents the macroeconomic impacts of H₂ supply chains for eSAF and LH₂ in potential exporting countries by comparing the multipliers of eSAF production on domestic production, value added (GDP), household income, and employment. In addition, the eSAF multipliers are compared against LH₂.

In line with the main project report, eSAF production is differentiated into three phases of economic activity: (i) key component manufacturing, (ii) installation and

balance of plant (BoP) supply, and (iii) operation. Figure 15 illustrates the structural potential of the selected export countries to benefit from these activities, assuming that all activities are performed within the country. It reports both IO-based and SAM-based multipliers for key macroeconomic indicators. IO-based multipliers capture direct and indirect upstream production linkages, while SAM-based multipliers additionally account for income generation and induced consumption effects.

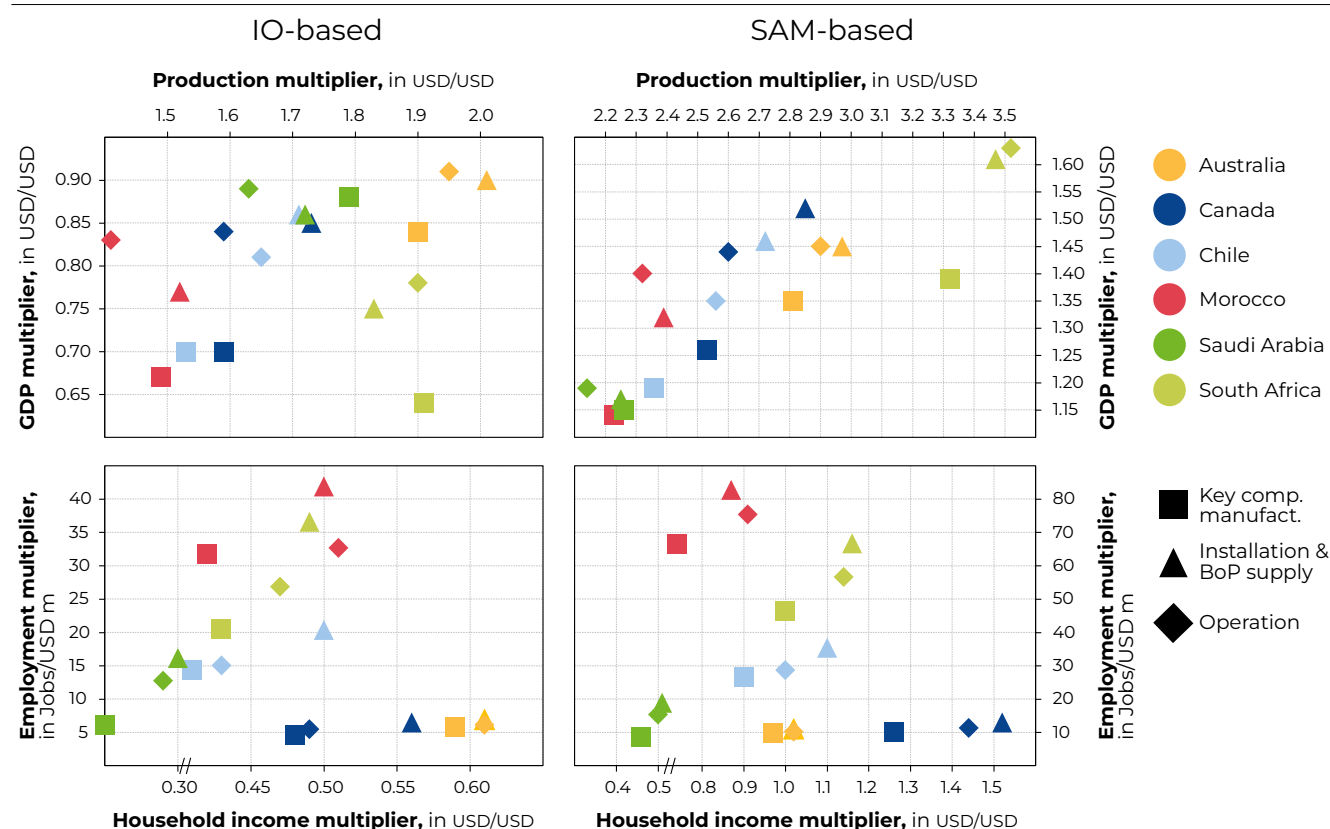


Figure 15: IO- and SAM-based multipliers of the eSAF industries for relevant macroeconomic indicators in potential exporting countries.

A clear country-specific pattern emerges. Australia exhibits the largest multipliers for household income, production, and GDP under the IO perspective, whereas Morocco and South Africa display particularly strong employment multipliers. The latter primarily reflects comparatively low labour productivity and wage levels, which translate into higher employment per unit of monetary output. Saudi Arabia shows relatively high GDP multipliers but the lowest household income multipliers among all countries considered. This mirrors the income distribution patterns identified in the main project report [1]. Canada and Chile, by contrast, display comparatively balanced multiplier profiles. Across most countries, differences between the three production phases remain moderate. However, key component manufacturing generally exhibits lower multipliers than installation and operation. This reflects higher import and lower domestic integration in upstream sectors.

Extending the perspective from IO-based to SAM-based multipliers substantially alters the ranking across countries. South Africa records the highest production and GDP multipliers under the SAM framework, while Canada exhibits the strongest household income multiplier. The employment differentials between Morocco and South Africa and the remaining countries become more pronounced. Figure 16 further illustrates these differences in production and employment, using the levelized cost of fuel (LCOF) perspective. This perspective does not assume full domestic performance of economic activities, but accounts for foreign dependencies in the economic base scenario. While production multipliers increase by roughly 20–30% for most countries when moving from IO to SAM multipliers, employment multipliers display much larger amplification effects. In Morocco and South Africa, employment impacts nearly double once the induced effects are considered.

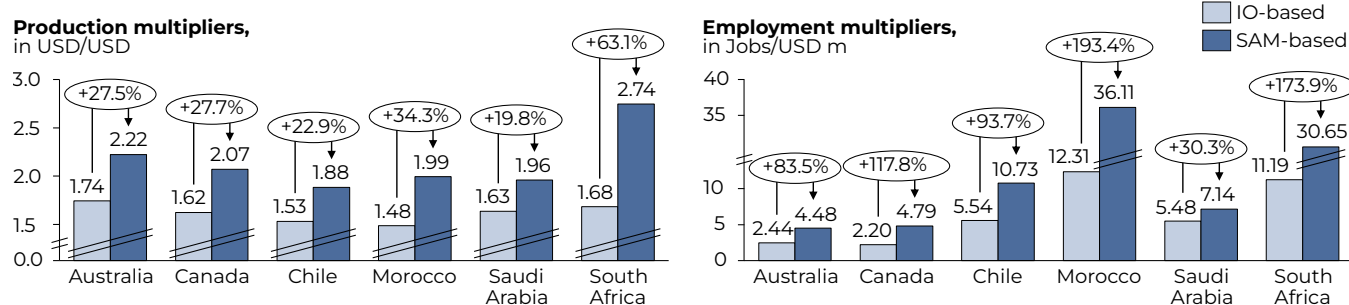


Figure 16: IO- and SAM-based production and employment multipliers for eSAF production (LCOF-based).

These patterns reflect structural characteristics of income use. In many emerging economies, such as SSA countries, final consumption shares are high, while saving rates are relatively low [38,39]. As many households live hand-to-mouth [40], a large share of consumption is flowing into labour-intensive sectors such as agriculture and textile manufacturing, which generate strong secondary employment effects. In contrast, Saudi Arabia shows the smallest relative increase in employment multipliers (around 30%). This can largely be attributed to the high share of migrant workers in the labour force [41,42]. Remittance outflows reduce the domestic recirculation of income, thereby limiting induced effects. Overall, the SAM-based results underline that macroeconomic impacts are not solely determined by supply chain structures but also by income distribution patterns, consumption behaviour, and the degree of domestic economic integration. Moreover, this analysis emphasises that eSAF production infrastructure can lead to economic benefits that go beyond the direct supply chain, once income generation and use are considered.

Next to production and employment, Figure 17 reveals substantial cross-country differences in GDP multipliers under the SAM perspective. Figure 17 decomposes these SAM-based GDP multipliers into their structural components. Morocco and South Africa exhibit particularly large induced value-added shares, consistent with the employment amplification effects discussed above. The composition also highlights the relevance of financing costs, represented by the net operating surplus of eSAF production required to cover financing costs. Country-specific weighted average costs of capital (WACC) are incorporated to reflect investment risks faced by project developers [43]. Higher political and macroeconomic risks imply higher required returns on investment. Consequently, in countries with relatively high WACC, such as Chile, Morocco, and Saudi Arabia (see Figure 4), the eSAF net operating surplus accounts for more than 40% of total value added. Although this surplus contributes to GDP, it generates limited domestic feedback effects, particularly when capital is provided by foreign investors and profits are repatriated abroad.

GDP multiplier, in USD/USD

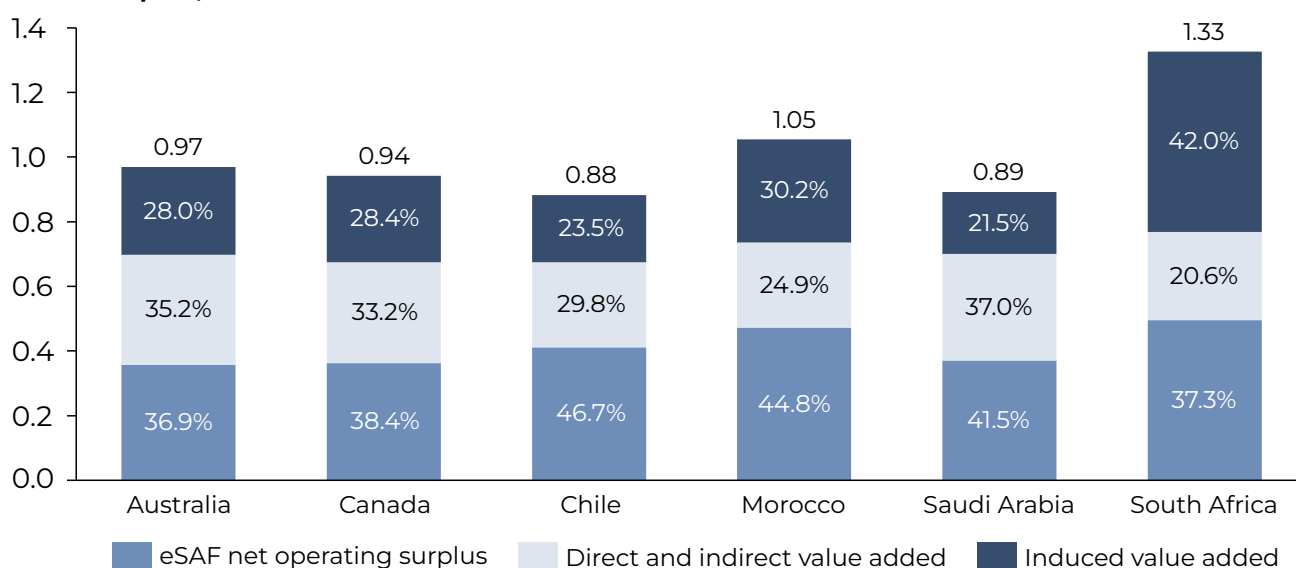


Figure 17: Composition of SAM-based GDP multipliers for eSAF production (LCOF-based) in potential exporting countries.

Finally, Figure 18 compares IO-based multipliers for LH₂ and eSAF production. Overall, differences are relatively small, particularly with respect to production multipliers. The similarity in results reflects the largely shared supply chain structure of both fuels. Renewable energy generation and hydrogen production account for the majority of production costs in both cases. Consequently, the differences in production multipliers do not exceed 6%. Although the eSAF multipliers are generally low, they are - with the exception of South Africa - slightly lower

than those of LH₂. The differences in employment multipliers are somewhat larger, ranging between 4% and 16% depending on the country. In most cases, eSAF generates slightly lower employment effects than LH₂, although the eSAF supply chain introduces DAC and FT synthesis as additional processing steps. Thus, these results indicate that the activities associated with LH₂ appear more labour-intensive than those needed for eSAF handling.

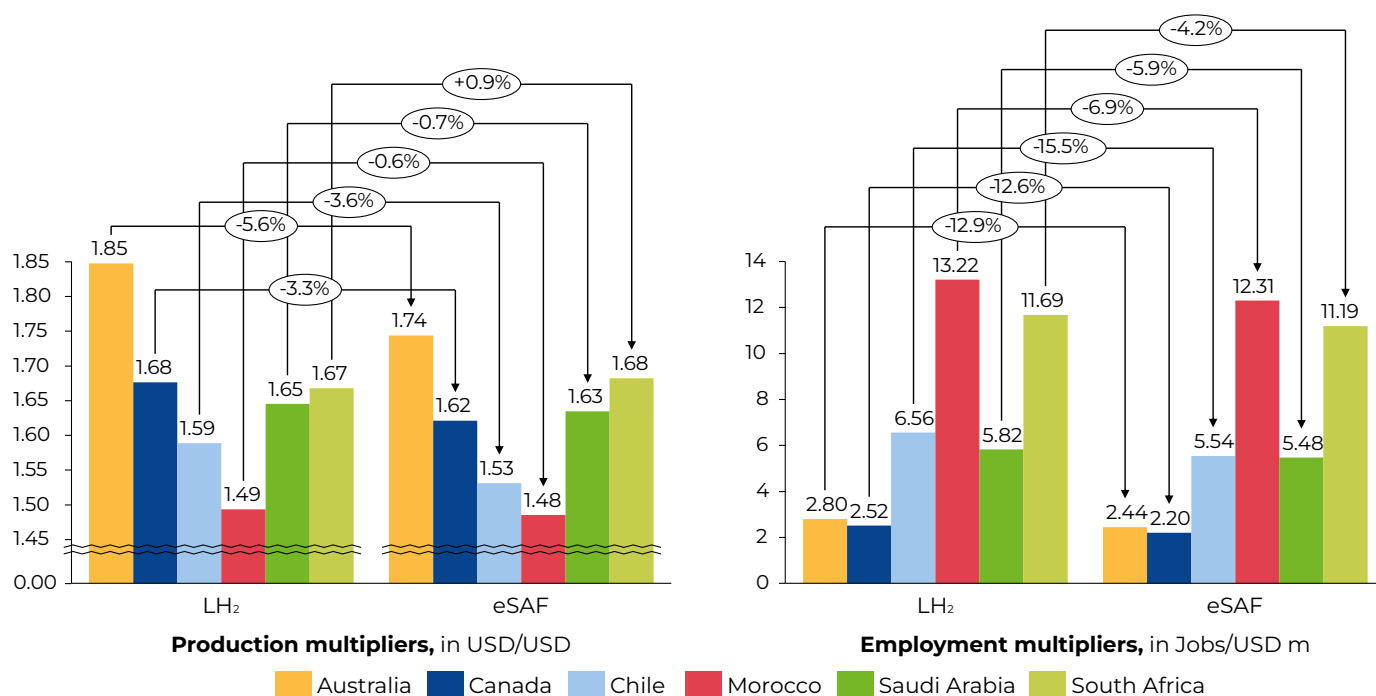


Figure 18: IO- and SAM-based multipliers of the eSAF industries for relevant macroeconomic indicators in potential exporting countries.

SUMMARY AND CONCLUSION

5 Summary and conclusion

This supplementary report expanded the main HyNEAT analysis by incorporating the H₂ demands for H₂-based sustainable aviation fuels alongside the direct use of LH₂. Since bio-based aviation fuels face severe sustainability, land-use, and scalability constraints, power-to-liquid eSAF is critical for decarbonising long-haul flights and meeting the ReFuelEU Aviation mandates. By evaluating the parallel supply chains for both fuel types, this study provides a holistic assessment of their combined impact on the H₂ supply infrastructure for a European airport network, the overarching energy system, and macroeconomic structures of exporting countries.

The integration of eSAF fundamentally shifts the scale of future H₂ demand in the aviation sector. The extended System Dynamics model demonstrates that eSAF introduces a massive indirect H₂ demand that far surpasses the demands for direct LH₂ propulsion alone. The uptake of eSAF is initially driven purely by regulatory blending quotas, but it could accelerate significantly once production costs fall below those of conventional kerosene and biofuels. This indicates that cost competitiveness, combined with strict policy mandates, will be the primary driver for a large-scale fuel transition.

Modelling the parallel supply chains reveals intense competition for low-cost renewable energy within Europe. Supplying refineries with gaseous H₂ for domestic eSAF production absorbs the most cost-effective European renewable energy potentials. Consequently, the cost-optimal supply of LH₂ to airports shifts predominantly to imports via vessels from highly favourable regions like Chile. This internal competition causes the average LH₂ network supply costs at European airports to rise compared to a scenario where eSAF is excluded.

Furthermore, the impact on the European energy system is profound. Even if 60% of the eSAF demand is imported, meeting the remaining European aviation demand requires a significant expansion of domestic infrastructure. The models project a necessary 76% increase in solar photovoltaic capacity, a 22% increase in

wind power, and a 90% increase in electrolyser capacity by 2050. This highlights a critical vulnerability: Although it could help to ensure supply security, aiming for high domestic production of both eSAF and LH₂ would place extreme pressure on the European energy system, risking disruptive and costly system bottlenecks.

To mitigate these domestic constraints, importing large quantities of eSAF and LH₂ is a necessity, which simultaneously offers substantial macroeconomic benefits for exporting countries. The global analysis shows that countries like Australia and Canada experience high gross domestic product and household income multipliers. Meanwhile, nations with lower labour productivity, such as Morocco and South Africa, benefit from high employment multipliers. Incorporating consumption-induced effects through social accounting matrix models proves that the economic benefits of H₂ and eSAF production extend far beyond the direct supply chain, heavily impacting the broader economies of the host countries.

In conclusion, achieving a climate-neutral aviation system relies fundamentally on the widespread adoption of eSAF, with direct LH₂ propulsion serving as a potential complementary technology. While eSAF is a necessity for decarbonising long-haul flights and meeting existing regulatory mandates, the possible parallel market introduction of H₂-powered aircraft would further compound the already staggering demand for green H₂. The European energy system might not efficiently support full domestic production of both fuel types. Therefore, establishing robust international trade partnerships and global import infrastructures is essential for supply security. Moving forward, policymakers and industry stakeholders must synchronise their infrastructure planning to accommodate the parallel demands of LH₂ and eSAF, ensuring that the necessary generation, liquefaction, and transport capacities are scaled up in time to meet the increasing demands of the aviation sector.

APPENDIX

A Appendix

In the following, the techno-economic assumptions for the project analysis, additional details on the used

methodology and data as well as additional project results are shown.

A.1 Hydrogen demand allocation for eSAF production

As discussed in Section 2.3, the eSAF production is located at either crude oil refineries or import seaports. In the following, the methodology for selecting the refineries is presented and the results are shown. Although the comparison of this approach to a greenfield scenario has resulted in similar eSAF production location, this approach is a simplification. We are choosing only a limited number of production locations and neglect the size of the individual production locations. This is necessary to reduce the number of demand nodes and thereby reduce the computation time required for network optimisation.

The total eSAF demand of the airport network discussed in Section 3 has to be fulfilled. As discussed in Section 2.3, for the eSAF supply, different import scenarios are analysed with a varying eSAF import share (60%, 70%, 80% and 90%). It is assumed that the airports closest to large import terminals will be supplied solely by this imported eSAF and are therefore let out of the model to determine the domestic European eSAF supply from the refineries. The selection of refineries has been done by solving a capacity facility location problem. The optimisation function is the minimisation of the total transport effort in ton-kilometres as

$$\min Z = \sum_{i \in A, j \in R} d_{i,j} \cdot m_{i,j} \quad (\text{A.1})$$

where d is the distance between an airport i and a refinery j and m the amount of transported eSAF. The equations A.2 to A.4 make sure that each airports gets the required eSAF demand as well as the selection of the available refineries y . The individual capacity of the refineries is set to be equal with a possible deviation of 20%, ensured by the boundaries of $K_{\min}$ and $K_{\max}$.

$$\sum_{j \in R} m_{i,j} = m_i \quad \forall j \in A \quad (\text{A.2})$$

$$\sum_{i \in A} m_{i,j} \geq K_{\min} \cdot y_j \quad \forall j \in R \quad (\text{A.3})$$

$$\sum_{i \in A} m_{i,j} \leq K_{\max} \cdot y_j \quad \forall j \in A \quad (\text{A.4})$$

The maximal number of refineries $N_{\max}$ is included to limit the number of chosen locations as follows:

$$\sum_{j \in R} y_j \leq N_{\max} \quad (\text{A.5})$$

Figure 19 shows the resulting selected refineries for the domestic eSAF supply for European airports for an eSAF of 60%. The H_2 demand required at the refineries to produce eSAF is used for the supply network model, the results of which are discussed in Section 4.1.



Figure 19: Domestic eSAF supply allocation to 20 refineries for an eSAF import share of 60%

A.2 Aggregation of hydrogen production potential of the NUTS regions

This section details the aggregation of H₂ production potential across European NUTS regions. This process was conducted to ensure methodological comparability with the main report while accommodating significantly higher H₂ demands. To maintain consistency, the analysis retains the 18 H₂ production nodes identified in the original study, which were initially selected for their high production potential and comparably low cost. Remaining NUTS regions were aggregated to these 18 nodes based on geographic proximity to their respective central anchor points. While this represents a geographic

simplification, it is supported by the assumption that a comprehensive H₂ pipeline system, the European Hydrogen Backbone, will be established across Europe. Consequently, the primary factor no longer explicitly captured is the precise intra-regional transport distance—a parameter that was already idealised in the original model. Figure 20 illustrates the resulting NUTS aggregation used as input for the H₂ supply network model, the results of which are discussed in Section 4.1.

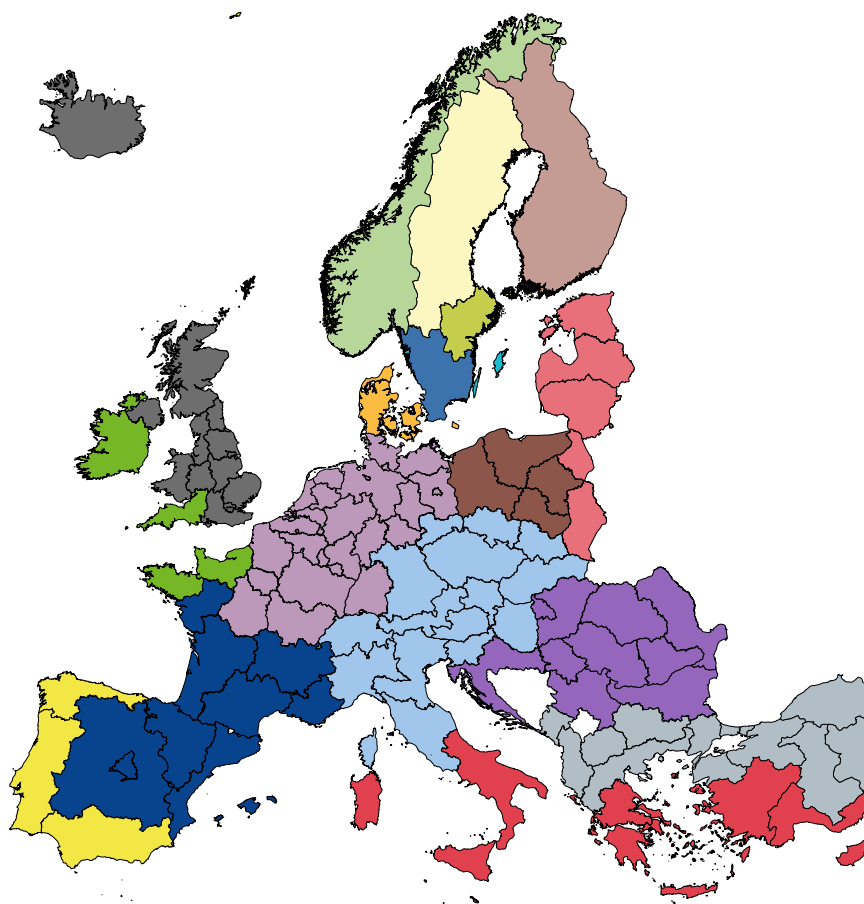


Figure 20: Aggregation of European NUTS regions to 18 H₂ production nodes

A.3 Methodology of the macroeconomic impact analysis

In this section, the methodology for the macroeconomic analysis presented in Section 4.3 is discussed.

A.3.1 Country Selection

The macroeconomic analysis of this supplementary report covers a selected group of potential export countries. Morocco and Saudi Arabia are retained from the main project report scope to represent the MENA region. In addition, four countries are included to ensure geographical coverage across North and Latin America, Sub-Saharan Africa, and the Asia-Pacific region. Consistent with the original project framework, the country selection is based on structural criteria relevant for large-scale LH₂ and eSAF production and export. These include energy transition ambitions, political and institutional stability, investment conditions, and overall economic capacity. For consistency with the original project scope, the following indicators are applied to characterise and compare the selected countries:

Gross domestic product (GDP):

The GDP represents the overall economic size and capacity to invest in new technologies and infrastructure. Data is obtained from the World Bank for 2024 [15].

Weighted average cost of capital (WACC):

The WACC reflects the country-specific investment risk and cost of financing. Lower WACC values typically indicate favourable conditions and reduced perceived risk for investors. Data is obtained from project-internal estimations.

Foreign Direct Investment inflows (FDI):

FDI inflows serve as an indicator of international investor confidence and openness to foreign participation in infrastructure projects, which is critical for capital-intensive LH₂ and eSAF investments. Data is obtained from the most recent United Nations World Investment Report for 2023 [32].

Economic Complexity Index (ECI):

The ECI is an indicator constructed by the Harvard Growth Lab and captures the diversification and technological sophistication of a country's economy. It indicates its ability to develop and produce complex products, which also play a key role for LH₂ and eSAF infrastructure. Data is taken for 2023 [44].

Fragile States Index (FSI):

This index measures political and institutional stability. Lower fragility scores suggest a stable environment for long-term investments and cross-border energy cooperation. Data is taken for 2024 [25].

Renewable energy share in electricity generation (RES):

This indicator shows the current integration of renewables in the national electricity mix which is a key requirement for green hydrogen production. Data is obtained from the Ember Energy Research Institute for 2023 [45].

Green Future Index (GFI):

The GFI is constructed by MIT Technology Review and reflects national progress and commitment towards low-carbon technologies and green innovation, offering a broader view of environmental ambition. Data is taken for 2023 [46].

Energy Transition Index (ETI):

This indicator, constructed by the World Economic Forum, evaluates how effectively countries pursue the energy transition. It considers the current performance regarding sustainable energy as well as the readiness for transitioning towards a sustainable energy system, including economic, political and institutional factors. The most recent scores for 2025 are obtained [47].

While the main report applied a quantitative pre-selection for Europe and MENA, the supplementary extension follows a streamlined approach. The selection of additional export countries is based on established export potential assessments in the literature [18,19] and on the global techno-economic potential analysis conducted in the main project report [1]. Countries with significant renewable resource potential and maritime export access are included for each considered world region. An overview of the selected countries and the corresponding indicators is provided in Table A.1.

Table A.1: Overview of potential export countries included in the analysis with relevant indicators.

	GDP in USD [31]	WACC	FDI in USD [32]	ECI [44]	FSI [25]	RES [45]	GFI [46]	ETI [47]
Australia	1,757 bn	4.9%	30.6 bn	0.07	19.6	35%	4.56	63.0
Canada	2,244 bn	5.1%	46.5 bn	0.84	18.6	65%	5.69	62.8
Chile	330 bn	6.1%	17.8 bn	-0.12	41.1	64%	5.08	65.7
Morocco	154 bn	7.8%	1.1 bn	-0.22	68.8	22%	4.73	53.7
Saudi Arabia	1,238 bn	6.1%	22.8 bn	0.45	63.2	1%	4.11	55.0
South Africa	401 bn	8.8%	3.5 bn	0.29	69.6	13%	5.23	52.6

For the macroeconomic analysis, SAMs are constructed as the underlying data framework. To ensure consistency with the original project scope and the previously analysed MENA countries, all SAMs are calibrated to the base year 2019. The SAMs are developed with a comparatively high level of sectoral disaggregation in order to capture detailed inter-industry linkages along the LH₂ and eSAF supply chains. However, the level of sectoral detail available in national supply and use tables differs across countries. While European SAMs can be

constructed under harmonised statistical standards, this consistency does not fully apply to the selected export countries due to differences in national accounting classifications and data availability. To address these discrepancies, country-specific aggregation levels are applied while maintaining conceptual comparability across the SAMs. An overview of the final aggregation levels, key macroeconomic indicators derived from the SAMs, and the respective data sources used for construction is provided in Table A.2.

Table A.2: Overview of the aggregation level of the SAMs, along with macroeconomic indicators obtained from the SAM and the data sources used for construction. COM = Commodities; ACT = Activities; GDP = Gross domestic product. Import share refers to the total commodity supply, while export share refers to the total commodity use, both at market prices. Domestic production and GDP are given in USD2023. The data for Morocco has been provided by the statistical office on request. The data source used here for Morocco refers to the general publications on national accounts in Morocco.

	Number of COM	Number of ACT	Domestic production	GDP	Import share	Export share	Data sources
Australia	44	44	3,090 bn	1,642 bn	9.3%	11.2%	[48–50]
Canada	57	57	3,644 bn	2,076 bn	15.6%	14.9%	[48,51–58]
Chile	46	46	578 bn	332 bn	13.9%	13.0%	[48,59]
Morocco	54	54	254 bn	153 bn	17.3%	11.8%	[60]
Saudi Arabia	20	20	1,610 bn	997 bn	12.6%	16.4%	[61–63]
South Africa	42	48	908 bn	464 bn	11.5%	11.7%	[64–66]

A.3.1 Country Selection

The eSAF supply chain largely builds upon the LH₂ supply chain. The extension to eSAF requires three additional process components: (i) DAC for the provision of circular carbon dioxide, (ii) an integrated synthesis plant combining RWGS and FT synthesis, and (iii) eSAF storage

tanks. Table A.3 provides a consolidated overview of all technologies considered for both LH₂ and eSAF, including the respective key components and the references used for the techno-economic cost breakdown.

Table A.3: Overview of technologies, outputs, key components, and references used for cost breakdown.

Category	Technology	Output	Key component(s)	References
Renewable energy sources	PV power plant	Electricity	PV module	[67,68]
	Onshore wind power plant	Electricity	Wind turbine	[69,70]
	Offshore wind power plant	Electricity	Wind turbine	[69,71]
Carbon supply	Direct air capture	CO ₂	–	[72,73]
Conversion systems	PEM electrolysis plant	GH ₂	PEM electrolyser stack	[74–76]
	H ₂ liquefaction plant	LH ₂	Claude-cycle liquefier	[77,78]
	eSAF synthesis plant	eSAF	RWGS + FT synthesis reactor	[34]
Storage systems	Battery storage	Electricity	Li-Ion battery module	[67]
	GH ₂ storage (above ground)	GH ₂	H ₂ compressor	[79–82]
	GH ₂ storage (cavern / underground)	GH ₂	H ₂ compressor	[79,83]
	LH ₂ storage	LH ₂	Cryopump	[79,81,84]
	eSAF storage	eSAF	–	[34]
Transport systems	Power grid	Electricity	–	[85]
	GH ₂ pipeline	GH ₂	H ₂ compressor	[86]
	LH ₂ vessel	LH ₂	Cryopump	[87–90]
	LH ₂ truck	LH ₂	Cryopump, fuel cell	[79,87,90–93]
Refuelling systems	Refuelling truck	LH ₂	Cryopump, fuel cell	[79,86,87,90–94]
	Refuelling pipeline + hydrant	LH ₂	Cryopump, fuel cell	[86,90–94]

A.3.1 Country Selection

In contrast to the main project report, which assessed multiple economic development pathways, the supplementary analysis concentrates on structural differences between LH₂ and eSAF supply chains and on cross-country comparisons among potential export regions. Accordingly, the analysis is conducted exclusively under the economic base scenario. The base scenario incorporates country-specific assumptions regarding: (i)

the degree of self-supply for key components, (ii) domestic shares during the installation and operation phases, and (iii) the extent of foreign investment. A comprehensive description of the economic base scenario is provided in the Appendix of the main project report [1]. Table A.4 summarises the data derived for the economic base scenario for the potential export countries under consideration.

Table A.4: Overview of values used in the base scenario. The countries are abbreviated by the ISO 3166 ALPHA-3 codes. The foreign investment share is taken for the EU27. Data refer to the base year 2019.

	AUS	CAN	CHL	MAR	SAU	ZAF
Wind turbines	0.3%	0.7%	0.0%	0.9%	0.0%	0.0%
PV modules	1.2%	29.3%	0.4%	12.7%	0.1%	7.8%
PEM electrolyser stacks / fuel cells	22.3%	55.3%	1.1%	0.5%	0.0%	78.1%
H ₂ compressors / Claude-cycle liquefiers	7.4%	38.5%	5.7%	1.8%	5.9%	19.6%
Li-Ion battery modules	7.0%	22.4%	2.1%	10.8%	0.7%	8.0%
Cryopumps	15.1%	28.1%	5.1%	0.7%	0.1%	25.7%
RWGS + FT synthesis reactor	12.1%	35.7%	7.1%	1.3%	2.8%	24.0%
Average domestic share of activities during the installation & BoP supply and operation phase	89.4%	81.6%	82.4%	74.9%	90.4%	86.8%
Foreign investment share [31,32,95,96]	52.5%	79.6%	88.2%	51.6%	16.8%	37.3%

A.4 Common techno-economic assumptions

Table A.5 shows the additional techno-economic assumptions for the analysis of Chapter 4. The assumptions for H₂, LH₂ and further energy system components are shown in the main report [1] and mostly based on

Hoelzen et al. [94,97], Schenke et al. [98,99] and Lohr et al. [100]. The assumptions for the eSAF production are taken mainly from Hoelzen et al. [101].

Table A.5: Techno-economic assumptions for the project analysis. The values for the years not shown are interpolated linearly.

Component	Parameter	Unit	2035	2050	Source
DAC (low temperature)	Specific total CAPEX	USD ₂₀₂₃ /kgCO ₂ /a	1.32	0.79	[101]
	Depreciation period	Years	25.00	25.00	[101]
	O&M factor	% of CAPEX	4.00	4.00	[101]
	Specific energy demand	kWh/kgCO ₂	1.73	1.28	[101]
Fischer-Tropsch + Reverse Water Gas Shift	Specific total CAPEX	USD ₂₀₂₃ /kg syncrude p.a.	0.61	0.53	[101]
	Depreciation period	Years	30.00	30.00	[101]
	O&M factor	% of CAPEX	4.00	4.00	[101]
	Specific electrical energy demand	kWh/kg syncrude	0.37	0.37	[101]
	Specific H ₂ demand	kgH ₂ /kg syncrude	0.48	0.48	[101]
	Specific CO ₂ demand	kgCO ₂ /kg syncrude	3.06	3.06	[101]
	District heating output	kWh heat/kg syncrude	2.61	2.61	[102]
	Output share Naphtha	% of syncrude	24.00	19.00	[101]
	Output share LPG	% of syncrude	6.00	3.00	[101]
	Output share eSAF	% of syncrude	70.00	78.00	[101]
eSAF fuel tank	Specific total CAPEX	USD ₂₀₂₃ /kg capacity	0.32	0.32	[101]
	Depreciation period	Years	20.00	20.00	[101]
	O&M factor	% of CAPEX	3.00	3.00	[101]

Glossary

ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene	GDP	Gross Domestic Product
ATJ-SKA	Alcohol-to-Jet Synthetic Kerosene with Aromatics	GFI	Green Future Index
BoP	Balance of Plant	GH ₂	Gaseous Hydrogen
CAPEX	Capital Expenditures	H ₂	Hydrogen
CEPCI	Chemical Engineering Plant Cost Index	HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
CHJ	Catalytic Hydrothermolysis Jet fuel	ICAO	International Civil Aviation Organization
COM	Commodities	IO	Input-Output
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation	LH ₂	Liquid Hydrogen
DAC	Direct Air Capture	LPG	Liquefied Petroleum Gas
ECI	Economic Complexity Index	NUTS	Nomenclature of Territorial Units for Statistics
EEA	European Economic Area	OPEX	Operational Expenditures
EHB	European Hydrogen Backbone	PEM	Proton Exchange Membrane
eSAF	Electricity-based Sustainable Aviation Fuel	PV	Photovoltaic
ESTRAM	Energy System Transformation Model	RED III	Renewable Energy Directive III
ETI	Energy Transition Index	RES	Renewable Energy Sources
ETS	Emissions Trading System	RFNBO	Renewable Fuels of Non-Biological Origin
FDI	Foreign Direct Investment	RWGS	Reverse Water-Gas Shift
FSI	Fragile States Index	SAF	Sustainable Aviation Fuel
FT	Fischer-Tropsch	SAM	Social Accounting Matrix
FT-SKA	Fischer Tropsch Synthetic Kerosene with Aromatics	SIP	Synthetic Iso-Paraffin
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene	TCO	Total Cost of Ownership
		tkm	Ton-kilometres
		WACC	Weighted Average Cost of Capital

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