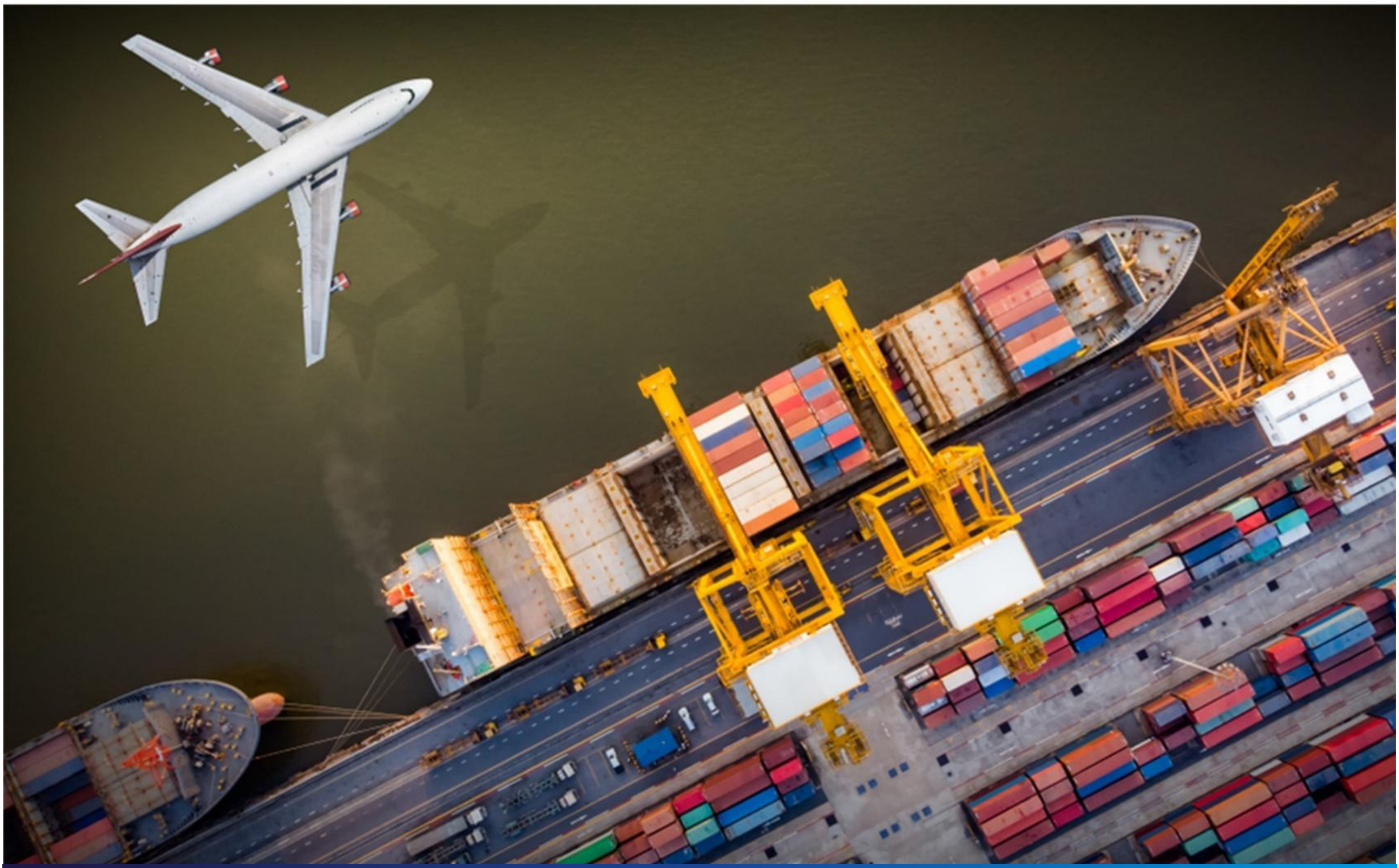

STUDY ON SUPPORT SCHEMES FOR RFNBOS IN SHIPPING AND AVIATION

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EXECUTIVE SUMMARY

Ricardo conducted this study on behalf of Transport and Environment (T&E) to demonstrate how public support for renewable fuels of non-biological origin (RFNBO) could be used to accelerate the energy transition in shipping and aviation. The aim is that the outcomes of this study provide policymakers with evidence-based guidance on scheme designs to effectively assist the transition in the transport sectors.

Considering both the existing policy landscape across each sector and alternative public support mechanisms (including carbon contracts for difference (CCfD), and fixed premiums), this study found that contracts for difference (CfDs) offer a favourable and flexible way to mitigate the high costs traditionally associated with low and zero carbon fuels in aviation and maritime sectors. Whilst not clear cut, the following recommendations were provided in terms of CfD design implementation.

- **For the aviation sector,** to efficiently deploy e-kerosene across the fuels value chain, a supply-side CfD can be placed on the sale of e-kerosene (at the end of the fuels value chain), while the steps higher up the value chain can be supported through bilateral purchase agreements. Hydrogen producers can enter power purchase agreements with renewable electricity generators. They can also sell their hydrogen to e-kerosene producers using bilateral purchase agreements. Unabated fossil fuel plants can adopt carbon capture technology and sell captured CO_2 to e-kerosene producers through a long-term purchase agreement. Hence, the fuels sector can organise itself through bilateral contracts that can provide investor confidence to invest in RFNBO capacity. The wholesale price of e-kerosene may be volatile and is therefore supported through a supply-side CfD to ensure it can honour its purchase agreements higher up in the fuels value chain. The e-kerosene producers would likely need to receive binding quotes from producers higher up in the fuels value chain to submit competitive bids in a CfD auction.
- **For the maritime sector,** to produce e-ammonia, a similar process can be used to that of aviation. A supply-side CfD can be used to incentivise e-ammonia production and the producer can enter purchase agreements to purchase adequate supplies of green hydrogen and nitrogen. However, to also incentivise uptake of e-ammonia in the maritime sector (in the absence of a firm mandate, unlike aviation), a demand-side CfD could be used instead of a supply-side CfD to ensure sufficient support for vessel operators. This would determine some of the demand for e-ammonia and ensure the wholesale price for e-ammonia is at a sufficient level for producers to invest in production capacity. There is a risk that if future price signals are not clear, the supply of e-ammonia would lag behind the demand, at a higher cost to the CfD counterparty (i.e. governments). A total cost of ownership (TCO) demand-side CfD would support vessel operators with the cost of retrofitting and adapting ships to run on ammonia.

In principle, multiple CfDs could be placed along the fuels value chain to ensure sufficient incentives at each point along the value chain. However, the EU has effectively limited the ability of companies to use multiple CfDs, by stating that green hydrogen cannot be classified as RFNBO if it uses renewable energy from the grid that has received financial support (European Commission, 2023b). Instead, the European Commission suggests power purchase agreements can be a suitable tool to procure renewable electricity for RFNBO producers.

The ability of the sector to coordinate itself along the fuels value chain depends on the vertical integration of the sector. If a large vertically integrated company operates across the fuels value chain (producing green electricity, and owning electrolysers and CCUS power plants), it will be able to plan internally to invest along the fuels value chain to produce RFNBO. If the sector is made up of different companies along the fuels value chain, close cooperation will be needed to ensure risk is mitigated and an end-producer of RFNBO can submit bids in CfD auctions while having conditional agreements in place for inputs (green electricity, hydrogen, CO_2 and/or nitrogen) higher up the fuels value chain.

Whilst possible, Ricardo suggest a demand-side only scheme (placed at the consumption of RFNBOs) would make it harder ensure the scheme is effective across the full fuels value chain, and each agent in the fuels value chain have the correct incentives to invest at the scale and pace needed.

Analysis to determine potential mechanism scope and implementation options was then delivered by sector.

Aviation sector findings

The findings of this report are based on modelling of the impacts of using 25% of EU Emissions Trading System (EU ETS) revenues from the aviation sector (including both the revenue from the aviation EU ETS and revenue from aircraft operators under the general EU ETS) to support a CfD for RFNBO. The modelling was conducted considering four scenarios for the possible implementation of a CfD in Europe including:

- **FF55:** a business as usual scenario, with alternative fuel mandates as agreed in ReFuelEU and the EU ETS with the existing scope and the agreed phase-out of free allowances.
- **DMan:** a scenario with passenger transport demand capped at 2019 levels, achieving carbon neutrality by 2050;
- **No DMan:** a scenario with increased uptake of RFNBO to deliver the same reductions in emissions found from DMan (achieving carbon neutrality by the same date);
- **FF55++:** a "Fit for 55 +" scenario, with the EU ETS extended to all EEA departing flights, and the ETD implemented at full rate on intra-EEA flights, delivering significant reductions in aviation emissions, but not full carbon neutrality by 2050.

Under each scenario, two options for the CfD scheme implementation were considered:

i. A "Basic scheme", with the CfD used to reduce the costs to aircraft operators of the mandated uptake of RFNBO under the ReFuelEU Aviation Regulation, by effectively reducing the price of RFNBO to that of biofuel-based SAF;
ii. A scheme in which the CfD has the aim of increasing RFNBO uptake to the full SAF mandate (i.e. displacing all biofuel-based SAF) at least to the extent that can be supported by the available funding.

Results of the modelled scenarios in section 5 suggest that the full mandated RFNBO uptake can be supported with the Basic scheme under the DMan and FF55++ scenarios. Under DMan, this results in a total RFNBO uptake between 2025 and 2039 (across two CfD auction periods) of 27.1 million tonnes at a scheme cost of €19.9 billion, while under FF55++, 22.1 million tonnes of RFNBO are supported at a cost of €15.5 billion (in both scenarios, the full mandated RFNBO uptake is supported; the differences in quantities are due to the different total fuel demand between the scenarios). The FF55 scenario provides support to less RFNBO, at a lower overall cost, while under the No DMan scenario, the required RFNBO uptake is significantly increased, leading to a substantial increase in costs (and still supporting only 20% of the total RFNBO uptake).

Under the alternative scheme design, in which the support is provided for RFNBO uptake up to the total mandated quantity of SAF, the total RFNBO that can be supported is increased, but it falls short of supporting all RFNBO uptake under all scenarios. The highest level of support is provided under the FF55++ scenario, with 58.6 million tonnes (out of a total uptake of 87.3 million tonnes) at a cost of €45.4 billion. Therefore, for the aviation sector, if the scheme is based on a budget of 25% of revenues from the EU ETS, the greatest impact will be obtained if the scheme is used to support uptake of RFNBO up to the total SAF mandate levels in the ReFuelEU Aviation regulation and if the EU ETS is also extended to all flights departing EEA airports (including extra-EEA flights).

Maritime sector findings

Similarly for the maritime sector a model was utilised to assess a CfD scheme supporting RFNBO uptake based on utilising 25% of EU shipping ETS revenues. Under each scenario the available ETS revenue to support RFNBO uptake was calculated at 25% of total available and allocated out to see how much could be supported during the auction periods (2025-2039). The revenue available from the ETS was allocated in two ways: proportionally to the expected uptake of each RFNBO; and split equally across RFNBOs and solely to support e-ammonia. The modelled implementation scenarios for the maritime sector included:

- **FEUM:** a baseline scenario with an emission intensity reduction target of 80% by 2050 and RFNBO sub-quota of 2% in 2034, as per the EU's FuelEU Maritime (FEUM) Regulation.
- **FEUM + efficiency:** As FEUM scenario but incorporating additional energy efficiency measures as per the IMO 4th GHG Study by vessel type until 2023 and then interpolating up to 38.6% additional energy efficiency by 2050.
- **DE_DK:** a scenario with a 100% emission intensity reduction by 2050 and RFNBO sub-quota if 2% in 2030 rising to 70% in 2050.
- **DE_DK + efficiency:** As DE_DK scenario but incorporating additional energy efficiency measures as per the IMO 4th GHG Study by vessel type until 2023 and then interpolating up to 38.6% additional energy efficiency by 2050.

For the maritime sector, it was concluded that a CfD scheme may be feasible to accelerate the uptake of RFNBOs in the short-medium terms (2035 and earlier).

Overall, the best option for scheme design, and ETS revenue allocation, is dependent on the overall objectives of initiating the CfD scheme. Subsiding 100% of the price differential between RFNBOs and HFO has a direct benefit in terms of GHG reduction and OPEX savings for a vessel operator. Overall although a lower volume of RFNBO could be supported it could allow operators to invest any OPEX savings made further into low and zero carbon technologies thus creating indirect GHG savings in the longer term. Subsiding only 60% of the price differential could have the converse effect. Though more absolute volume of RFNBO could be supported under a 60% price subsidisation the OPEX savings to operators is less therefore it is unlikely they will invest (or invest as much) into other low or zero carbon technologies. However, support for greater volumes of RFNBOs would help to stimulate the market demand to a greater extent as more operators can benefit from a subsidise RFNBO fuel.

When choosing between allocating the ETS revenue on a proportional, equal or only to e-ammonia basis the choice of “best” scheme design is subjective. An equal allocation basis would give industry support for production and use of a wider range of RNFBOs (e-ammonia, e-diesel, e-methanol and e-LNG) this could be a more technology agnostic approach to follow and from the results of the modelling work conducted could serve as a springboard for greater uptake of e-LNG, e-diesel and e-methanol than predicted under the modelled scenarios. Allocating on a proportional basis seeks to back whichever fuel (e-ammonia in this case) has the greatest long term promise as a future marine fuel. This approach is less agnostic but it would avoid spending public funds on fuels that may not stand the test of time. Allocating only to e-ammonia provides a clear sign to industry that e-ammonia will be the future fuel of the global shipping industry and gives a clear signal and confidence to investors to transition to ammonia-powered vessels. Whilst providing greater certainty caution must be taken as some companies may have already invested, or are planning on investing, in alternative technologies and may feel aggrieved if public funds are also not available for the fuel technology they have selected.

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1. INTRODUCTION

Ricardo has been commissioned by Transport and Environment (T&E) to conduct a study to demonstrate how public support for hydrogen (such as contracts for difference (CfD)) can accelerate the energy transition and make renewable fuels of non-biological origin (RFNBO) production competitive in shipping and aviation. The aim is that the outcomes of this study provide policy-makers with evidence-based guidance on scheme designs to effectively assist the transition in these transport sectors.

This report provides an overview of the outcomes of the research. It is organised as follows:

- **Chapter 2 – Available Design Options:** Overview of the main design options for support schemes, including existing schemes and potential challenges of a renewable fuels from non-biological origin (RFNBO) support scheme.
- **Chapter 3 – Current Policy Landscape:** Overview of current policy and legislation impacting aviation and maritime sectors, and where appropriate interactions with a proposed public support mechanism.
- **Chapter 4 – Risk Register:** Overview of risk register, exploring ten key risks identified.
- **Chapter 5 – Scheme Size and Scoping:** Modelling outcomes addressing the appropriate size of a subsidy scheme to positively increase the uptake of RFNBOs in the aviation and shipping sectors.
- **Chapter 6 – Conclusions:** Overview of conclusions relating to the potential of a CfD mechanism for RFNBOs in aviation and maritime sectors, as well as areas for future research.
- **Appendices:** Two appendices, the first includes the Risk Register methodology and full risk table, the second provides further details on modelling outputs.

1.1 CONTEXT

GHG emissions from maritime and aviation sectors are growing rapidly

The most recent statistics show that the maritime and aviation sectors were responsible for a total of 4% of global energy-related CO_2 emissions in 2022, with each sector contributing around 2% (IEA, 2023a) (IEA, 2023b). Whilst other sectors are set to decarbonise, without intervention[1] the contribution of maritime and aviation activities to global emissions will continue to grow, and by 2050 greenhouse gas (GHG) emissions from international aviation and shipping could see an increase of 329% (ATAG, 2021) (IEA, 2023a) and 130% (IMO, 2020a) from 2008 levels respectively.

Low-carbon fuels options for the 'hard to abate' maritime and aviation sectors

The expected growth in demand for both sectors would require an acceleration in the uptake of low-carbon and alternative fuels. The production processes for these fuels have reached high levels of technological maturity in recent years, key alternatives include biomass-derived fuels, such as biofuels; as well as synthetic fuels (referred to from now as RFNBO). However, the availability and cost of these fuels represent a key barrier to their adoption and therefore decarbonisation of the sectors. This renders maritime and aviation as 'hard to abate'.

According to the ReFuel EU Aviation Regulation, SAF is defined as a drop-in aviation fuel produced from feedstocks listed in Annex IX of the Renewable Energy Directive (RED II) or synthetic aviation fuels; which in both instances comply with sustainability and emission criteria set out in the Renewable Energy Directive (EU/2018/2001). This means GHG emission savings must be a minimum of 65% to 70%, depending on the renewable fuel in question (European Council, 2018). In addition, fuel should not be derived from food- and feed-crop fuels. There are currently eight SAF production pathways certified for use in commercial aviation under ASTM D4054 as outlined in Table 1-1.

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[1] Assuming 2050 traffic growth projections of 10 billion passengers travelling 22 trillion passenger kilometres, sustained fleet demographic, an no improvements in operational efficiencies as of 2021.

Table 1-1: Approved SAF pathways

Pathway	Blend	Feedstocks
Annex A1: Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	50%	Flexible, synthesis gas (or syngas, a mixture of CO and H_2)
Annex A2: Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	50%	Fatty acids and oils
Annex A3: Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	10%	Sugar, Lignocellulose
Annex A4: Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	50%	Flexible, synthesis gas (or syngas, a mixture of CO and H_2)
Annex A5: Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	50%	Sugar, Lignocellulose
Annex A6: Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	50%	Fatty acids and oils
Annex A7: Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)	10%	Specific algae
Annex A8: Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	50%	Starches/Sugars

For the maritime sector, several alternatives to conventional fuels exist (see Table 1-2). These include carbon-based fuels, such as LNG, LPG, alcohols, as well as hydrogen-based fuels, such as hydrogen and ammonia. Biofuels and lower-carbon fossil-based fuels (such as LNG and HVO) are early movers in the decarbonisation transition whereas other fuel types are expected to reach commercial maturity in the coming years.

Table 1-2: Zero and near zero carbon maritime fuels

Category	Fuel	Feedstocks
Green Fuels	e-ammonia	Renewable electricity
	e-methanol	Renewable electricity + captured carbon
	e-LNG	Renewable electricity + captured carbon
	e-diesel	Renewable electricity + captured carbon
	Hydrogen	Renewable electricity + water
Blue fuels	Blue ammonia	Natural gas (must capture carbon emitted during process)
Biofuels	Hydrogenated Vegetable Oil	Bio-feedstock
	Fatty acid methyl ester	Bio-feedstock
	On-shore power	Electricity
Fossil fuels	LNG/LPG	Natural gas/By-product of oil refining

FuelEU Maritime requires eligible fuels to meet sustainability criteria outlined in RED II and disincentivises food- and feed-crop fuels (Ricardo, 2023a). The Regulation also sets shore-side electricity infrastructure requirements for vessels to meet the zero-emission berth conditions.

Whilst biofuels are eligible in both instances under ReFuelEU Regulation and provide credible GHG savings, they present several challenges including limited feedstock availability and potential for land-use change (Ricardo, 2023a). RFNBOs are a favourable route of decarbonising aviation and maritime due to their reduced land use impacts, abundant feedstock availability, and high potential for GHG emission savings (T&E, 2021).

The value chain of RFNBOs

RFNBO are typically produced by converting renewable electric energy to an alternative energy carrier via green hydrogen and can also be mixed with nitrogen or captured CO_2. The term RFNBO encompasses a diverse array of both liquid and gaseous fuels including green hydrogen (produced by electrolysis using renewable energy), green ammonia (green hydrogen combined with nitrogen), and other electricity-based fuels such as e-methanol, e-diesel, and e-kerosene, which are produced using a combination of green hydrogen and captured CO_2 (T&E, 2021). The CO_2 can be captured from either industrial sources or direct air carbon capture (DACC) (E4Tech, 2023).

In order for the maritime and aviation sectors to use hydrogen, current infrastructure may require modification, however, RFNBO can be used directly in existing infrastructure as drop-in fuels. Aircraft can use hydrogen either through modified gas-turbine engines, or via retrofitted fuel cells which convert hydrogen into electrical power; a combination of the two can create an efficient hybrid-electric propulsion chain (Airbus, 2023). Ships can use hydrogen through modified internal combustion engines, hydrogen gas turbines and fuel cells (Ammar & Alshammari, 2018).

RFNBO are considered a feasible option for decarbonisation by policy makers

To support their scale up, ReFuelEU stipulates increased levels of synthetic aviation fuels (or RFNBO). The SAF mandate targets 1.2% RFNBO as part of the overall jet-fuel consumption between 2030 and 2031 and 2% between 2032 and 2035. Whilst FuelEU Maritime establishes a general greenhouse gas intensity target for fuels and a conditional target for RFNBOs, of 2% by 2034. Scale up of these drop-in fuels is critical to meeting climate objectives as technological advances in other technologies, such as batteries, are unlikely to develop sufficiently within this time to be able to power long-haul shipping and aviation. Given that these fuels and technologies are at technology readiness level (TRL) 5-6[2] (E4Tech, 2023) financial support is key in bridging the gap for their production, and to enable wide-scale use of RFNBOs in aviation and maritime sectors.

Demand and Supply of RFNBOs

Public support schemes are one option under consideration to support commercialisation of these fuels. Those named by the European Commission in relation to hydrogen policy include CfDs, carbon contracts for difference (CCfDs) and fixed premiums (European Commission , 2023a).

Today, the cost of producing RFNBOs is significantly higher than traditional fuels. McKinsey estimates that the production of RFNBO is currently 3–9x the historical cost of jet fuel on average (Mckinsey, 2022). Without policy instruments in place, those that consume maritime and aviation fuels will typically choose fuels most cost-effective for the company. Whilst the EU Emissions Trading System (EU ETS) and ReFuel EU mandate go some way by placing a minimum uplift volume, more needs to be done to significantly scale RFNBOs; as ultimately the price differential between fuels of same quality and function will drive the investment decisions. Therefore to scale RFNBOs, the price differential between this and its alternatives needs to be reduced, one such method is public support mechanisms.

Through public support mechanisms there are multiple ways to encourage the uptake of RFNBO

The government could procure a certain quantity of RFNBO[3] through a (supply-side) Contract for Difference scheme (see section 2.1.1.1). This fixes the supply of RFNBOs and ensures the full amount of RFNBO will be sold through a market clearing price. To ensure there are buyers of RFNBO, the market price of RFNBO will be near or equal to conventional fuels of the same quality and function. If this was not the case, microeconomic theory suggests (Varian, 2010) consumers of fuels would only purchase the lower priced fuel (including carbon prices), resulting in no demand for the higher priced fuel. For example, if the price of RFNBOs was above alternative fuels, maritime and aviation firms would in theory only purchase the alternative fuel. Conversely, if the price of RFNBO fell below the conventional price, maritime and aviation firms would only like to purchase RFNBO as this becomes the more cost-effective fuel. To secure continuous supply, the price of the two fuels would be adjusted such that the combined supply of the two types of fuels equals demand.

Alternatively, the government can require a minimum renewable obligation on use of RFNBOs, which would fix the demand for RFNBOs, while the wholesale price would reach a level that would incentivise RFNBO producers to produce at the required level of demand. This could allow the price of RFNBO to be higher than

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[2] TRL definitions available at https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

[3] Assuming other barriers to entry are dealt with

alternative fuels, as the minimum demand for RFNBO is now determined by the obligation. Or, governments could stimulate demand for RFNBOs by introducing demand-side CfDs (see section 2.1.1.2).

A third option is to subsidise the price of RFNBOs such that they are competitive with the market price of conventional fuels. This is effectively equal to the first option (if no mandate is in place), where producers of RFNBO are guaranteed a price, and the government pays for the difference between the guaranteed price and the market price of the alternative fuel.

1.2 SCOPE OF STUDY

T&E is exploring how public financial support could be made available to increase RFNBO production and deployment in the EU for aviation and shipping using part of revenue generated from the EU ETS (European Commission, 2022b). It is however, recognised that uncertainty on the final design of such a mechanism remains and there are questions as to whether it will be sufficient to achieve the desired increase in production and uptake of RFNBOs in shipping and aviation.

The outcomes of this study aim to provide evidence-based guidance on the type of scheme design best fitted to assisting the energy transition, and more specifically the scale up of RFNBO in aviation and shipping sectors.

2. AVAILABLE DESIGN OPTIONS

This section provides an overview and analysis of key examples of public support schemes which could be employed to support scale up of RFNBOs in the aviation and maritime sections. Sub-section 2.1 introduces public support measures identified by the European Commission, focusing on CfD, Carbon Contracts for Difference (CCfD), and Fixed Premiums. Whilst sub-section 2.2 details examples of existing schemes globally, showcasing best practice and highlighting lessons.

2.1 PUBLIC SUPPORT MECHANISMS

As identified in section 1.1, low carbon fuels in the maritime and aviation sector are currently more expensive to produce than conventional fuels and have therefore had limited uptake to date. Public support schemes can affect the relative prices of low-carbon fuels and promote their deployment by increasing their competitiveness vis-à-vis conventional fuels. This can be either via:

- the supply side (i.e. supporting producers of low carbon fuels); or
- the demand side (i.e. supporting buyers/consumers of low-carbon fuels)

Two pathways can help the attractiveness to invest and consume low-carbon fuels:

1) A mechanism that provides price stability by determining a fixed price for a commodity. This can reduce the cost of capital requirement of investments in low-carbon fuels, taking away the risk inherent in volatile commodity markets.
2) Governments can subsidise the price of a commodity to reduce the gap between what the producers require to cover costs, and the willingness of consumers to pay for low-carbon fuels.

Why commodities are traded on markets

Commodities markets allow producers and consumers of commodity products to gain access to them in a centralised and liquid marketplace. A marketplace is key to setting efficient prices for buyers and sellers. As prices vary across time (in some markets every minute or second), producers can update their “offers” in response to fluctuations in production costs or market dynamics. Trading through markets ensures all producers that are willing to sell a commodity at or below the clearing price (see Table 2-1 for definition) will be able to do so, and any consumers willing to purchase the commodity at or above the clearing price will be able to do so too. Forward contracts allow for the exchange of commodities at a later date, with the terms agreed upfront; a market for such contracts can reduce uncertainty in future pricing and avoid windfall gains and losses.

Within this section, each scheme has been explained to understand its role as well as design options for the aviation and maritime sector. A summary of pros and cons of each support scheme is provided in section 6.

2.1.1. Contracts for Difference

A CfD scheme is a mechanism for providing price stability in volatile wholesale markets, while ensuring the price support incentivises profitable investments in capital-intensive projects. CfDs have typically been designed to support investments in renewable projects with high upfront capital costs but uncertain revenue streams, such as installing wind and solar farms. Investors in these sectors faced similar barriers to those involved in RFNBOs production today.

Table 2-1. Glossary for CfDs

CfD counterparty	A counterparty to the CfD that guarantees a strike price (typically a government body).
Strike price	A fixed price for which a producer or consumer is guaranteed by the CfD counterparty when selling or purchasing a unit of a commodity as part of a CfD scheme.

Reference price	This is the price the producer receives when selling a commodity[4]. This is typically the wholesale price of a commodity or the average wholesale price of a commodity over a set period. If the reference price is above the strike price, the party must return the difference between the two. When the reference price is below the strike price, the party receives the difference.
Market clearing price (also known as wholesale price)	The equilibrium price that clears the market (i.e. when demand equals supply).
Hedging	A mechanism for removing the price volatility in markets.

A CfD scheme mitigates this risk by setting a strike price (see key definitions in Table 2-1) for which a producer of a commodity is guaranteed over a set period. If the reference price (i.e. the market price) is above the strike price, the producer will need to pay back the difference between the reference price and the strike price. If the reference price is below the strike price, the producer will be topped up the difference, to ensure they receive the strike price. CfDs are typically introduced by governments, which ensure the balance of payments is honoured. For example, if the market price is consistently below the strike price, the government will need to cover the deficit in the scheme, whereas if the market price is consistently above the strike price, the government will have a surplus balance. For power generators, the CfD balance can be passed on to retail electricity consumers, which pay higher tariffs when there is a sustained deficit, and lower tariffs when there is a surplus.

To ensure producers do not make windfall profits from artificially high strike prices, governments can award CfDs based on the outcomes of an auction. Bidders in the auction submit sealed bids for the quantity of a commodity they offer to produce, and at what strike price they are willing to accept. If CfDs are awarded on a pay-as-bid[5] basis, different market players will be awarded different strike prices. If there are sufficient market players bidding for a CfD, the strike prices will be awarded at competitive levels. Auctions can be designed as technology-neutral or technology-specific, depending on the importance of supporting specific technologies. Technology-neutral auctions mean different technologies (i.e. wind and solar PV in an electricity generation CfD) compete in the same auction. Technology-specific auctions means there are different auctions for different technologies, which ensures some technologies are not disadvantaged in an auction due to having higher costs than other technologies.

CfD schemes have historically been designed to support producers of a commodity. These are known as supply-side CfDs. A CfD scheme could be developed to support the production or uptake of RFNBO. RFNBOs have typically high upfront capital costs and the fuel will likely compete on global wholesale markets. A supply-side CfD could procure sufficient quantities of RFNBO at prices that cover the cost and return required by RFNBO investors.

But CfDs can also be designed to incentivise consumption of a commodity. For example, if governments want airlines and ships to adopt low-carbon fuels, they can design a demand-side CfD, which provides a stable and lower price for RFNBOs to make them more competitive with conventional aviation and maritime fuels. This will encourage producers of RFNBO to produce enough RFNBO to meet demand. There is a risk that as the demand for RFNBO increases, supply will take time to scale up, which can lead to extreme prices in the wholesale market in the short run, which a counterparty will have to cover.

The cost to the CfD counterparty is usually guaranteed by the government, but the actual cost could be passed on to consumers through general taxation or through taxes on fuels. Although the market price is de-coupled from the subsidies, the price of RFNBO could increase if the cost of the CfD scheme is passed through to fuel excise tax etc.

The current EU ETS policy provides a limited allocation of allowances in the aviation sector. The total number of allowances auctioned is decreased over time (a reduction of 25% in the number of free allowances in 2024, 50% in 2025 and complete removal in 2026), which should lead to an increase of the price of each allowance, thus providing further incentive to decarbonise. Such allowances can incentivise the development of alternative fuels in the aviation sector, due to industry players selling their allocated free allowances and investing into

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[4] Or the price a consumer pays when purchasing a commodity (in relation to demand-side CfDs)

[5] The other option is to design the auction as pay-as-clear, where all successful bidders receive the same strike price.

alternative fuels and technologies. Revenues from the sale of auctioned allowances by the Member States could be utilised to fund the CfD mechanism proposed, supporting direct sector support for decarbonisation.

Design elements:

Some key design elements of a CfD are listed in Table 2-2 below.

Table 2-2. Key CfD design elements

Design elements	Options
Allocation of CfDs	CfDs can be allocated directly to relevant parties or can be allocated competitively using an auction mechanism.
Auction design	As part of the auction design, successful bidders can be awarded based on a pay-as-clear auction, where the highest successful bid in a supply-side CfD (or lowest bid in a demand-side CfD) sets the strike price for all successful producers (or consumers) in the auction. Alternatively, a pay-as-bid auction will award strike prices according to successful agents' individual bidding price, and thus the strike price can be different for different agents.
Duration of contract	The number of years for which a party is guaranteed a strike price. Alternatively, it could be volume-based, i.e. support for a fixed number of tonnes of RFNBO production.
Reference price	Reference price can be the wholesale market price of the commodity or can be the price of a substitute commodity. For example, for the aviation sector, the reference price can be set to be the price of biofuel-based SAF, to enable RFNBO to be competitive with biofuels.
Payment conditional on reference price	To avoid subsidising RFNBOs if the market price becomes negative during a particular period, the CfD design could include options to not pay the strike price when the reference price is negative. This has been implemented in CfD for renewable electricity generation, where electricity usually cannot be stored in large quantities. However, this is unlikely to be needed if there is sufficient demand for RFNBO or RFNBO can be stored in large quantities.
Geographical criteria	To stimulate production near hubs such as airports and ports, or near existing pipelines, geographical criteria can be included to incentivise this.

The subsections below analyse the difference in impacts between a supply-side CfD and a demand-side CfD.

2.1.1.1 *Supply-side CfD*

In a **supply-side CfD**, producers of commodities (i.e. fuels) submit quantities and offers in an auction for strike prices they are willing to sell the fuel for. The offer price is set such that the producer expects to recover the full capital and operational costs of producing the fuel, plus a reasonable rate of return. If the producer is successful in the auction, it is guaranteed a strike price for each unit of fuel sold. The commodity is sold on the wholesale market where end-users (here aircraft or ship operator) pay the market prices for the commodity.

A supply-side CfD can be administered to provide price stability and subsidies to RFNBO producers. RFNBO producers are guaranteed a fixed strike price by the CfD counterparty while selling RFNBOs on wholesale markets. This strike price is expected to cover the total cost of owning and operating a RFNBO installation, rather than a specific cost component (in contrast to a fuel-only demand-side CfD, see section 2.1.1.2). As different RFNBO fuels are traded on different markets, they cannot easily compete in the same auctions. This is because the reference price will be different for different RFNBOs. Hence, technology-specific auctions are preferred, which allows governments to provide CfDs that promote a specific uptake of each fuel type. Alternatively, it could run the auction only for hydrogen producers, where other RFNBO producers can purchase hydrogen as an input at the same competitive market price.

Supply-side CfDs can be effective in promoting a set quantity of RFNBOs. Auctions ensure a specific amount of RFNBOs are procured and produced, based on the quantity allocated by the CfD counterparty (i.e. government). As the supply of RFNBO is effectively fixed by the amount procured, the wholesale price will be set by the demand for RFNBO. To stimulate demand, the wholesale price for the various types of RFNBO are likely to track the substitute conventional fuel price plus any carbon price. This means that the level of subsidy depends on the price of the substitute conventional fuel. This will make the cost of RFNBO competitive but could come at a significant cost to the CfD counterparty depending on the price differential between the strike price and the market price for substitute conventional fuel plus carbon price. Where there is a mandate for aviation or maritime operators to use RFNBO, this can determine the demand for RFNBO to a point where the market price of RFNBO differs from conventional fuels.

However, in the maritime sector, there is a risk that vessel owners make decisions on the type of engines, without knowing how exactly much demand their competitors will have for RFNBO. As the supply of RFNBO is effectively fixed and determined through an auction, over-investing in vessels that use, for example, e-ammonia can cause competition between vessel owners for e-ammonia. Hence, a supply-side CfD is not ideal for ensuring price stability for vessel owners when demand is not coordinated. In the shipping industry, this risk can be mitigated by purchasing ships that have dual-fuel engines, that can run on both traditional and RFNBO fuels. For fuels such as methanol and ammonia, a reduced demand from the maritime sector may mean chemicals and fertilizer sectors will demand those fuels. In the aviation sector, the minimum demand for RFNBO is set by the ReFuelEU Aviation legislation, which mandates a minimum percentage of fuel that must be SAF (starting from 2% in 2025 and increasing over time to 70% in 2050), with a sub-mandate for RFNBO (starting at 1.2% in 2030 and rising to 35% by 2050). As RFNBO are expected to be significantly more expensive than biofuel-based SAF, the mandated minimum RFNBO percentages are unlikely to be exceeded without some support to ensure their competitiveness with biofuels.

2.1.1.2 Demand-side CfD

Under a **demand-side CfD**, end-users (such as airlines or ship operators) bid for the auction. Upon winning, they pay the strike price for alternatives fuels or vessel development. This allows the end-user to adopt the novel fuel or technology at subsidised rate, promoting uptake.

A demand-side CfD can be administered to reduce the price differential between low-carbon fuels and conventional fuels (or in the base of aviation, biofuels) in one of two ways (Global Maritime Forum, 2021):

1) **Fuel Only:** Functions as a normal CfD specific to the demand-side, where airlines or ship operators have price certainty on the price of purchasing RFNBO fuels over a period of time determined by the CfD. It covers the price differential between the agreed strike price and market price of RFNBOs. If the strike price is higher than the market price, the CfD counterparty pays the difference as a subsidy to the end-user of the fuel.
2) **Total Cost of Ownership (TCO):** This approach covers all costs associated with building and running zero-carbon emission operations, including the infrastructure and retrofitting costs needed to change fuel. This can help break the so-called chicken and egg problem, where the infrastructure is needed to adopt RFNBOs, but the infrastructure relies on availability of RFNBO at competitive prices. The TCO price support variant can also be applied to the Carbon Contracts for Difference described in section 2.1.2.

The TCO version has been designed to overcome the challenges of “fuel-only” demand-side CfDs. Though simple and effective in driving immediate change, “fuel-only” demand-side CfDs can fall short of covering the substantial costs associated with switching to zero-emissions vessels and aircraft, particularly in infrastructure and retrofitting in the maritime sector. The complexities of certification and regulation of fuel for compliance with safety standards (including both fossil and alternative fuels) in the aviation sector may also slow down progress in CfD implementation, which in turn could delay production plan capacities as producers wait for clarity on scope and scale of a CfD.

A demand-side CfD cannot easily work as a technology agnostic auction. This is because auctions determine the most cost-effective bids. Demand-side auctions favour higher priced bids (as opposed to lower priced offers in supply-side auctions), as the most competitive aviation and ship operators will be able to accept higher costs than other less efficient companies. However, different RFNBO fuels are traded on different markets, and thus the strike price in relation to the technology-specific reference market price is not clear ex-ante. Hence, technology-specific auctions are preferred, which allows governments to provide CfDs to a fixed quantity for each type of purchased RFNBO. If a demand-side CfD were to be designed as technology agnostic, a methodology for determining the most price competitive bids would need to be devised.

A demand-side CfD is effective at stimulating demand for RFNBOs. If RFNBOs have the same quality and function as conventional fuels in the maritime and aviation sector, strike prices for RFNBO are likely to be near the long-term projected price of substitute conventional fuels (plus projected carbon prices). If this was not the case, and in the absence of a mandate, all consumers would be incentivised to only purchase the cheaper fuel. For example, airlines may only enter a demand-side CfD for e-kerosene if its strike price is equal to the expected future price of fossil fuel kerosene plus the carbon price. Otherwise, it would not be in the airlines incentive to adopt e-kerosene. However, the strike prices will typically be fixed or indexed over time and will thus not trail the short-term market price for substitute conventional fuels. There is a risk that changes in the market means substitute conventional fuels would become more expensive than the strike prices of RFNBO, for which market players with a demand-side CfD for RFNBO will have a cost advantage over other consumers. This means a government could technically be subsidising RFNBO more than would be required to stay competitive with substitute fuels. The opposite could also occur, where the market price for conventional fuels falls below the strike price of RFNBOs for a longer period, where these market players will benefit. However, there is value to price stability, and the choice of entering a hedging agreement is not new to CfDs. Market players can decide the level of hedging by purchasing forward or futures contracts.

The suitability of the CfD scheme for demand-side considerations is significant, particularly due to its alignment with the extended life cycles of aircraft and vessels in aviation and shipping industries. Nonetheless, challenges may arise, particularly for the maritime sector, from the myriad and sometimes conflicting viewpoints on fuel technologies, making it difficult to stay technology-neutral and necessitating a carefully detailed scheme design to ensure the right level and range of RFNBO production and uptake. Additionally, the differing infrastructure requirements for zero-carbon and net-zero carbon fuels in the maritime sector pose hurdles, as promoting simultaneous infrastructure scaling can be undesirable. A trade-off between technology neutrality and the complexity of CfDs must be carefully managed. It is unclear whether demand-side CfDs covering the vessel's fuel expenses alone will be enough to justify an investment in zero-emission vessels.

There is a risk that a broad demand-side CfD fosters undesirable competition on two fronts: between the shipping sector and other industries if they use the same type of fuel, and between zero-emission fuels and alternative environmental impact reduction solutions. However, competitive auction will still incentivise airlines and shipping companies to purchase energy efficient aircraft and vessels. Another related concern is the potential inclination of producers to mitigate market risks by serving multiple markets.

Flexibility is another crucial aspect, allowing the CfD scheme to adapt to specific RFNBOs and industries. It supports flexibility in capacity and allocation, enabling it to cater to various needs. It also provides a hedging mechanism to protect against price fluctuations, whilst multiple rounds over several years allow for new price discovery in RFNBOs and traditional fuels, making it adaptable to market dynamics.

Combining CfD schemes with targeted actions addressing policy, regulation, safety, and infrastructure requirements can enhance its impact, especially when focused on specific routes in aviation or maritime. However, complications arise from the segmentation of the shipping market, necessitating separate CfD programs for different segments. Regulatory complexities in aviation also pose challenges to scheme implementation. A shipping specific demand-side subsidy may yield potential competition with blend-in fuels and other solutions, depending on the design.

2.1.2 Carbon Contracts for Difference

Carbon Contracts for Difference (CCfD) schemes are designed as a mechanism that provides stable carbon prices to agents that invest in emissions reduction activities or adopt renewable fuels.

CCfD schemes are suitable to agents that are covered by an emission trading system (ETS) and want to invest in emissions reduction technology or purchase low-carbon fuels for consumption. For example, the EU ETS applies at the point at which fuel is combusted and emitted into the atmosphere. This means an unabated fossil fuel electricity generator can capture its CO_2 and thus reduce its emissions. In the context of maritime and aviation, aircrafts and vessels can reduce their emissions by adopting renewable fuels. By reducing carbon emissions, an entity can reduce the number of ETS allowances it must surrender at the end of the compliance period. This cost saving varies depending on the volatile allowance price.

In response to volatile ETS allowance prices, a CCfD scheme can help eliminate this volatility by hedging the carbon price with a counterparty. If allowances are allocated for free, agents can earn money by reducing emissions, and by selling surplus emission allowances. CCfDs are also valuable to technologies that are not covered by an ETS but are direct substitutes to products covered by the ETS. For example, fossil fuel generation with Carbon Capture Utilisation and Storage (CCUS) does not emit carbon into the air, but still produces a direct substitute to unabated fossil fuel generation, which could be covered by an ETS. In this case, the generator with CCUS could earn carbon pricing revenue through its decarbonisation of electricity. As CO_2 is a component in the production of e-kerosene for aviation, a CCfD can incentivise capture of CO_2 for this use.

Many capital-intensive emission reduction technologies such as CCUS, electrolysers (to produce green hydrogen), and battery storage have high upfront capital costs that are additional to the electricity generation input cost (cost of coal, gas, bioenergy generation in the case of CCUS, renewable energy generation in the case of green hydrogen and battery storage). These technologies require a higher revenue than unabated generators, to be able to pay for the capital cost of the abatement technology, as well as the electricity generation cost. The only clear rationale for supporting these additional investments is due to the additional value society places on renewable fuels and electricity generation. Carbon prices, in the form of carbon taxes or emission trading allowances, place a cost on polluting. This cost can be mitigated by not emitting carbon. Hence, there is a market value of not polluting, which is equal to the carbon price. Agents that undertake emissions reduction activities can then be paid a stable CCfD strike price per unit emissions reduced relative to a conventional technology. Emissions reduction activities become profitable when their average costs are lower than the carbon price. A CCfD works by agreeing a fixed carbon price over a given time which constitutes the remuneration to installations for reducing emissions. For example, a company can invest in emission reduction activities and receive a fixed strike price as compensation for the emission reductions.

If airline and vessel operators adopt renewable fuels, they will no longer need to surrender an ETS allowance for the emissions conventional fossil fuels emit. If allowances are allocated for free, the aircraft or vessel operator earns money by selling the spare allowance in the secondary market for allowances. A CCfD can provide a guaranteed price for selling ETS allowances, and thus provide stable income stream from reducing emissions by adopting RFNBOs.

CCfDs are a variation of the CfD concept and can be designed with fixed strike prices (similar to CfDs) or can have variable strike prices based on other underlying variable cost drivers. In its fixed form, the strike price can be the hedge against a volatile carbon market (such as the EU ETS). A variable strike-price mechanism links the carbon emission price for the agent to other variable costs (such as reference plant costs, fossil fuel reference price, input material market price, or output material market price) (Gerres & Linares, 2020). In a similar way to fuel-only or TCO CfDs, each design impacts reduction in the cost differential differently. A fixed CCfD can reduce initial investment risks and financing cost and support the capital expenditure (CAPEX) of an installation. However, it fails to address the operational expenditures (OPEX) component. To address OPEX, a variable strike price mechanism is favourable.

As a price support mechanism, the government can be the counterparty to a CCfD. Alternatively, contracts can be signed between two private agents. In the latter, the government facilitates the contracts by providing financial guarantee. During the contract period the agent can sell any carbon emission reductions (or allowances) at the agreed price. If the reference price (also known as market price) exceeds the strike price, the agent typically reimburses the scheme administrator. Conversely, if the reference price is below the strike price, the counterparty reimburses the agent (Gerres & Linares, 2020).

CCfDs are commonly allocated through auctions, where successful bidders typically sign CCfDs for a period of five to 20 years. During auctions, the administering body (for example a government) will set a budget for the round. Sealed bids are then placed by agents wishing to install new processes aligned with emission reduction objectives of the bid. CCfDs can also be administered through negotiations.

Despite their benefits, CCfDs can make it riskier and more financially challenging for governments, as the support provided depends on the underlying carbon prices. The choice between CfDs and CCfDs depends on the maturity and stability of the carbon price, as well as the importance of carbon pricing to the impacted industries' business decisions. If innovation processes present knowledge spill overs, governments may want to subsidise further innovation such that the full social benefits are captured. However, a carbon price, does not factor in these additional benefits of innovation. In this case, additional technology support to aid technologies' competitivity is needed.

Through CCfDs, 100% of support would be provided, as long as it complies with environmental safeguards and is awarded through a competitive process. Administrative requirements might also create barriers for smaller companies and favour incumbents. One way to address this would be to award CCfDs to small companies directly, but with the price resulting from the tender. In this way they would not need to go through the administrative process of submitting a bid but could piggy-back on the successful CfD strike prices.

CCfDs work in conjunction with the carbon market and are reliant on emission trading systems. In principle, CCfDs ensure that projects can sell the allowances they have been granted for free (through the current benchmark process in the EU).

CCfDs also have similar disadvantages to CfDs when considering their flexibility. The shipping market is made up of several sub-markets, each with its own prices and economic incentives. Without separate CCfD programs, shipping or aviation segments with the ability to pass on a greater portion of extra costs to customers would benefit disproportionately more than others because they could bid at more competitive strike prices. The ability to pass on carbon costs to customers is driven by elasticity of demand, as it would not be ideal to have different pricing signals for different segments of the same sector; if demand for specific cargo is highly elastic, and suppliers cannot pass costs onto customers, this may be due to the type of activity the carbon price is aiming to prevent (e.g. transport of flowers through air cargo). Similarly, different RFNBOs (ammonia, hydrogen, methanol, synthetic LNG) are more suitable for different segments of the industry and so require different programs.

2.1.3 Fixed Premiums

Fixed premiums provide a fixed subsidy per unit sold of a commodity in addition to the market price a producer can earn in the wholesale market. Fixed premium schemes thus allow market prices to provide price signals to producers while also providing producers with additional revenue to support the financial viability of its production.

Fixed premiums are a support mechanism where the government pays producers of a commodity a fixed payment per unit in addition to the price the producer receives from selling the commodity in the market. Fixed premiums have been used in the power sector under the name feed-in premiums (FiP), where a renewable generator receives a subsidy per unit in addition to the wholesale electricity price. Fixed premiums can be introduced to support producers of RFNBO, where they sell the fuel in the wholesale market, and receive an additional top-up subsidy from the government to cover its higher costs compared to conventional fuels. Alternatively, fixed premiums can in theory be offered on the demand-side, where purchasers of RFNBO instead receive a fixed subsidy. The rationale is that end-users would purchase RFNBO at high market prices, but would be willing to purchase it due to the lower effective price it pays after receiving the fixed premium subsidy.

Depending on the rates at which they are set, fixed premiums create stable and fixed revenue streams for industrial players, the price differential of which they would otherwise not be able to cover on their own.

Fixed premiums can incentivise RFNBO production by providing a premium to the market price of RFNBO. This can help cover the higher costs of producing RFNBO, while still allowing trades at wholesale prices competitive to substitute fuels. A feature of using fixed premiums is that there is still a price signal that feeds into a producer’s investment and operating case. A higher wholesale price might incentivise more firms to enter the market for RFNBO, while sustained low wholesale prices might cause some producers to reduce their output or exit the market.

Government spendings on fixed premiums are more predictable compared to CfDs, thus often making it more politically acceptable from a budget planning perspective. However, there is the risk of overcompensation, as has occurred with several feed-in-tariffs for renewable electricity suppliers; this is particularly the case if there is a rapid decline in prices, due to technological advancement after the fixed premium is set. An advantage of fixed premiums is driven by their lack of interactions with the market; unlike CfDs and CCfDs, there is no downward pressure on prices from auctions.

Fixed premiums can be implemented without auctions, or auctions can be used to determine the fixed premium, as is the case for the European Hydrogen Bank auction. Fixed premiums are suitable for various stakeholders, from small-scale producers to larger industry players. Fixed premiums can be offered as technology neutral or technology specific. Technology neutral fixed premiums can favour existing technologies that have existing infrastructure, at the expense of nascent technologies. However, their overall flexibility is limited due to the constant subsidy, regardless of market variations or technological advancements. They may also require adjustments over time to remain relevant and effective in an evolving market landscape.

2.2 EXISTING SCHEMES

To provide further context and examples of CfDs supporting the development of establishing industries, this section details two case studies on clean hydrogen. The section should provide policy makers with a set of established outcomes and lessons learnt for consideration in any future scheme implementation.

2.2.1 The UK's National Clean-Hydrogen Subsidy Scheme

Status

In effect, July 2022

Scheme Description

The United Kingdom's national clean-hydrogen subsidy initiative was launched in July 2022 with the aim of accelerating deployment of low-carbon hydrogen production ventures. The scheme supports electrolytic projects producing hydrogen with less than 2.4kg of CO_2-equivalent emissions per kilogram of hydrogen. The UK Government is a key stakeholder in this initiative committing up to £240 million of grant funding across two allocation rounds in 2023 and 2024, as well as ongoing contractual revenue support provided in annual allocation rounds.

The scheme is comparable to a CfD, due to the use of a variable premium price support model where the subsidy is the difference between a 'strike price' reflecting the hydrogen production cost, and a 'reference price' reflecting the hydrogen market value (BEIS, 2021a), thereby providing the producer with price certainty. The reference price is set based on the hydrogen market price, or where a market price is not available, it is based on the producer's achieved sales price. The reference price has a floor at the natural gas price, to avoid artificially low hydrogen prices from emerging. There is also a Price Discovery Incentive which incentivises producers to sell its hydrogen above the floor price, to reduce the subsidy payments from the scheme[6]. If hydrogen offtake fails, the mechanism provides "volume support" in the form of a higher striker price per unit.

The UK government's Science and Technology Committee discussed the issue around different uses for hydrogen, and that "direct subsidies may be more appropriate in certain areas" (House of Commons Science and Technology Committee, 2022). Additionally, the risk of failure from non-competitiveness was highlighted by the Commons committee. *"There are costs associated with the development of infrastructure and the uptake of hydrogen use within every use case. The relatively higher prospective cost of low-carbon hydrogen will increase overall costs of, for example, manufacturing, transportation, or heating. There is a risk that because of these costs and impacts on end user prices, the companies and other entities forming these new hydrogen-based, low-carbon, value chains risk failure from non-competitiveness."* (House of Commons Science and Technology Committee, 2022).

2.2.2 The UK's Contracts for Difference for renewable energy

Status

In effect, October 2014

Scheme Description

This CfD established in October 2014, is a government-funded initiative supporting large-scale renewable energy projects with the goal of covering approximately 30GW of renewable energy generating capacity, mainly from offshore wind, by 2030 (DESNZ, 2016) (IEA, 2019). Eligible technologies encompass various renewable sources. The UK Government funds the scheme, allocating funding across five rounds to achieve a significant proportion of wind and solar energy by 2035.

The UK's CfD scheme uses auctioning to allocate CfDs to renewable generators. The CfD counterparty is the governments' Low Carbon Contracts Company (LCCC). Generators are guaranteed a strike price for a 15-

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[6] Producers receive an additional 10% of the price differential between the achieved sales price and the floor price as incentive to achieve higher sales prices that reduce the subsidy paid by the government.

year period. Eligible technologies include onshore wind, offshore wind, solar PV, hydropower, geothermal , ocean power, landfill gas, sewage gas, anaerobic digestion, biogas, biomass, and CHP plants (IEA, 2019).

Encouraging competitive supply chains promoting innovation and skills is a key objective to reduce the long-term costs of low carbon electricity generation and benefit consumers. For projects that exceed 300 MW, bidders must have carried out a supply chain plan to enter the CfD allocation process (UK Government, 2017). Notable projects securing CfDs include Neart Na Gaoithe offshore wind farm and East Anglia one offshore wind farm (NnG Offshore Wind, 2015).

The UK's 5th round of CfD struggled to receive any bidders for the auction for offshore wind; this was due to a low price set for the maximum strike price for offshore wind, meaning that producers could not foresee development at that price, resulting in no investors bidding for the auction (Wind Europe, 2023). As a result, the spare budget had to be split between other technologies, mostly onshore wind, with only 3.7GW of renewable energy capacity secured overall. More successful wind projects funded through a CfD scheme may negatively impact the corporate power purchase agreement (CPPA) market, which also competes for onshore wind projects (Guidehouse insights, 2023). This could mean that such buyers see the CfD win as an appealing alternative to CPPAs to secure financing, negotiate project terms, and reach final investment decision. For the next allocation round, CfD strike prices should be increased, with structural changes being made to the funding; the UK government published their plans for allocation round 6, with updates such as an increase in the administrative strike price, as well as the introduction of a dedicated funding pot for offshore wind, to address the issues from round 5.

The CfD scheme is funded through the electricity retail tariff. This means that electricity consumers absorb the risks related to the CfD counterparty (the LCCC). There is a wholesale price risk, where a lower wholesale price increases the subsidy to the CfD party. There is also a cannibalisation effect, where intermittent generation is correlated and produce the most at similar times, thus depressing the wholesale price through the merit order effect[7]. This means that consumers typically provide the largest subsidy when wind and solar farms generate the most.

Other key issues arising from CfDs include that they mute electricity price variation; generators do not benefit from producing electricity when it is needed most (Schlecht, Maurer, & Hirth, 2023). As the revenue generated is equal across all hours of production, there is no incentive to increase output when demand is higher, to schedule maintenance during times of low demand, or invest in power plants which generate above-average market prices. Some of these issues are fixed in more advanced CfD specifications proposed or implemented by European countries; these include no support payments made if negative prices prevail for several hours, use of a longer reference period, suspending distortive payments, and basing difference payments on potential to produce rather than actual production. However, these changes may introduce other problems related to the functioning of the CfD (Schlecht, Maurer, & Hirth, 2023).

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[7] The merit order effect captures the effect of decreasing wholesale prices during times when more zero marginal cost generators naturally produce.

3. CURRENT POLICY LANDSCAPE

From analysis of scheme options presented in section 2.1 of those assessed, CfDs have been identified as one of the strongest mechanisms to support the uptake of RFNBOs in aviation and maritime.

When considering the implementation of additional mechanisms such as a CfD, established policy has the potential to enable or hinder their effectiveness. Building on analysis in earlier sections this section reflects on the current policy landscape to provide policy makers with some key considerations for policy design and potential interactions. The policy assessment provided in sub-section 3.1**.** describes the current policy landscape covering both aviation and maritime sectors. Within each policy, their general aims and targets are described as well as an evaluation of any potential interactions between the policy and the proposed CfD scheme.

3.1 POLICIES COVERING BOTH MARITIME AND AVIATION

3.1.1 Renewable Energy Directive

The latest Renewable Energy Directive (RED III) revision raised the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030 with an additional 2.5% indicative top up to allow the target of 45% to be achieved[8] (Council of the EU, 2023). Crucially in the context of this report, RED III encompasses both the maritime and aviation sectors mandating a 29% share of energy in the transport sector to come from renewable sources by 2030. RED III also sets a sub-target of 5.5% for Annex IX advanced biofuels and RFNBOs, of which at least 1% must be supplied as RFNBOs.

While the policy shift towards RFNBOs addresses challenges like indirect land use change and fossil LNG uptake, some concerns remain over the adequacy of reduction targets and the potential for low-carbon solutions to enter the market.

Interaction with CfD scheme

RED III includes targets for RFNBOs used to cover 1% of energy consumption in transport, driving production and potentially reducing alternative fuel prices. The RED III includes an indicative 1.2% sub target for the supply of RFNBOs to shipping, which Member States have the discretion to implement. However, every MJ of RFNBO can be counted as double towards this target. There is also a 1.5 multiplier towards the RED target if RFNBOs are supplied to aviation and shipping.

The multipliers for aviation and shipping eventually mean that the effective requirement for RFNBOs in aviation and shipping will be considerably lower than 1% (about a third of that). This low target for 2030 may dilute the market signal and disincentives early investments in RFNBOs for aviation and shipping as the target could be more easily reached thus reducing the competition needed to auction for RFNBO CfD. On the other hand, the multipliers for shipping and aviation provide a clear signal that RFNBO fuels for these modes would be prioritised.

3.1.2 EU Emissions Trading System

Established in 2003, the EU ETS is the EU's flagship policy, aimed at reducing GHG emissions through a cap-and-trade market-based approach. Th Emissions Trading Scheme e policy is positioned to support the European Commission's ambitious target of reducing emissions from EU ETS sectors by 62% by 2030 compared to 2005 levels (Official Journal of the European Union, 2023)

In the aviation sector, the EU ETS only applies to flights departing from and arriving at an airport inside the European Economic Area (EEA), plus flights departing the EEA and arriving in the UK or Switzerland (Official Journal of the European Union, 2023). This scope could be expanded in 2027 to all flights departing the EEA, if the EU considers that CORSIA is not sufficiently aligned with the Paris Agreement. The policy sets allocation percentages and surrender requirements for all sectors in scope; polluters acquire permits through the annual allocation system, with some sectors receiving an annual allocation of free allowances to acquit their previous years' emissions. In phase three of the EU ETS for aviation, the allowances were distributed as follows: 82% granted for free, 15% auctioned, 3% in a special reserve for distribution to fast-growing aircraft operators and

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[8] Previous EU-level energy targets in RED II was 32% by 2030.

new entrants (European Commission, 2022). During this phase of the EU ETS, aviation CO_2 emissions in the EU increased from 115.3 million tonnes in 2012 to 146.8 million tonnes in 2019[9] (European Commission, 2022).

Free allowances in the aviation sector will be gradually phased out, with a reduction of 25% in the number of free allowances in 2024, 50% in 2025 and complete removal in 2026. By 2026, most allowance will thus be auctions, except up to a maximum of 20 million allowances per year until 2030 that will be used to cover the price differential between fossil kerosene and SAF (Clifford Chance, 2023). These allowances are aimed at incentivising early movers in developing a market in the EU for SAF. Additionally, 5 million allowances will be redirected to the Innovation Fund to fund aviation decarbonisation projects (Parliament, 2023b). The total number of allowances auctioned is to decrease as well over the years, which should lead to an increase of the price of each allowance, thus providing further incentive to decarbonise.

In December 2022, an extension of the EU ETS to cover maritime transport was agreed upon. Set to be implemented from January 2024, emissions from ships will be included based on certain criteria: 100% of emissions from voyages starting and ending at EU Member States' ports or within EU ports, and 50% of emissions for voyages between EU and non-EU ports. The phased implementation will encompass cargo and passenger vessels over 5,000 gross tonnage (GT) from 2024, with offshore[10] ships included from 2027. The emission cap will gradually decrease to ensure alignment with the EU's climate goals, requiring shipping companies to acquire and surrender EU ETS allowances for each tonne of CO_2-equivalent they report[11]. Initially, operators will surrender allowances for 40% of verified emissions in 2024, increasing to 70% in 2025, and reaching 100% in 2026 (Official Journal of the European Union, 2023).

Interaction with CfD scheme

The interaction of EU ETS with a proposed CfD scheme is complementary. While EU ETS will, by increasing the cost of fossil fuels, help reduce the cost gap between alternative and fossil fuels, there is awareness this will not by default achieve price parity, making CfDs a valuable tool to complement the policy to achieve price stability and increased competitiveness for low-carbon fuels. The EU ETS will by increasing the market price for fossil fuel also increase the market price for RFNBOs. This market price increase would result in a reduced differential between a potential auction strike price and the RFNBO market price, which defines the level of subsidy required per RFNBO quantity supplied. This will improve the effectiveness of any CfD scheme as it will allow the support of larger quantities of RFNBOs with the same funding level. Especially for aviation, as the free allowances phase out, the effect of the EU ETS on reducing the price gap between conventional fuel and RFNBOs will improve.

Should ETS allowance prices be expected to increase in the future, it would also readjust market prices for conventional fuels and RFNBOs, meaning that repeat CfD auctions could be more effective overtime.

It should also be noted that the EU ETS provides a revenue stream through which to fund a CfD, utilising ETS revenues from the sector as a result of emission production to support long term decarbonisation.

3.1.3 UK Emissions Trading Scheme

The UK ETS is a cap-and-trade scheme, established to replace the UK's participation in the EU ETS from January 1, 2021, and maintain emissions trading within the UK. It currently covers energy-intensive industries, power generation, and aviation.

In the aviation sector, the UK ETS covers UK domestic flights and flights departing the UK to the EEA and Switzerland, plus flights between the UK and Gibraltar (GOV UK, 2021). As with the EU ETS, it is proposed that from 2026 the UK ETS will phase out free allocations for flight operators, requiring operators to purchase allowances for each tonne of carbon emission they produce. Currently the UK ETS is technology agnostic with respect to SAF production pathways, with all SAF used in routes covered under the UK ETS being "zero rated", and operators being able to claim a reduction in their UK ETS obligations (UK Department for Transport, 2023a).

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[9] 2020 was not considered in the analyses because of the Covid pandemic (total emissions in that year were 63.3 million tonnes). It should be noted that these emissions relate to the entire EU aviation sector, including the extra-EEA flights not covered by EU ETS.

[10] Offshore vessels are ships that serve only operational purposes in the high sea such as oil exploration and construction work (Marine Insight, 2019)

[11] GHGs covered by the EU ETS include CO_2, methane (CH_4) and nitrous oxide (N_2O); the latter two from 2026 onwards.

Starting from 2026, it will also apply to large maritime vessels. Under proposals, only domestic UK shipping would be covered and vessels above 5,000 gross tons (GOV UK, 2023a). The UK ETS shares several benefits with the EU ETS, such as avoiding taxation for emissions reduction, driving innovation through financial incentives, and allowing industries with challenging emission reduction needs to continue operating. With a 5% lower emissions cap, the UK ETS aims to be slightly more ambitious in emissions reductions than its EU counterpart (Energy Advice Hub, 2023).

Interaction with CfD scheme

Similar to the EU ETS, the UK ETS would result in an increase in the market price of conventional fuel resulting thus also in an increase in the market price for RFNBOs. Consequently, the market to strike price differential for RFNBOs will be thus reduced, increasing the effectiveness of CfD funding.

As with the EU ETS, under the UK ETS, revenues could be used to support CfD payments, funded by emissions trading revenue from the aviation and/or maritime sectors. This in turn could help reduce production costs for alternative fuels and bring them closer to cost parity with fossil fuels. Furthermore, in September 2023 the UK government announced that it would introduce “a revenue certainty scheme to support SAF production in the UK”, pending an upcoming consultation on the design and implementation of such scheme (Gov.uk, 2023b). It is conceivable that UK ETS revenues could be part of that of the funding solution for that scheme.

3.1.4 Innovation Fund

The Innovation Fund was established to support the European Commission’s strategic vision for a climate-neutral Europe by 2050. The Innovation Fund is financed through the monetisation of 530 million EU ETS allowances, as well as the remaining funds from the NER300 programme (the Innovation Fund’s predecessor). As a result, the fund’s annual budget is dependent on the carbon price – estimated as €40 billion between 2020 to 2030, calculated by using a carbon price of €75/tCO$_2$ (European Commission, 2023i).

The fund is designed to provide financial support for both companies and public authorities investing in cutting-edge low-carbon technologies (PNO, 2019); and delivered in partnership with DG Climate Action, The European Climate Infrastructure and Environment Executive Agency (CINEA); European Investment Bank; and member states. Each plays a role in ensuring that the fund calls, priorities, volumes, and management are delivered in accordance with EU and state level objectives for innovative low-carbon technologies (European Commission, 2023j).

The first competitive auctioning under the Innovation Fund opened in 2023 and will close February 2024, through a pilot auction to support renewable hydrogen production. A share of €800 million will be available for bidding projects. The funding is awarded as a fixed premium in €/kg of verified and certified RFNBO hydrogen produced, in addition to market revenues achievable by developers guaranteed within 10-years of operation (European Commission, 2023j).

This pilot auction is a key element of the European Hydrogen Bank, which through the Innovation Fund pillar aims to support establishment of EU financing instruments to secure domestic supplies of renewable hydrogen in the EU.

Interaction with CfD scheme

The Innovation Fund focuses on demonstration and bringing to commercialisation, particularly targeting highly innovative technologies and large-scale flagship projects. In its current approach of providing fixed premiums, the Fund supports RFNBO production in a technology agnostic way but it does not guarantee price stability, meaning the Fund could also end up under- or over-compensating RFNBO producers. This lack of future flexibility could be addressed by a CfD scheme that provides further certainty on revenues (through price certainty) after commercialisation.

The ETS suggests enhancements of the Fund's allocation of emission certificates and possibly incorporate it into CfDs, which would further support hydrogen production and utilization (Parliament, 2021). The Innovation Fund would therefore be seen as a key facilitator for the technologies required in enabling scale up of RFNBO and complimentary to a CfD in this context.

3.1.5 Energy Taxation Directive

The Energy Taxation Directive (ETD) aims to align the taxation of energy products with EU energy and climate policies.

In the maritime sector, it involves taxing energy products and electricity produced from fossil fuels used in waterborne navigation, with taxes calculated based on the net calorific value of the fuel. Initially, there are tax exemptions to incentivise the use of sustainably produced alternative fuels, electricity, and shore-side electricity when vessels are at berth. However, it is crucial to note that carbon leakage risks may emerge if high taxation is levied on bunkering within the EU. The ETD offers a potential avenue to promote renewable energy and enhance energy efficiency, with taxation now based on environmental performance rather than volumes sold.

In the aviation sector, exemptions and incentives for fossil fuels, particularly kerosene, are yet to be removed. However, the revision being discussed intends that sustainable and alternative aviation fuels will enjoy a zero rate minimum tax for a transitional period of ten years when used for air navigation (European Commission, 2021c). These updated rules, first proposed in 2021, include a minimum excise duty rate for fuels used in intra-EU passenger flights. Over a ten-year transitional period, aviation kerosene for intra-EU flights would be taxed at least €10.75/GJ EU-wide (European Commission, 2021c). The directive also states that the minimum tax rates can be adjusted annually by delegated acts of the commission. It should be noted that the Council reports on the requirement of further work on the minimum levels of taxation, and taxation of aviation and maritime sectors; several compromise solutions were identified by the Swedish presidency, however no compromised has been reach yet (Council of the European Union, 2023).

Interaction with CfD scheme

The ETD is aimed at increasing the cost of fossil-based maritime and aviation fuels and making alternative fuels more economically attractive. The ETD will support improvements in cost parity between fossil-based conventional fuels and RFNBOs, which would reduce the differential between market and strike price used in defining the funding level required in the CfDs.

By introducing a zero-rate minimum tax level for all sustainably produced fuel in the short- to mid-term, the ETD does not necessarily promote the fuels most efficient in achieving GHG reductions, such as the case with RFNBOs. Should this differentiation account also for the difference in GHG emissions between sustainably produced fuels, the market price of RFNBOs would be even more supported further reinforcing the CfD scheme effectiveness as mentioned earlier.

3.1.6 Alternative Fuels Infrastructure Regulation

The Alternative Fuels Infrastructure Regulation (AFIR) introduces mandatory deployment targets for various alternative fuels infrastructure.

In the maritime sector, it stipulates that the main EU ports, known as TEN-T ports, must provide shore-side electricity supply for seagoing container ships and passenger ships over 5,000 GT by January 2030 (Parliament, 2023). Designated ports should also provide refuelling points for liquified methane by January 2025 as long as there is sufficient demand. This initiative aims to address the issue of the previous 2014's Directive that left Member States to decide on shore-side electricity supply based on availability and cost-benefit analysis. A key highlight is the introduction of a zero-emission berth mandate, requiring ships to use shore-side electricity rather than running polluting engines at the port (IRENA, 2021).

In aviation, the policy requires Member States to ensure electricity supply to all stationary aircraft contact stands used for commercial air transport at airports of the TEN-T core network and comprehensive network by 2025. By 2030, this requirement will expand to include all aircraft remote stands (UK Department for Transport, 2023b).

The primary goal of AFIR is to promote the necessary infrastructure across all transport modes so that the use of alternative-fuelled vehicles is incentivised (European Commission, 2022c). The AFIR ambition is supported through TEN-T legislation funding delivered via the alternative fuels infrastructure facility (AFIF) – part of the European Union's Connecting Europe Facility (CEF) transport programme. The AFIR will allocate €1.5 billion in EU grants before the end of 2023 dedicated to supporting 'the deployment of alternative fuel supply infrastructure to contribute to decarbonising transport along the TEN-T network' (European Commission, 2021b).

Interaction with CfD scheme

The AFIR will be an important facilitator of alternative fuel infrastructure, which in turn will support the development of RFNBO across both sectors. In the maritime sector, AFIR aligns with FuelEU Maritime and TEN-T requirements, enhancing investments in alternative fuels and technologies. While AFIR funds may not cover project costs completely, CfDs could narrow this financial gap and increase the rate of production as well as supporting infrastructure.

Still, by not specifying requirements for fuelling infrastructure for further alternative fuels e.g. hydrogen or ammonia, AFIR does not provide for the infrastructure to support the deployment of all possible RFNBOs and fails though to be technology agnostic. In this respect, it wouldn't match-up well with technology agnostic CfDs as AFIR current supports the deployment of RFNBOs that can be used as drop-in fuels for the current fuelling infrastructure.

3.1.7 UK Renewable Transport Fuel Obligation

The Renewable Transport Fuel Obligation (RTFO) is a policy encouraging the production and use of renewable fuels. Suppliers of relevant transport fuel in the UK must demonstrate that a portion of the fuel they supply comes from renewable and sustainable sources. The latest revision of the RTFO has seen an increase in the target of renewables supplied by 2032 (by 5%) from 9.6% of fuels for road transport and non-road mobile machinery, to 14.6%. This aligns with the broader target to reduce emissions by 78% by 2035 compared to 1990 levels. The RTFO includes criteria for carbon and sustainability, which must be met by renewable fuels to ensure they are environmentally sound.

In aviation, the RTFO addresses specific aviation fuels. The RTFO outlines requirements for any rewarded fuel; for example, RFNBO's must achieve a 65% GHG emission saving over the entire life-cycle relative to a baseline fossil fuel[12]. However, the RTFO permits the electricity used in production to have received support, such as through a CfD (UK Department for Transport, 2023c). Recently, the buy-out price for suppliers under the RTFO has been increased to 50 pence (£) per Renewable Transport Fuel Certificate (RTFC). This is implemented from the 2021 obligation year onwards and is a response to the rising cost of biofuels compared to petrol and diesel (Transport & Environment, 2021). This incentive in the RTFO is forecasted to be removed once the UK SAF mandate is in place in 2025 (UK Department for Transport, 2023a).

Interaction with CfD scheme

CfDs complement supply-side policies such as the RTFO. While the RTFO sets the supply target and thus can secure investments, CfDs provides coordination in terms of which producers undertake investments and guarantee them price certainty over the longer term, shifting the risk of fuel price reductions and certificate value reductions from producers to the government. This can make alternative fuels more appealing by reducing their cost difference compared to fossil fuels.

3.1.8 Inflation Reduction Act

The IRA was signed into US law in 2022 with the aim of enabling the achievement of the US target to reduce economy wide GHG emissions to 40 percent below 2005 levels by 2030. The IRA supports enablement of this by providing over $370 billion in federal spending to subsidies to deliver clean energy solutions through loans, grants, and tax credits to public and private organisations from all sectors. It is hoped that these public investments will in turn accelerate private investment, scaling domestic production of green technologies in the US through increased manufacturing and R&D. It also allocates funds to environmental justice priorities and requires recipients of the funding to conduct all production and final assembly in the US.

This domestic positioning is where the scheme has seen most opposition from the EU. The EU's concerns relate to the significant subsidies available, and the potential of this drawing production away from the EU in favour of the US. Although the political focus has been on the automotive sector, a similar viewpoint can be taken with the EU SAF industry without appropriate intervention. The US already favours a carrot rather than stick approach in developing national SAF production, through initiatives such as the California Low Carbon

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[12] Fossil fuel baseline is 94 gCO_2eq/MJ. Equivalent RFNBO carbon intensity would be 32.9 gCO_2eq/MJ

Fuel Standard (CA-LCFS), U.S. Sustainable Skies Act, tax credits and a suite of additional funding opportunities. Whilst the EU has promoted the delivery of mandates to firm demand.

Despite agreement that mandates do provide clear demand signals, stakeholders across the aviation sector have opposed their use in isolation suggesting they rarely provide optimal economic outcomes. Instead, it is suggested that positive policies should be used to accelerate the deployment of SAF, using incentive programs or direct financial project support such as the IRA (IATA, 2021).

Interaction with CfD scheme

The IRA includes generous subsidies for the usage of SAF as well as for hydrogen production. For SAF, there is a minimum level of $1.25 subsidy per US gallon (3.79 litres) increasing to $1.75 if the SAF reduces 100% of emissions compared to jet fuel (US Internal Revenue Service, 2023). The subsidy is available to producers or importers of SAF. For hydrogen, the Clean Hydrogen Production Tax Credit provides subsidies for hydrogen producers between $0.60 and $3.00 per kilogram, depending on carbon intensity of the production (from a maximum of 4 kg CO_2e per kg of hydrogen to receive the lower amount to a less than 0.45 kg CO_2e per kg of hydrogen to receive the maximum amount (US Deparment of Energy, 2023).

The IRA can therefore lower the cost of capital requirement in a similar way to a CfD, by reducing risk and uncertainty about the financial case for nascent technologies. Where the IRA and CfD overlaps there is a risk that some companies receive higher subsidies than required. However, if the CfD is procured competitively, producers or consumers would only bid for the require amount of strike price taking into account existing subsidies from IRA, otherwise they may not be successful. There is a risk that uneven allocation of IRA subsidies will put certain companies at an advantage, which they can use to be competitive in CfD auctions, which can disadvantage other companies receiving smaller or no subsidies. There is also a risk that companies with a set pot of capital expenditure will invest in The US instead of the EU, and therefore choose not to compete for EU CfDs, which could be deemed less attractive than receiving IRA support. This can reduce the competition for EU CfDs, which could cause higher strike prices and higher cost for the CfD counterparty.

3.2 AVIATION POLICIES

3.2.1 ReFuelEU

The ReFuelEU Aviation policy, part of the EU's "Fit for 55" package, is designed to accelerate the adoption of SAFs within the European aviation sector (European Commission, 2023d). It entails a progressive blending mandate for SAF, including a sub-target for RNFBOs, with SAF mandate beginning at 2% in 2025 and culminating in 70% by 2050, and the RNFBO mandate beginning at 1.2% in 2030, reaching 35% in 2050 (Council of the EU, 2023). The policy prioritises innovative and sustainable fuels, including advanced biofuels and synthetic fuels, to reduce carbon emissions and enhance energy security.

Research conducted for the ReFuelEU Aviation initiative, suggests that the implementation of this blending requirement will result in an estimated demand of approximately 2.3 million tonnes of SAF (out of a total of 46 million tonnes of aviation fuel) at EU airports by the year 2030 (Ricardo, 2021). Whilst a preliminary review of publicly available resources has identified SAF production plants in the EU that are either existing or planned for deployment by 2030 have an expected capacity of 2.3 million tonnes. This EU supply is expected to be supplemented via a growing list of global offtake agreements, which within 2023 alone have attributed to a further 11,337 million litres of SAF confirmed to be uplifted across the next 20 years (ICAO, 2023b). However, scaling the required volumes over the near to long term to achieve the targets set out by ReFuelEU presents a significant challenge as fuel suppliers in the EU work to blend a minimum proportion of SAF into their jet fuel supply.

Therefore, despite substantial environmental and economic advantages, such as potential emissions savings of up to 100% and job creation, the mandate does come with challenges. Notably, it demands significant CAPEX infrastructure investments, increases fuel costs for airlines due to SAF production expenses, and raises concerns about economic competitiveness without intervention.

Interaction with CfD scheme

A progressive blending mandate will ensure there is increasing demand for SAF over time. This will help increase the market price for SAF and encourage producers to invest according to the progressive blending timeline. Further the sub-mandate introduced for RFNBOs, would further secure RFNBO demand. This could complement a CfD, by ensuring the difference between the required strike price and market price for RFNBOs is reduced, reducing the cost to the CfD counterparty.

Effectively, the mandate ensures predictable demand for SAF, such that producers need less of an incentive for a supply-side CfD and may as well be less exposed to price competition, keeping SAF production costs, and therefore also CfD auction strike prices, high. However, supply-side CfDs can help with the coordination problem, which is to determine which producers should undertake the investment to prevent a potential future over-supply of SAF, which puts downward pressure on the market price of SAF.

Alternatively, a demand-side CfD could be introduced to protect the cost increases due to the mandate to ensure they are cost competitive with other sectors. However, as most maritime and aviation operators compete in sector instead of across sectors, this is likely not needed, as the mandate will apply consistently to each sector.

3.2.2 Carbon Offsetting and Reduction Scheme for International Aviation

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is an offsetting scheme for international flights developed by ICAO with the aim of reducing CO_2 emissions from the international aviation sector (ICAO, 2022a). CORSIA aims to stabilise aviation's net CO_2 emissions, allowing resources to be allocated to other emissions reduction measures, including technology, sustainable aviation fuel, and operational and infrastructure improvements. The scheme will be implemented in three phases: a pilot phase (2021-2023); a first phase (2024-2026); and a second phase (2027-2035). Participation in the pilot and first phases are voluntary, while the second phase is mandatory for all ICAO Member States.

Under CORSIA, airlines and aircraft operators are required to offset CO_2 emissions that exceed 85% of the 2019 baseline level starting in 2024 (IATA, 2023a)[13]. This scheme differs from the EU ETS as it focuses on compensating for emissions through reductions in other sectors globally, whereas the EU ETS establishes a cap for the EU aviation industry and is limited to intra-EEA, EEA to UK, and EEA to Switzerland flights. Key elements of CORSIA include the requirement for airline operators with annual emissions exceeding 10,000 tonnes of CO_2 to report their emissions from international flights, track fuel use for each flight, and verify annual emission reports by an independent third-party verification body. Technically, offsetting requirements began in 2021, with operators demonstrating compliance by cancelling the appropriate number of emissions units at the end of each three-year compliance period. However, given the still lower-than-baseline traffic in 2021 and 2022, no actual offsetting was required. Participating in CORSIA increases demand for emissions units, encouraging investment in emissions reduction projects in participating States. While CORSIA will cover all international flights during the mandatory phase from 2027 onwards, there are exemptions for least developed countries, small island developing states and land-locked developing countries as well states with less than 0.5% of air traffic (ICCT, 2017) Several large aviation markets have also not yet indicated their participation in the scheme (India, China, Brazil, Vietnam).

CORSIA includes provisions to allow a "CORSIA sustainable aviation fuel" or a "CORSIA lower carbon aviation fuel" to be used to reduce the offsetting requirements. To be eligible to be considered in CORSIA, fuels have to comply with certain sustainability criteria and life cycle emissions (ICAO Secretariat, 2019) (ICAO, 2023a). In terms of emissions, to be eligible under CORSIA a SAF must achieve net greenhouse gas emissions reductions of at least 10% compared to jet fuel on a life cycle basis (ICAO, 2022b)[14]. In principle, this SAF provision would foment the uptake of SAF, as operators would have an incentive to use SAF instead of buying offsets. However, as will be discussed in the following price, the expected impact of CORSIA offsets on operating costs is so small, that the incentive to use SAF just to avoid buying offset is expected to be quite small.

A cost analysis by International Air Transport Association (IATA) indicates that the costs associated with CORSIA offsetting are expected to have a smaller impact on aviation than fuel price volatility. In 2030, the estimated offsetting cost is roughly equivalent to a $2.60 increase in jet fuel price per barrel (ReedSmith, 2022). Whilst a study commissioned by T&E suggests that the total cost of CORSIA if applied only to outbound flights is between €47.6 and €70.6 million per year for their pollution, representing 0.2% of airlines' operating costs

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[13] During the 2021-2023 pilot phase, the baseline was 100% of 2019 emissions.

[14] There are other requirements related to land use, see ICAO (2022b) for more details.

(Transport & Environment, 2020). This cost is significantly lower when compared to the potential impact of fuel price fluctuations. Over the past decade, the standard deviation of annual jet fuel prices has been up to $40 per barrel, meaning airlines have coped with oil price volatility significantly larger than the projected offsetting cost in 2030. The Commission's assessment of CORSIA[15] indicated that the policy's level of ambition for international aviation was not in line with that at the global scale, or sufficient to enable achievement of temperature goals set out in the Paris Agreement (European Commission, 2022a). This was in part due to the oversupply supply of cheap offsets limiting direct in sector reductions (Parliment, 2022a). As noted in section 3.1.2, the Commission reserves the right to apply the EU ETS to all flights departing EEA airports starting in 2027 if by then they conclude that CORSIA is still not in alignment with the Paris Agreement.

However, CORSIA is still considered a key piece of international aviation legislation, with IATA estimating that without it the CO_2 footprint of international aviation would increase from slightly over 600 million tonnes in 2019 to almost 900 million tonnes by 2035 (IATA, 2022).

Interaction with CfD scheme

CORSIA will require airline operators to purchase carbon offsets for emissions above the threshold mentioned above. This will create a demand for carbon offsets, while increasing the costs for airlines that struggle to reduce emissions. In a supply-side CfD an airline operator can benefit from lower carbon fuels at more affordable levels, which can help reduce its need to purchase carbon offsets. However, this depends on the relative costs of carbon offsets and the cost of SAF or strike price of SAF (using a CfD). If the carbon offset price is high enough, airline operators will prefer to purchase SAF, which will increase the demand for SAF, which will increase the market price of SAF. However, the projected increase in jet fuel price as a result of CORSIA is very low, and while any price differences could be offset via a CfD scheme, CfDs alone will not make projects 'bankable' without feedstock security and off-taking agreements in place (UK Department for Transport, 2021). Therefore, it can be considered that the level of ambition of CORSIA would not be sufficient to impact the RFNBO market and strike price differential that affect the effectiveness of a CfD.

The fact that the current CORSIA ambition level can be met without necessitating the use of RFNBOs means that this scheme would fail to create sufficient demand for CfD auctioned RFNBOs.

3.2.3 UK SAF Mandate

The SAF mandate in the UK aims to create a long-term demand for SAF in the UK, delivering direct in-sector emission reduction and supporting increases in UK production capacity (UK Department for Transport, 2023a). Under the proposed SAF mandate, jet fuel suppliers are obligated to supply a minimum of 10% as a percentage of the UK's overall jet fuel consumption by 2030 (UK Department for Transport, 2023a). The proposed mandate applies to jet fuel suppliers, and eligible SAFs include waste-derived biofuels, recycled carbon fuels, and power-to-liquid (PtL) fuels. Under the proposed mandate, SAFs must meet strict sustainability criteria, with a minimum of 50% GHG savings relative to fossil jet fuel.

There are however several challenges and uncertainties associated with the implementation of a UK SAF mandate. The UK SAF industry is expected to be in its infancy until 2025. Today, planned production capacity is currently half of that required to meet the 2030 target. Producers may subsequently struggle to produce at the ambitious volumes required by the proposed mandate (0.5% SAF UK jet fuel demand by 2025, 10% by 2030, and 75% by 2050) resulting in a high level of buyouts in the initial years (Sustainable Aviation, 2022) as costs remain high, and supply volumes low resulting in suppliers failing to meet their obligations. To promote scale up of domestic support and reduce concerns around the price differential between SAF and fossil kerosene should the UK Government is exploring price support mechanisms, however a CfD has been ruled out (Quantum Commodity Intelligence, 2023).

Interaction with CfD scheme

The SAF mandate will support the supply for SAF. The high mandates required early in the process (10% SAF in 2030) might mean that less mature technologies will need to be utilised that could significantly drive up the prices for SAF. Without a RFNBO-specific sub-mandate, it is unlikely that these fuels would be

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[15] ICAO's global market-based measure (CORSIA) pursuant to Article 28b and for studying cost pass-through pursuant to Article 3d of the EU ETS Directive

prioritised, at least in the short-term. It should also be noted that the buy-out scheme introduced may mean in reality, if prices remain high, that SAF is not uplifted.

To encourage actual demand for SAF, a demand-side CfD scheme (see 2.1.1.2 could ensure SAF prices are competitive with conventional jet fuel avoiding the extended usage of the buy-out scheme. A CfD would also provide investors with the price stability needed to leverage long-term investments in SAF production.

A supply-side CfD would overlap with the mandate, as the mandate would target a minimum quantity of supply, and a supply-side CfD scheme would basically do the same through its budget.

3.3 MARITIME POLICIES

3.3.1 FuelEU Maritime

The FuelEU Maritime policy is one of the key policies on maritime decarbonisation as part of the "Fit for 55" package with the aim of achieving an 80% reduction in fuel greenhouse gas intensity by 2050 compared to a 2020 baseline on a well-to-wake basis (Council of the EU, 2023). The reduction in greenhouse gas intensity of fuels is gradual, starting at 2% in 2025 through to 80% by 2050 and is currently applicable to vessels above 5,000 GT. FuelEU Maritime also stipulates that all passenger and container ships will have to connect to shore power at TEN-T ports from 2030 onwards for berths longer than two hours in duration with some exceptions (Council of the EU, 2023). A further incentive to increase the uptake of alternative fuels is a sub-target that from 2034, 2% of fuel (averaged annually) must be renewable fuels of non-biological origin (RFNBOs). This sub-target will come into effect if the share of RFNBOs for the reporting period of 2031 is less than 1%.

Interactions with CfD scheme

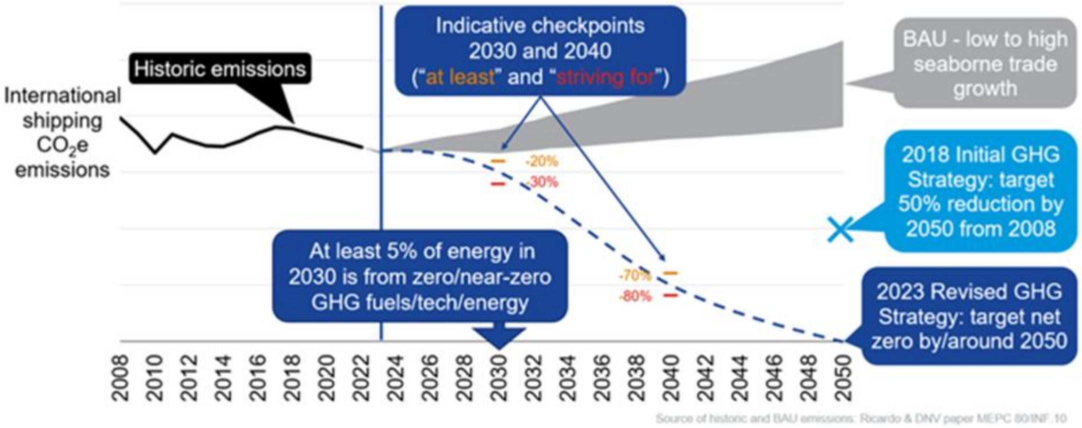
FuelEU Maritime encourages the use of RFNBOs to meet the required GHG reduction levels and through the sub-target. This guarantees the demand for some RFNBOs by providing a clear market signal to RFNBO suppliers incentivising investments though not as clear as set by the SAF mandates in the aviation sector. The guaranteed demand for RFNBOs, even in small quantities can drive its market price up, reducing the differential with the auction strike price and reducing thus the funding needed for the CfD scheme. On the other hand, the guaranteed demand could also drive the uptake on itself making a CfD redundant.

A CfD scheme in combination with these policy drivers could encourage the further use of RFNBOs in the maritime sector. The RFNBO mandate can reduce the cost of adopting them, and enable an accelerated uptake of RFNBOs. A CfD could be implemented at the supply-side incentivising production of RFNBOs leading to greater availability for the maritime sector to use to meet the reduction levels or sub-target required.

3.3.2 IMO GHG Strategy (including EEDI/EEXI/CII)

At an international level, the IMO sets global standards for the environmental performance of international shipping. The current IMO GHG Strategy, includes an ambition to target net zero on or around 2050 with indicative checkpoints targets for 2030 and 2040. An additional target was set of at least 5% (aiming for 10%) of energy used by international shipping by 2030 to be from zero or near zero GHG fuels or technologies (see Figure 3-1) (Ricardo, 2023b).

Figure 3-1: Revised IMO GHG strategy targets (Ricardo own)



Source of historic and BAU emissions: Ricardo & DNV paper MEPC 80/INF.10

Further international measures introduced by the IMO include the energy efficiency measures Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). The EEDI has set mandatory energy efficiency targets per capacity mile for *new* ships produced globally. These have increased incrementally from 2013 and 2025 new ships will need to achieve a 30% reduction from the average efficiency of ships built between 2000 and 2010 (IMO, 2023a). Additionally, the continuous reduction in the GHG emissions of the *existing* fleet will be pursued using the EEXI and the CII rating from 2023 onwards. According to these measures, vessels' energy use performance will be rated every year in relation to the average of other vessels of similar type and size and required to improve if found to underperform. Further energy efficiency improvements will be required to meet the revised targets and indicative checkpoints. The IMO has stated that updating the calculation of CII is the likely method of achieving this.

Interaction with CfD scheme

Measures such as EEXI and EEDI will necessitate to switch to lower carbon fuels over time, a CfD can ensure the availability of such fuels. The IMO GHG strategy sets out an emission reduction timeline for the maritime sector. While the demand for alternative fuels may increase as a result of these measures, it is not guaranteed that a shift to RFNBOs would be guaranteed in the short term. A CfD scheme can complement this policy by ensuring that the supply of RFNBOs matches the emission reduction needs of the sector through subsidising their production and ensuring their availability.

As part of the set of mid-term measures proposed by the IMO (still under negotiation) a technical and economic measure are expected to achieve long term decarbonisation. The technical measure, likely a goal-based fuel standard, will set sustainability criteria of maritime fuels which will promote the use of low/zero carbon fuels such as RFNBOs which the proposed CfD looks to support. The economic measure, could take the form of a GHG levy which could either complement or duplicate the efforts of a CfD scheme; depending on what the levy revenues were used for.

3.3.3 Maritime MRV Regulation

The EU ETS relies on MRV to robustly identify the emissions from each source. Current legislation, in effect from 2017, collects data on the emissions from ships within EEA ports, for intra-EEA voyages and extra EEA-voyages (European Union, 2015). The MRV regulation sets requirements for shipowners to monitor and report their emissions each calendar year on a cyclical basis. All ships performing voyages within the geographical scope of the MRV regulation, regardless of their flag status, must submit a monitoring plan detailing how they intend to collect emission data within two months of their first call to a port in an EEA Member State. The monitoring plan must be assessed by a verifier prior to data collection, and the collected data (the annual emission report) must be verified at the end of each period. Upon verification, a final submission is made to the Commission via the THETIS MRV database, and a Document of Compliance is issued by the verifier (LR, n.d.). Current MRV regulation only applies to cargo and passenger vessels over 5,000 GT and covers carbon dioxide emissions only[16] (Ricardo, 2013).

However, from 2025 the reporting requirements will be extended to include cargo and offshore vessels above 400 GT. From 2024 CH_4 and N_2O are to be also included in the MRV as additional GHGs that must be monitored and reported in preparation for their inclusion in the EU ETS (European Commission, 2022b).

The update of the MRV Maritime Regulation introduces requirements for the shipping companies to submit all their ships' monitoring plans for approval to the administering authority in the Member State to which they are assigned. They must furthermore submit a company-level annual emission report to that authority, which contains additional data, on the fraction of their emissions for which EU ETS allowances need to be surrendered. Those emissions deviate from those to be reported at ship level under the MRV Regulation by the scope (GHG gases, coverage of voyages), but also regarding the phase-in percentages, the use of biomass and RFNBOs/RCFs and exemptions regarding certain small island ports, ice-class routes shipped, etc.

Interaction with CfD scheme

There is no direct interaction between the MRV and the implementation of a CfD scheme. However, there are some indirect effects, such as through the EU ETS where the larger scope of MRV will facilitate the inclusion of certain vessels (as mentioned above) as well as CH_4 and N_2O. As RFNBOs will be zero-rated under the EU ETS a CfD scheme promoting their uptake and production can incentive shipping companies to purchase RFNBO to reduce their emission costs.

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[16] Although the original impact assessment considered also the threshold of 400 GT.

4. RISK REGISTER

As set out at the start of section 3, CfDs have been identified as one of the strongest mechanisms to support the uptake of RFNBOs in aviation and maritime. This section assesses the inherent risks associated with implementing a CfD scheme specifically targeted at the aviation and/or maritime sector. The CfD scheme may be a supply-side CfD targeting hydrogen or other RFNBO fuels production, or a demand-side CfD that supports ship operators with switching to using RFNBO fuels.

There are different risks at different points in the fuels value chain. The fuels value chain can be thought of as ranging from upstream generation of green electricity, capture of CO_2, to mid-stream production of hydrogen and other RFNBOs, and to downstream distribution and use of fuel in for example aircraft and vessel engines. Aircraft are most likely to adopt e-kerosene, which is biologically identical to conventional kerosene, and does thus not need a change or retrofit of engine. The long-term penetration of hydrogen-fuelled aircraft into the fleet is likely to be small (restricted to short-to-medium range aircraft) and the main use of RFNBO will be as drop-in e-kerosene fuel, which will not require any changes to aircraft engines or fuel systems. Although, recertification of existing engines may be required to allow them to operate on fuel blends greater than 50% RFNBO (or, indeed, biofuel SAF). Large hydrogen-fuelled aircraft are likely to only become commercially available beyond 2050.

In the maritime sector, ammonia is expected to play a large role, while methanol, e-LNG and e-diesel can also play roles. Using ammonia is expected to require new engines and infrastructure that can combust ammonia.

To identify these risks, Ricardo conducted a desk-based high-level risk assessment utilising publicly available sources. The output of this was a risk register, categorising risks identified, highlighting their specific impact across the fuels value chain and outlining a suitable approach to mitigation (the full risk register can be found in appendices 8.1). This process has identified the most severe risks through an assessment of risk likelihood and impact magnitude.

For the purposes of this report, ten key risks have been selected for further analysis. The objective of section 4 is to provide a clear overview of key issues arising for aviation and maritime fuels value chains as a result of the implementation of a CfD scheme. These risks and identified mitigation measures should be taken into consideration by policymakers to ensure the implementation of an effective, suitable, and flexible scheme.

4.1 COMMON RISKS

4.1.1 Immature stage of technological development for low-carbon vessels/aircraft

Context of risk

Struggles to reach a mature stage of technological development for zero-emissions vessels and aircraft pose risks in two distinct areas. Firstly, for specific RFNBO types that depend on large-scale uptake of low carbon vessels or hydrogen-fuelled aircraft, hurdles to achieving this uptake can reduce the demand for these specific RFNBO fuels. This is only considered a case for vessels with ammonia engines, where maritime actors are likely to be one of the main consumers of e-ammonia. Ammonia produced from unabated natural gas is already scaled up for use in the fertilizer industry. However, unless the fertilizer industry starts demanding (higher cost) e-ammonia, there is a risk that immature ammonia engine development will pose a risk to e-ammonia producers.

The direct impact on a supply-side CfD for ammonia is a larger difference between the reference price and the strike price, where the reference price is depressed due to subdued demand for e-ammonia stemming from delays to the development and commercialisation of vessels with ammonia engines. If there is an oversupply of e-ammonia, the wholesale price for e-ammonia can fall to that of conventional ammonia, which can be used by the fertilizer industry. Vessel operators will not be able to act upon this price signal if the technology is not mature enough to commercialise. The impact affects governments that must subsidise the scheme by a larger sum than expected, without getting the intended effect of the scheme. As a consequence, the government may end up subsidising low-carbon ammonia for the fertilizer industry.

Secondly, for demand-side CfDs that support the scale up of vessel and aircraft that use zero-emission technology, hurdles to technological development of aircraft and vessels can mean the demand-side CfDs become redundant (i.e. if the technology is not ready and safe to use, it does not matter how attractive a demand-side CfD is). This applies in particular to the zero carbon emission fuels such as hydrogen and ammonia, which require new technology vessels and aircraft for their use. The benefits of such fuels are that the engine exhaust emissions contain no CO_2 emissions, unlike other RFNBO fuels such as e-kerosene and e-methanol, which produce CO_2 emissions in the engine exhausts but deliver zero, or very low, emissions on a lifecycle basis. However, hydrogen-fuelled aircraft and hydrogen or ammonia-fuelled vessel technology are currently comparatively immature, and the introduction of such technology at scale in the operating fleets may be some years away.

Mitigation action

To mitigate this risk, governments can ensure a CfD for ammonia production/consumption are only entered once vessels with ammonia engines are commercialised. However, there can be a chicken and egg problem regarding developing ammonia technology without clear signals for commitments to produce sufficient quantities of e-ammonia. Governments can overcome this hurdle by politically committing to offer supply-side CfDs once vessels with ammonia engines are commercially available. Furthermore, governments can implement a set of complementary policies to encourage investments and technology development for low carbon vessels or aircraft. This includes providing innovation subsidies, CAPEX funds and tax breaks to reduce the high risk of investing in and developing nascent technologies. Major research programmes, such as Clean Aviation and Horizon Europe (and their follow-on programmes) could be focused on zero-emission technology developments. Consideration could also be given to mandating the use of low-carbon aircraft and vessels on particular routes (e.g. domestic flights of less than 150km, where existing services already use comparatively small, short-range aircraft).

For vessel and aircraft operators, the risk around production capacity limit and infrastructure scalability can be dealt with through a clear government policy (examples being infrastructure investment grants, public-private partnerships for infrastructure development, fuel production and infrastructure development initiatives) that ensures the value chain for zero-emission vessels and aircraft can reduce their go-to-market risks while working in coordination to allow scaling up for larger production volumes. Ensuring sufficient available future supply of RFNBO fuels will be key to this and examples of government support to achieve this is already evident through initiatives such as the UK Department for Transport Advanced Fuel Fund, Horizon Europe and Innovation Fund.

4.1.2 Fuel production capacity limit and infrastructure scalability issues

Context of risk

To produce RFNBO at scale, there are a number of steps in the fuel value chain that can have long lead times. For example, the time it takes to plan and build new renewable energy capacity, electrolysers, including finding suitable land and water source, electricity network to connect to electrolyser if not on site, CCUS installations for RFNBO types that require CO_2 etc. If there is a capacity limit on one part of the value chain, this can limit the overall availability of RFNBOs. There is also a risk that large energy conglomerates will provide a vertically integrated supply chain, which could put them at a competitive edge to smaller companies bidding for CfDs at specific parts of the value chain.

There can also be issues around infrastructure scalability when new technologies go from prototypes to commercialisation phase. These risks can limit the growth of RFNBOs on the market. In the maritime sector there are several possible fuels that could be utilised as an energy source but these are not compatible with existing storage and fuel delivery infrastructure. Some storage may exist for traded commodities such as ammonia or methanol. However, storage does not exist at the scale required for use as a fuel and the delivery mechanism of the fuel to a ship also does not exist.

There is also a risk that implementing a demand-side CfD offers a price incentive that is too far down the fuels value chain (at the consumption stage). As a demand-side CfD is placed at the end of the fuels value chain, it is not an efficient means of stimulating increased RFNBO production capacity higher up in the value chain. Unless there is a lag between the announcement of the scheme and its implementation, agents in the RFNBO value chain will not have sufficient lead times to invest in sufficient capacity before the demand-side CfD enters into action. Once a demand-side CfD is entered, a maritime or airline operator can purchase RFNBO fuels at a set strike price, while the reference price may shoot up if there is a shortage of RFNBO fuels. The high reference prices will incentive agents in the RFNBO value chain to invest, but the increased RFNBO production comes with an investment lag, but the price signal will be abnormally high until there is available supply to meet the demand determined by the demand-CfD, which can take years to achieve. If demand outstrips supply this could lead to increased prices or scarcity, which would need to be covered by the CfD counterparty (i.e., government). There is also a risk that this will increase the cost of aviation and shipping companies that were not successful in a CfD auction and must purchase higher cost RFNBO than successful CfD bidders or choose not to purchase RFNBO fuel. In the face of increased demand driven by the CfD scheme, there may be challenges in rapidly scaling up the infrastructure to meet the higher demand for RFNBOs. This could lead to logistical bottlenecks, supply chain disruptions, and increased costs.

There is also a risk that RFNBO producers with a supply-side CfD face non-price hurdles, such as disruptions in feedstock supply, technical issues in production plants, or transportation bottlenecks can constrain the availability of alternative fuels, impacting the effectiveness of the subsidy scheme. There could also be wider supply chain issues which limits producers from entering the market, even with a CfD scheme. Or there is the risk that they will enter the market and bid very high strike prices in a supply-side CfD auction.

Mitigation action

Complementary policies are important to address supply-chain issues to ensure there are producers willing to invest in RFNBO capacity. Coordination amongst the value chain will be important, and the government should make sure the price support schemes are aligned at the correct points in the value chain. For example, to produce green kerosene, a CfD might be needed for a new solar and wind farm, another CfD might be needed to stimulate investment in electrolyser capacity. A CCfD may be needed to incentivise CCUS to capture CO_2 as an input into e-kerosene. There is no overlap between subsidies in this case: A solar or wind farm owner receives a supply-side CfD strike price while selling electricity at wholesale market prices. A hydrogen producer receives a supply-side CfD strike price for the sale of hydrogen but purchases green electricity at the wholesale price. A CCUS installation receives a CCfD strike price for capturing CO_2. Multiple CfDs along the value chain can thus be desirable to ensure agents across the whole fuels value chain are sufficiently incentivised in a coordinated way. Governments should play a leading role in facilitating that different companies (wind developers, electrolysers, CCUS) have the right incentives along the value chain.

The risk of fuel production capacity limits resulting from a demand-side CfD can be solved by introducing a supply-side CfD instead. A supply-side will fix the supply of a RFNBO fuel type, and demand will be met through the market clearing price. This will mitigate the risk of a demand-supply imbalance that can occur by only implementing a demand-side CfD.

From a demand perspective (aviation and ship operators), the longer-term decisions required around engines and supporting infrastructure mean governments can play a role by providing long term emission targets for the sector. For the maritime sector, international emission reduction targets have been set by the IMO (run until 2050). Within the EU, there are FuelEU maritime targets as well as the EU climate targets to reduce net GHG emissions by 55% in 2030 and 90% by 2040, relative to 1990 levels. Long term planning and certainty can reduce the risk, while complementary policies, such as market reform, public R&D, tax incentives, RFNBO mandates, etc. can provide additional incentives for fuel producers which can reassure aviation and maritime companies that competitively priced RFNBO will be available to meet their long-term demand.

4.2 AVIATION RISKS

4.2.1 Support scheme may only apply to fuel producers.

Context of risk

The implementation of the ReFuelEU Aviation Regulation will mandate a minimum level of RFNBO use within the mandated SAF uptake. As RFNBO is expected to be more expensive than biofuel-based SAF until approximately 2050, airlines are unlikely to increase their uptake of RFNBO beyond the minimum level without financial support. This limits the demand for RFNBO and hence the incentives to fuel producers to increase production. While, in principle, a supply-side CfD scheme would ensure that the price paid by airlines is the competitive with that for biofuel-based SAF, there is a risk that other parts of the full RFNBO value chain may not be able to manage increased costs, or the fuel producers may not wish to pass all the savings through to fuel consumers, leading to fuel prices still increasing for aircraft operators. This would reduce the impact of the CfD scheme in incentivising RFNBO uptake beyond the minimum mandated.

Mitigation action

A demand side support scheme could avoid some of the issues of a supply side scheme; however, that also brings risks a shortfall in supply and of being seen to support non-EU operators using EU funds (see below). Further, as a SAF mandate, together with a RFNBO sub-mandate, is already in place, providing support to aircraft operators within the mandated quantity could be seen as a double incentive. As described elsewhere in this report, EU regulations would not allow CfDs to be provided to other parts of the fuels value chain, such as renewable energy generators and hydrogen producers (if provided to the fuel producers themselves); however, other forms of support may be provided to assist the development of the full value chain (through purchase agreements) to ensure that the benefits of the CfD are fully realised in ensuring that RFNBO production capacity is sufficient to meet demand (including demand for RFNBO beyond the mandated minimum).

4.2.2 Subsidy reinforcing market power to a small number of suppliers

Context of risk

Currently, fuel is supplied to the aviation sector by a limited number of fuel producers, which gives them considerable market power. Airlines may sign long-term contracts with fuel suppliers with the aim of obtaining stability in their fuel costs. Currently, there are several companies developing SAF production facilities across Europe, with a total of 64 plants planned or in operation (the majority of those plants in operation are based on co-processing with conventional fuel) with a total reported capacity of 3.4 million tonnes per year (Argus Media, 2023), which should deliver healthy market competition, leading to improvements in production efficiency and reductions in SAF prices. This should particularly be the case for RFNBO, as it will be less sensitive to variations in feedstock prices. Nonetheless, there is a risk that a CfD scheme, with limited fuel production companies available to bid for support at auctions, will lead to market concentration, where higher strike prices are agreed than would happen with more players. There is also a risk that the strike prices will be impacted by land prices, where increases in acquiring suitable land for feedstock will increase the revenue requirement of SAF producers. Access to adequate land and other resources can also limit new companies from entering the market.

Further, a ‘book and claim’ system in the mandate may be able to be more easily exploited by large producers, with a wide range of outlets, than by small producers who are more constrained on the airports that they supply

Mitigation action

Complementary policies can be introduced to ensure there is available land, available financing, and risk mitigation for new entrants to enter the market. Introducing national CfD schemes can also mean different players can bid, and there could be requirements to have a footprint in the country, which would stimulate local jobs and growth. By stimulating support at different levels of the value chain can mean different specialised firms can enter parts of the value chain, without requiring vertically integrated companies to deliver the full product from start to finish. In terms of CfD design, there could in theory be introduced a max cap on production capacity/volume per entrant, which would stimulate more competition, but at possibly higher strike prices.

4.2.3 International nature of aviation

Context of risk

This risk relates to the fact that fuel sales within the EU will include sales to non-EU registered airlines and those not contributing to the EU ETS. Currently, it is estimated that about 25% of fuel on EEA departing flights is used by non-EEA airlines[17].

The principles of the proposed CfD scheme include that it would be funded through a portion (25% is currently suggested) of revenues from airlines under the EU ETS. However, the ReFuelEU Aviation mandate is for all fuel sold at EEA airports to include a specified minimum percentage of SAF (including RFNBO). As a result, airlines registered in other countries that fly to and from the EEA (but not within it) will benefit from lower prices for RFNBO SAF, even though they do not contribute to the EU ETS (assuming that the current “Stop the clock” derogation remains in force and the EU ETS does not revert to full scope). Ultimately, the environmental

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[17] Analyses of Eurostat data, table avia_tf_apal (Eurostat, 2024), indicate that, in 2023, approximately 24% of passengers departing from European airports were carried on non-EU airlines. Similarly, the European Aviation Environmental Report 2022 (EASA, 2022), Figure 1.14, shows that 49.6% of CO_2 is emitted on flights to non-European destinations. Assuming an equal share of traffic between European and non-European airlines on these routes suggests about 25% of emissions, and hence fuel, is used by non-European airlines.

benefits of the CfD scheme through increased production and sales of RFNBO SAF would still be achieved, but European airlines may consider that they are at a disadvantage in terms of the costs to achieve their desired level of decarbonisation.

Mitigation action

It is important to review the environmental benefits that the scheme is intended to deliver and to consider whether having emissions reductions being achieved by airlines that do not contribute to the funding of the scheme is detrimental to the promotion of its benefits. If having non-European airlines benefitting from the support provided to RFNBO producers is considered to be detrimental to the aims of the scheme, consideration could be given to restricting support only to RFNBO SAF provided to airlines for use on intra-EEA flights, as the vast majority of these are performed by EEA-registered airlines (and all such flights fall under the scope of the EU ETS). However, an alternative view is that the provision of sufficient RFNBO will deliver associated environmental benefits, independent of whether it is used by EEA airlines on intra-EEA routes or airlines of all nationalities on intra-EEA and extra-EEA departing flights. Under such a view, the use of supported RFNBO by non-EEA airlines is not a problem and no mitigation is required.

4.3 MARITIME RISKS

4.3.1 Variable bunkering traffic within shipping industry

Context of risk

Tramp trade refers to the shipping of goods without a fixed schedule or route. They operate on a voyage-to-voyage basis accepting cargo wherever they find it. The unpredictable nature of tramp trade means it will be challenging to ensure a consistent supply of RFNBOs as their availability could vary widely across different ports and regions. The infrastructure for traditional marine fuels (such as heavy fuel oil) is well-established globally. However, infrastructure for alternative fuels like methanol or ammonia or even LNG is not as widespread. Tramp vessels may find themselves in regions where there is a lack of infrastructure for alternative fuels, making it difficult or impossible for them to refuel with the preferred alternative fuel. This can lead to operational disruptions and increased costs.

Mitigation action

To maximise the chances of RFNBO being available for tramp trade vessels a supply-side CfD scheme could look to incentivise RFNBO supply at key bunkering location or ports. Determination of which ports to incentivise could be based upon total traffic volume, criticality of trade route, commonality of port pairing (journey predictability) or similar metric. A demand-side is more challenging to implement for tramp-trade as there is no guarantee RFNBO is available for them to purchase, a CfD scheme could be designed such that if RFNBO was not available tramp trade vessels buying RFNBO could receive a rebate on future RFNBO purchases.

4.3.2 Scope of scheme (Fuel only vs TCO)

Context of risk

There are 2 leading options to design a demand-side CfD scheme to support RFNBO uptake in the maritime sector. A “fuel only” scheme will ensure price stability for purchasing RFNBO. A total cost of ownership-based (TCO) scheme broadens the scope of the scheme to cover costs associated with the construction and operation of a RFNBO-powered vessel.

A fuel only demand-side CfD is far more simplistic to administer as the subsidy only applies to fuel purchases. Given the simplicity it is more accessible across the shipping sector, and it is ship-agnostic (as long as RFNBOs are used to power the ship). It can quickly incentivise RFNBO uptake, assuming that vessels already have capability to operate on RFNBOs, and producers are offering RFNBO in adequate supply. Given that the majority of the total cost of vessel ownership is taken up by the cost of fuel a fuel-only CfD scheme would have the largest cost reduction impact (Alex Clark, 2021). Downsides of a fuel-only CfD scheme is that the largest barrier to RFNBO uptake, the high capital costs of building a RFNBO-powered ship and the capital investment needed by ports and bunkering facilities to store RFNBOs, is not addressed through this scheme design.

A TCO–based CfD scheme would help to overcome that barrier thus providing a more holistic approach to adopting RFNBOs on a wider scale. This in turn could lead to wholesale reductions in costs across the shipping sector from ship building to infrastructure costs to fuel cost reduction. Additional costs associated with the switch to RFNBOs would also be accommodated by a TCO scheme throughout the supply chain including fuel costs, retrofit costs, bunker costs and additional safety/staff training costs. However, this comes at the costs of additional complexity in administering such a scheme. As each ship type, and operation is somewhat unique, the benchmark reference price for a CfD scheme would vary greatly from ship to ship. It may need to be the case that separate TCO scheme exist to accommodate different vessel types and operations. Given that, a TCO-based scheme would require careful management of a diverse range of costs across many different stakeholders in the maritime sector from vessel construction through to fuel producers. However, not providing a TCO CfD can cause vessels to not switch to RFNBO as the economic case for the CAPEX investment in new engines and infrastructure is not supported.

Mitigation action

Governments should take a leading position by offering support, either as a TCO based demand-side CfD, or via a fuel-only CfD supported by CAPEX funding to install the necessary infrastructure or through the provision of subsidies or tax breaks that will encourage vessel owners to invest in the necessary modifications and infrastructure to run on RFNBOs. Alternatively, international mandates could be set via the IMO stating that beyond for example 2030 all new-build ships to be RFNBO-ready. At the IMO-level, although the economic measure to accompany the set of mid-term has not been decided one option is to set aside any revenue generated through a levy into a sustainable shipping fund or similar. Revenue in this pool could be used to support development of infrastructure.

5. SCHEME SIZE AND SCOPING

5.1 ANALYSIS OVERVIEW

To support the qualitative analysis and discussion in earlier chapters of this report, Ricardo also conducted a range of quantitative modelling analyses to assess the potential impacts of different scenarios for the uptake of RFNBO in the aviation and maritime sectors. In each case, the aim was to identify the expected uptake of RFNBO under each scenario, the costs associated with that uptake, and the potential for a support scheme (assumed to be a CfD scheme for the purposes of these analyses) to reduce costs and to encourage the defined uptake (or to increase it).

The key outputs that the modelling aimed to provide are summarised in Table 5-1, with a high-level summary of the modelling approaches given below. Further details of the analysis methodology are then given in the following sub-sections, with additional details for the aviation sector provided in Appendix 2.

Table 5-1: Key modelling outputs

#	Output	Notes
1	Total size of the scheme	Theoretical maximum size needed, under the assumption that 25% of EU ETS revenue is recycled for the scheme.
2	Cost difference of switching under scheme	Using route case studies. Fuel cost obtained from modelling results with additional cost factors to account for infrastructure.
3	Potential changes to cost of RFNBOs	See Section 5.5
4	Uptake of RFNBOs over time	Based upon projected fuel uptake scenarios and level of subsidy available.

For the aviation sector, the overall projections of passenger demand and fuel consumption to 2050 were obtained using the EASA AERO-MS tool, with detailed calculations for specific years and interpolation/extrapolation used to provide results for other years. A bespoke Excel-based analysis was then used to implement the variations of fuel types (fossil kerosene, biofuel-based SAF, RFNBO SAF, hydrogen) over the period, according to the scenario. The estimates of fuel consumption by fuel type were then used to calculate the available funding for the scheme, together with the proportion of the fuel consumed that could be supported. This also provides projections of the annual cost of the scheme (based on the differences in fuel prices, together with the additional costs of fuel taxes and ETS requirements, including the fuel types to which each are applicable), and hence the total costs over two auction periods (starting in 2025 and 2030 respectively, each lasting for a period of 10 years).

For the maritime sector, the analysis used a bespoke Excel-based model to quantify the potential effects of a subsidy scheme under four scenarios. Similarly to the analyses for the aviation sector, input data and projections of a number of key factors, including shipping activity, fuel consumption, fuel pricing and ETS carbon prices, were combined to explore estimates of the level of funding that may be available under the subsidy schemes and the level of RFNBOs that could be supported.

Sections 5.1.1 and 5.1.2 provide definitions of the four scenarios considered under each of the aviation and maritime sectors, together with further details of the analyses performed. Results from these analyses are then given in Sections 5.2 and 5.3. Section 5.4 then provides some more detailed insights into the impacts of the different scenarios and the CfD support schemes on some specific example routes for each sector.

5.1.1 Aviation

The four scenarios used for the analysis of the aviation sector include one that represents a continuation of the existing policies that have been adopted (mostly under the EU Fit for 55 (FF55) policy) and baseline demand growth projections. The existing policies include the ReFuelEU Aviation mandate, which provides the projected evolution of the fuel mix (i.e. changes in the use of biofuel-based SAF and RFNBO SAF). The DMan and No DMan scenarios, in contrast, use fuel mixes based on the T&E roadmap recommendations. The DMan scenario achieves decarbonisation of the sector through the management of passenger demand (implemented as a cap on demand), while the No DMan scenario achieves the same levels of emissions reduction through an increased uptake of RFNBO SAF. The fourth scenario, referred to as FF55++, extends the FF55 scenario, again using a fuel mix based on the ReFuelEU Aviation mandate, with additional measures including an extension of the EU ETS and the implementation of a tax on fuel for intra-EEA flights.

Further details of the four scenarios are presented in Table 5-2.

Table 5-2: Aviation modelling scenarios

Scenario	Description
FF55 – adopted policies	**Fit for 55 – adopted policies:** Already adopted policies and expected aviation growth projections. Baseline growth in demand (revenue passenger kilometres (RPK) for passenger services and revenue tonne kilometres (RTK) for freight services) using existing projections in AERO-MS, with adjustments to reflect the impact of the COVID-19 pandemic. SAF mandates as per the adopted ReFuelEU Aviation regulation. e.g., 70% total SAF by 2050, comprising: ● 35% biofuel-based SAF. ● 35% RFNBO-based SAF. Carbon pricing: ● No fuel tax (not yet adopted) ● ETS, as per the adopted EU ETS
DMan	T&E decarbonisation roadmap[18] scenario, including demand management through a cap on passenger demand. Demand limited based on T&E aviation roadmap capped at: ● 100% 2019 leisure demand (RPK); ● 50% 2019 business demand (RPK). SAF mandates as per T&E roadmap. Penetration of SAF[19]: Gradual ramp-up reaching 100% alternative fuel by 2050, comprising: ● 17.9% hydrogen; ● 19.1% biofuel-based SAF; ● 63.0% RFNBO-based SAF. Carbon pricing: ● EU ETS extended to all flights departing EEA airports (intra-EEA and extra-EEA) ● Fuel tax applied to all EEA departures, starting in 2025 and increasing linearly to €0.33 per litre (equivalent to €129 per tonne CO_2) by 2035.
No DMan	Assumptions based on T&E aviation roadmap as per the DMan scenario. T&E decarbonisation roadmap, without demand management: Demand: ● No limit on demand, but increased e-fuel (RFNBO) uptake used to deliver the same emissions reduction as DMan. Penetration of SAF: Gradual ramp-up reaching 100% alternative fuel by 2050, comprising:

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[18] It should be noted that the modelling of the impacts of these measures, including other assumptions such as fuel price projections, differ between those presented in this report and those in the T&E aviation roadmap. As a result, there may be differences in aviation traffic and emissions between the two studies.

[19] The DMan and No DMan scenarios include assumed uptake of different alternative fuels, rather than formal legislative mandates. Throughout the report, the measures that deliver the uptake of alternative fuels are referred to as “mandates” whether they are formal legislative measures (the FF55 and FF55++ scenarios) or not (the DMan and No DMan scenarios).

Scenario	Description
	● 17.9% hydrogen; ● 19.1% biofuel-based SAF; ● 63.0% RFNBO-based SAF. Carbon pricing as per DMan
FF55++	Improved carbon pricing to deliver emissions reductions, building on the EU 'Fit for 55' policy: SAF mandates as per the adopted ReFuelEU Aviation regulation. 70% total SAF by 2050, comprising: ● 35% biofuel-based SAF. ● 35% RFNBO-based SAF. Carbon pricing: ● EU ETS extended to all flights departing EEA airports (intra-EEA and extra-EEA) from 2027[20] ● Fuel tax (intra-EEA) implemented as per the compromise text of the Council with reduced rates for islands, exemptions for outermost regions and very low rates for SAF as of 2033 (Contexte.com, 2023) EU ETS extended to all flights departing EEA airports (intra-EEA and extra-EEA)

The fuel price projections used for alternative fuels were those used in the ReFuelEU Aviation study (Council of the EU, 2023). For fossil kerosene, it was noted that recent price fluctuations suggested that previous projections might be out of date. Therefore, for this study, kerosene prices were calculated using:

- For 2023, the average of prices for 1 January 2023 to 30 September 2023 from the IATA jet fuel price monitor (IATA, 2023b) (noting that the price was significantly lower during May and June 2023 than it was in September 2023, for example);
- For short-term development (to 2027), the fuel price trends were set to be in line with the projections from BMI (Rigzone, 2023);
- For longer-term development (to 2050) the fuel price trend was set to be in line with the projections from the US Energy Information Administration (EIA) Annual Energy Outlook 2023 (Energy Information Administration, 2023).

Combined, the different sources of fuel price projections gave the variations shown in Figure 5-1.

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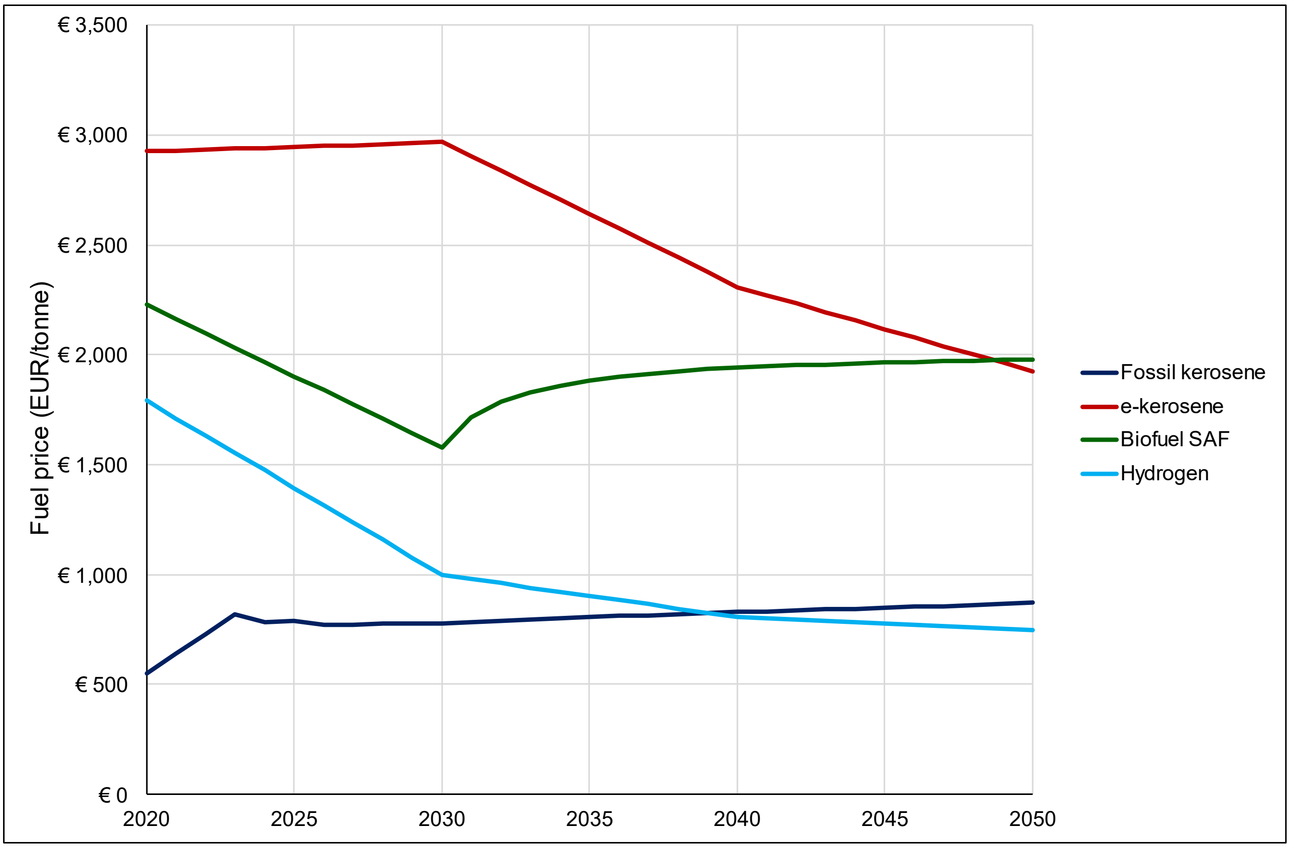
[20] When adopting CORSIA on extra-EEA flights under the revised EU ETS Regulation, the EU stated its intention to review the effectiveness of CORSIA and to implement the EU ETS on departing flights from the EEA if CORSIA was found not to be effective.

Figure 5-1: Fuel price variations used in study



The overall passenger transport demand and fuel consumption was calculated using the AERO modelling system[21] (AERO-MS). This model calculates the development of the global aviation sector under a baseline set of conditions (no economic policies) and user-defined economic and regulatory policies. For the current study, the inputs to the model captured the differences in economic factors (average fuel prices, taxes and EU ETS allowance costs), while the key outputs obtained were the transport demand (RPK) and fuel consumption. These were then input to post-processing calculations to derive further details such as the fuel costs associated with the different fuel uptake assumptions for the scenarios.

At the time of performing these calculations, baseline scenario calculations were available for AERO-MS for years 2016, 2025 and 2035. As the preparation of new baseline scenario calculations is a relatively time-consuming process, for this study the available baseline scenarios were used. The different analysis scenarios (FF55, DMan, No DMan and FF55++) were then represented in the inputs to AERO-MS as policy cases for these three years; results for all other years were obtained by interpolation or extrapolation. As the key focus of this study is the period in which CfD support schemes are being considered (i.e., 2025 to 2040), the level of extrapolation required was relatively small, and the approach was considered suitable for the study's requirements.

The AERO-MS baseline scenarios used were derived prior to 2020 and, therefore, did not include the impacts of the COVID-19 pandemic on aviation demand (and hence fuel consumption). To capture these effects, factors were derived from EUROCONTROL forecasts for aviation movements to 2029 (EUROCONTROL, 2023). These showed aviation movements returning to 2019 levels by 2025. The factors were, therefore, calculated by dividing the EUROCONTROL forecast (or actual values for years between 2019 and 2023) by the demand in 2019. These factors were then applied to both the RPK demand[22] and fuel consumption calculated by AERO-MS. For years after 2029, the same factor as calculated for 2029 was applied, thus retaining the same annual growth rates as in the baseline AERO-MS calculation). Long-term (post-2029) this

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[21] The IP for the AERO-MS rests with the European Union Aviation Safety Agency (EASA). A licence was obtained from EASA for its use on this study.

[22] It should be noted that the EUROCONTROL historic data and forecasts are for movements, while the application of the factors is to RPK. There was a reduction of passenger load factor during the pandemic, so the impact on RPK was greater than that on aircraft movements; however, load factors have recovered as the aviation sector recovers, so the factors derived are relevant for both movements and RPK in future years.

gave a demand of approximately 81% of that which would have been the case if the COVID-19 pandemic had not occurred. The use of the same factors for demand and fuel consumption suggests that the efficiency of the air transport sector would not be affected by the lower demand. Whilst, in reality, it might be expected that there could be some impact (lower demand could lead to a slower fleet replacement and hence a slower improvement in efficiency), it was not felt that this would have a significant impact on the results of the analysis.

The fuel consumption values obtained from AERO-MS were for the total consumption (as if it were all fossil kerosene). The specific energy (MJ/kg) of SAF is the same as that for fossil kerosene, so the derivation of the quantity of each type of SAF (biofuel or RFNBO) simply applied the percentage penetration (from the scenario definition) to the calculated total fuel consumption. Hydrogen has a very different specific energy; therefore, the quantity of hydrogen was derived as an equivalent mass of kerosene, assuming the same energy consumption for a hydrogen-fuelled aircraft as a kerosene-fuelled one.

As noted above, the AERO-MS is a global model. To derive results specifically for the European aviation sector, fuel consumption was output at a flight stage[23] level. The fuel consumption for the relevant European route categories (e.g., intra-EU, intra-EEA, EEA-UK) was then obtained by summing the fuel consumption for all flight stages falling in those categories. To allow some elements of the scenario assumptions to be applied (e.g., the lower fuel tax applicable to flights to and from airports on islands), relevant flight stages that included at least one island airport were identified separately.

Further details of the methodology for the aviation calculations are provided in appendices 8.2.3.

5.1.2 Maritime

For this study no readily accessible model to assess the level of emissions, fuel consumption and cost of introducing alternative marine fuels was available therefore, it was decided to create a bespoke Excel-based tool exclusively for use in this study. As will be elaborated in 5.2.2 the model uses data on current and future activity within the global shipping sector to build up the picture of current and expected fuel use from the present through to 2050 and apply this to the expected fuel uptake scenarios as defined in the scenarios presented in Table 5-3. From this starting point the EU's contribution to global shipping was calculated to estimate the level of revenue generate under the EU ETS, this revenue was then distributed via a subsidy to observe the amount of RFNBO that can be supported under each of the scenarios assessed.

The scenarios to be analysed as part of the maritime modelling were provided by T&E and align to their current modelling work. To ensure consistency we have kept the naming convention as per the T&E model used to during their impact assessment of FuelEU Maritime on EU Shipping (Transport & Environment, 2023).

The four scenarios consist of two standard scenarios as defined in the aforementioned T&E model FEUM and DE_DK which have differing levels of emission intensity reduction and RFNBO sub-quotas as per Table 5-3.

The additional scenarios build upon these baseline scenarios to include additional energy efficiency improvements.

Table 5-3: Maritime modelling assumptions

Scenario	Description
FEUM	Emissions intensity targets (80% by 2050), RFNBO sub-quota (2%) and RFNBO Multiplier as per final FEUM agreement.
FEUM_eff	As per FEUM with added energy efficiency measures as per Table 5
DE_DK	Denmark + Germany's Council proposal (Transport & Environment, 2022) including higher-ambition emissions intensity targets (100% by 2050), RFNBO sub-quota (2% in 2030 rising to 70% in 2050) and multiplier.
DE_DK_eff	As per DE_DK with added energy efficiency measures Table 5

It was agreed that energy efficiency improvements in the baseline scenarios would be taken from the IMO's 4th GHG gas study (IMO, 2021) per year and per vessel type and additional improvements beyond the baseline

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[23] In AERO-MS, a flight stage represents an annual number of flights between a specific pair of airports. The model includes approximately 123,000 flight stages globally.

defined as per Table 5-4. For the additional energy efficiency scenarios, energy efficiency improvements were developed based on a modified version of T&E ‘optimistic’ roadmap scenarios, defined as per Table 5-5

Table 5-4: Energy efficiency improvements

Year	Bulker	Tanker	Container	Other unitized
2018	0%	0%	0%	0%
2020	1%	2%	1%	2%
2025	8%	8%	8%	7%
2030	15%	15%	15%	12%
2035	19%	18%	19%	14%
2040	24%	22%	23%	16%
2045	25%	23%	24%	16%
2050	26%	24%	25%	17%

Table 5-5: Additional energy efficiency scenario improvements

Year	Increased energy efficiency
2017-2023	As per IMO scenario
2030	23%
2035	30%
2040	37%
2045	38%
2050	39%

Given the variety of fuels currently and projected to be used in the maritime sector their price over time is a key input to the maritime model created as part of this study. Table 5-6 summarises the fuel pricing used in the maritime model and the source of the data. Where not explicitly stated Ricardo utilised prices used in a previous study conducted for Concawe where current and project fuel prices were provided by IHS (Ricardo, 2022).

To reflect the impact the ongoing conflict in Ukraine has on LNG prices, we have included an additional interpolation point for 2023 prices (€16.01/GJ) to account for short-term increases in LNG prices. Thereafter, we revert to the original projections made in Ricardo’s previous studies. Green methanol prices are taken from the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (MMMZCS) input files for their fleet modelling software NavigaTE (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022). From 2020 to 2030 the captured carbon is assumed to be from point sources thereafter, from direct air capture. BioLNG prices are taken from a SeaLNG report from 2022 (Sea-LNG, 2022) examining the role of LNG in decarbonising shipping.

Table 5-6: Fuel price inputs for maritime model (€/GJ)

Fuel	2020	2030	2040	2050
HFO (VLSO)	7.73	10.33	9.77	8.71
LNG	6.37	7.79	8.72	8.85
BioLNG	28.2	25.07	21.93	18.80
e-LNG	63.92	52.64	47.0	35.72

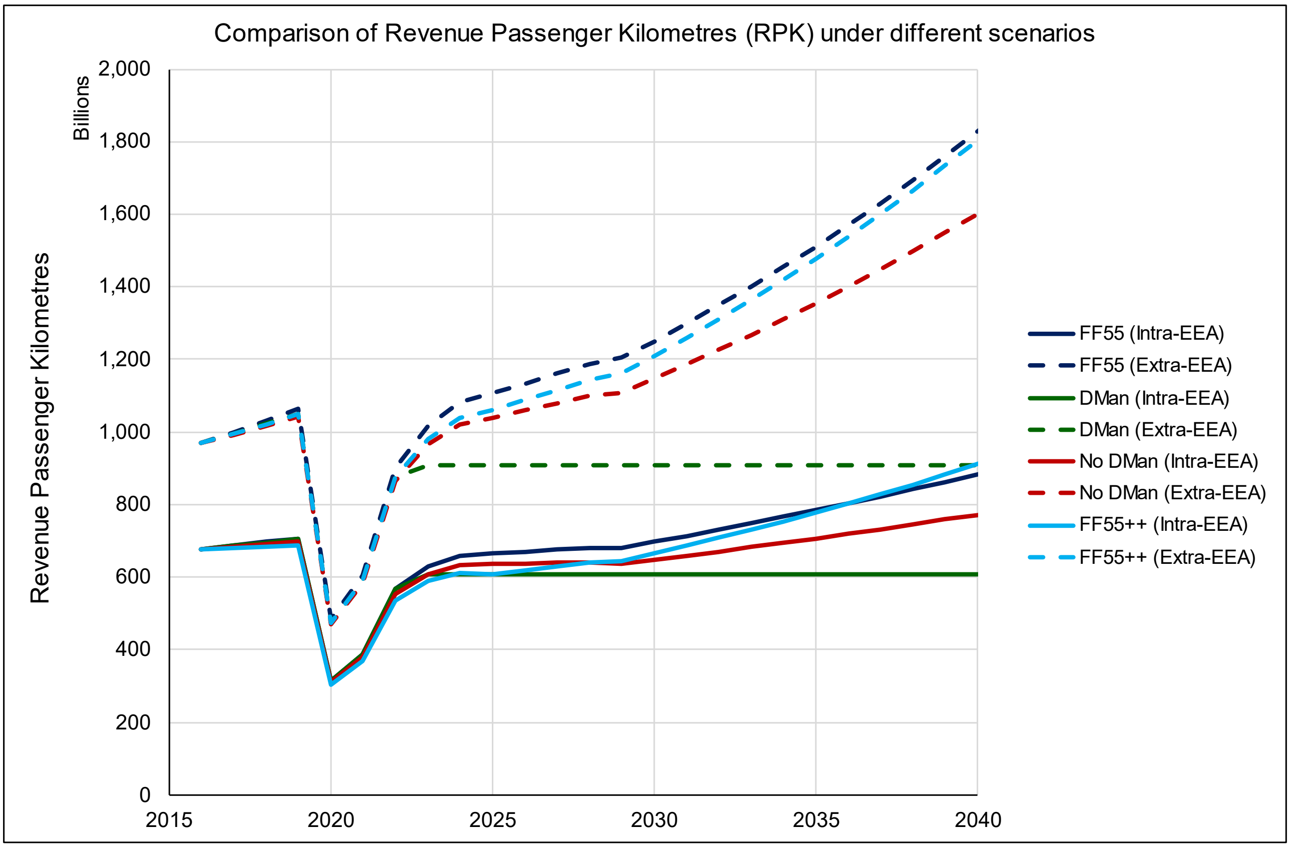
Fuel	2020	2030	2040	2050
e-methanol	62.98	50.76	46.06	32.9
e-ammonia	34.39	34.24	29.71	27.66
FAME	32.66	31.34	28.91	25.56
e-diesel	158.86	139.12	119.85	100.11

5.2 SUBSIDY LEVEL

5.2.1 Aviation

The calculations of passenger transport demand described above gave the distribution of RPK through to 2050 shown in Figure 5-2.

Figure 5-2: RPK for intra-EEA and extra-EEA flights under all scenarios



The results are presented for both intra-EEA and extra-EEA[24] flights separately. The distributions show the impact of the COVID-19 pandemic on demand in 2020 and the subsequent recovery to 2019 levels by 2025. For extra-EEA flights (dashed lines in Figure 5-2), The FF55 and FF55++ scenarios show very similar growth in demand, reaching approximately 1,800 billion RPK in 2040. The RPK for the DMan scenario is constrained to a function of the 2019 demand, as described above; this is seen as the Scenario does not recover fully following the COVID-19 pandemic and demand continues at the same level thereafter. No DMan scenario is not constrained, but the effects of the increased RFNBO use and average fuel price, feeding through to increased ticket prices, results in lower long-term demand than the FF55 and FF55++ scenarios. On intra-EEA flights (solid lines), The FF55++ scenario shows lower demand in the earlier years due to the fuel taxes under the revised ETD being implemented in full, while it recovers to similar levels as the FF55 and No DMan

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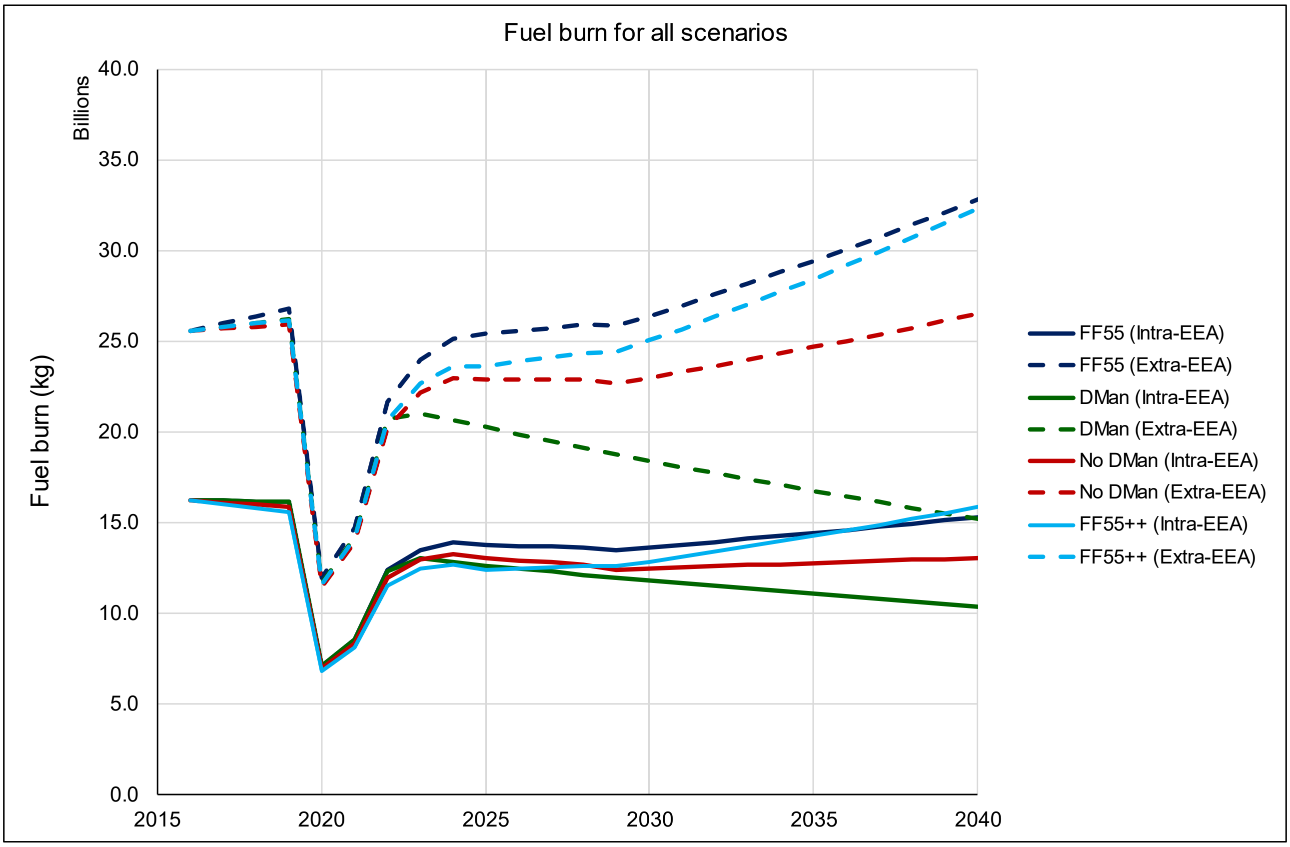
[24] In general, the term “extra-EEA” can be used to indicate both flights departing EEA airports for third countries and those arriving at EEA airports from third countries. In this report, to align with the extension of the EU ETS to all departing flights under the scenarios described, “extra-EEA” is used to indicate flights departing EEA airports for third countries.

scenarios by about 2035 as the full tax is implemented in the FF55 by then (and the No DMan scenario is impacted by the increased fuel prices).

The distributions of total fuel consumption associated with these levels in demand are shown in Figure 5-3. This figure includes consumption of all fuel types; where modelled, the consumption of hydrogen fuel is included as the equivalent mass of kerosene for the same energy consumption.

Figure 5-3: Fuel burn on intra-EEA and extra-EEA flights for all scenarios



In general, the results in Figure 5-3 show very similar development of fuel consumption to passenger transport demand (Figure 5-2). There is an impact of improved fleet fuel efficiency over time, as can most clearly be seen in the results for the DMan scenario, which show a gradual reduction in fuel consumption for the (capped) constant RPK. Under the FF55 scenario, the calculated fuel consumption reaches approximately 65 billion kg (65 million tonnes) by 2040 on extra-EEA flights and 15 million tonnes on intra-EEA flights.

The variations in percentages of this fuel consumption by fuel type are shown for the four scenarios in Figure 5-4 to Figure 5-7. Under the FF55 scenario (Figure 5-4), there is a gradual reduction in the percentage of fossil kerosene, with its displacement by biofuel SAF and, more slowly, by RFNBO SAF. By 2050, there are equal percentages of the two SAF types, with fossil kerosene reduced to 30% of the total.

The DMan scenario includes a more rapid reduction of fossil kerosene (as a percentage of the total fuel consumption), with an accelerated uptake of RFNBO SAF relative to that of biofuel SAF. This scenario also introduces the uptake of hydrogen fuel from 2035; for comparability with the hydrocarbon fuels, the percentage consumption is based on the energy consumption by fuel type[25]. No DMan targets the same emissions reduction as achieved in DMan, but through an increased uptake of RFNBO. The uptake profile under FF55++ is then similar to that under FF55.

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[25] Alternatively, the presentation of hydrogen fuel consumption can be considered as the mass of kerosene that would have the same energy content as the hydrogen fuel consumed.

Figure 5-4: Fuel mix under FF55 Scenario

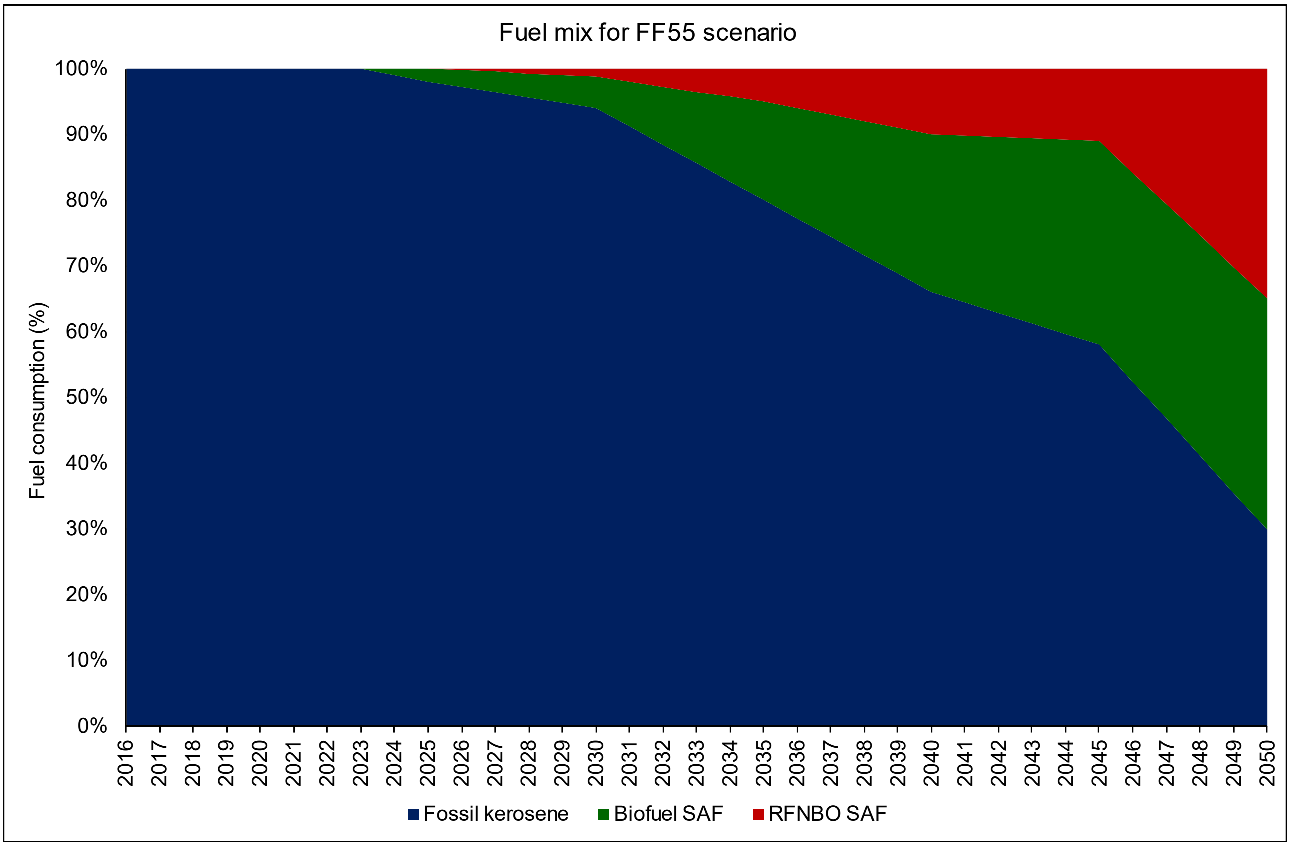


Figure 5-5: Fuel mix under Scenario 1 (DMan)

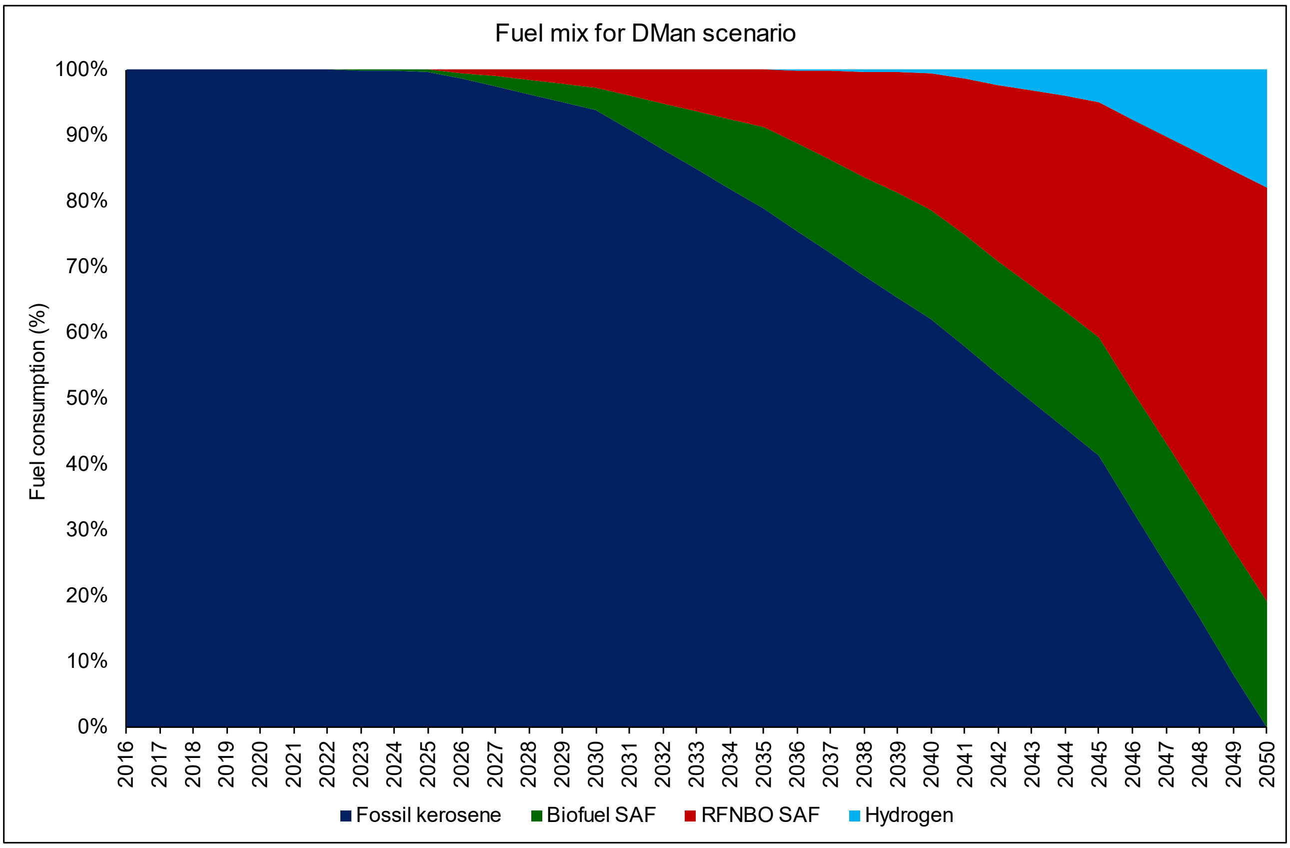


Figure 5-6: Fuel mix under Scenario 2 (No DMan)

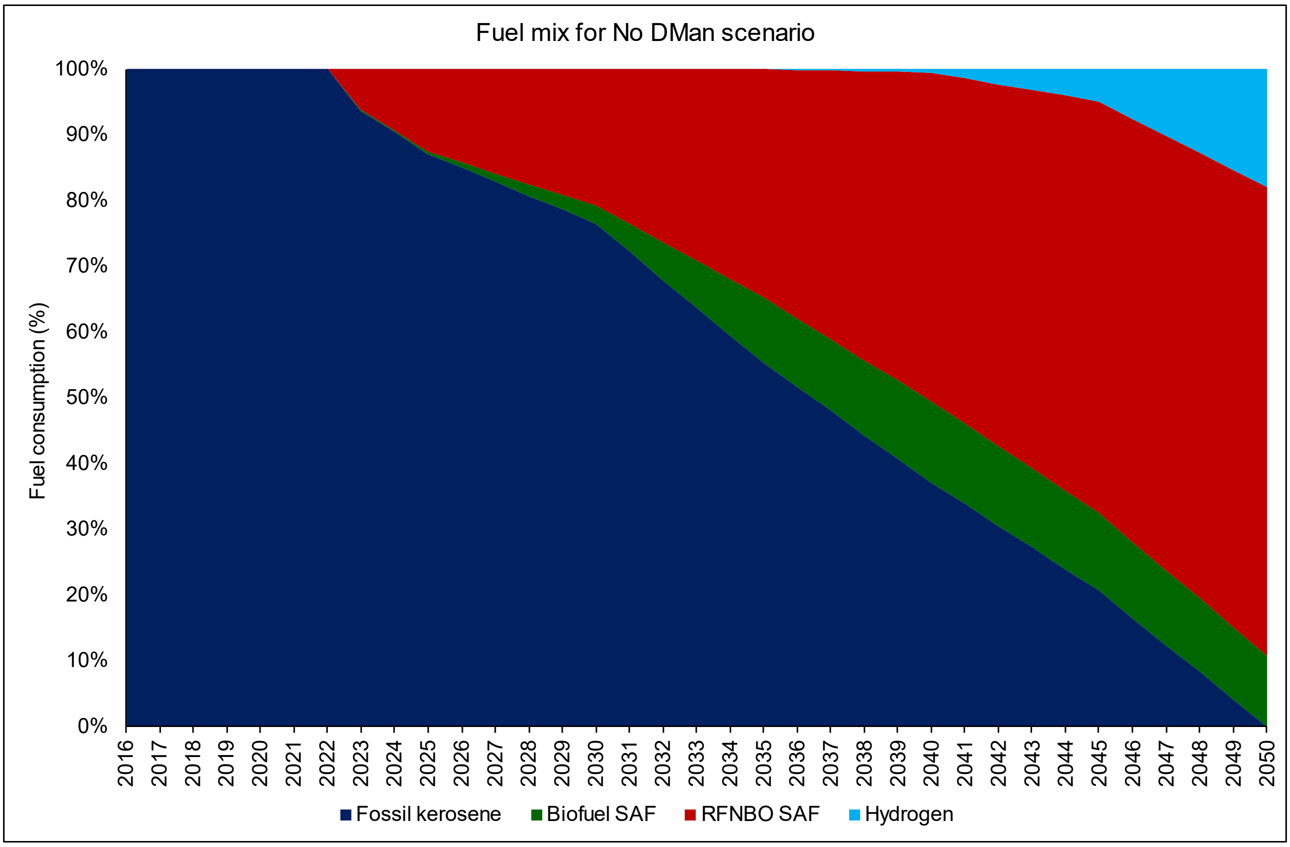
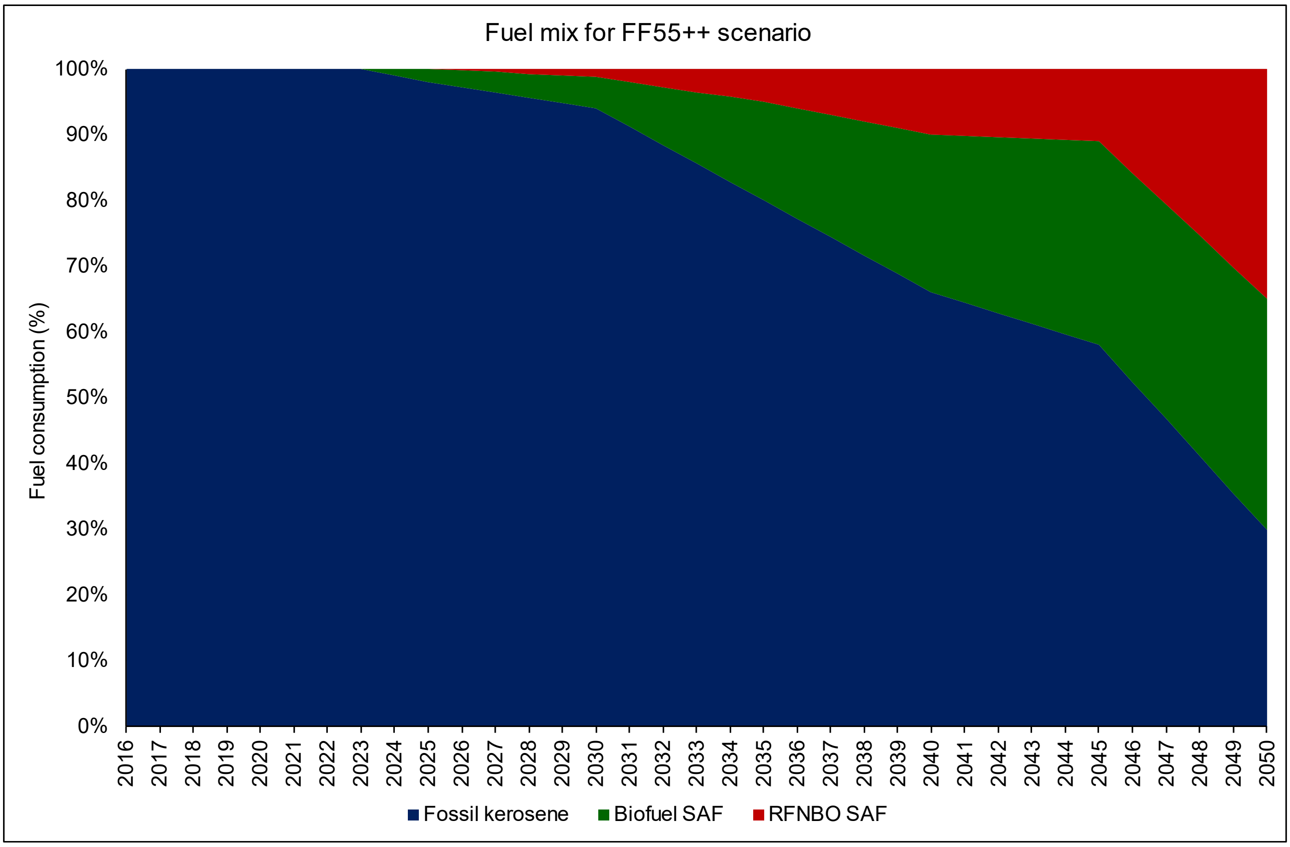
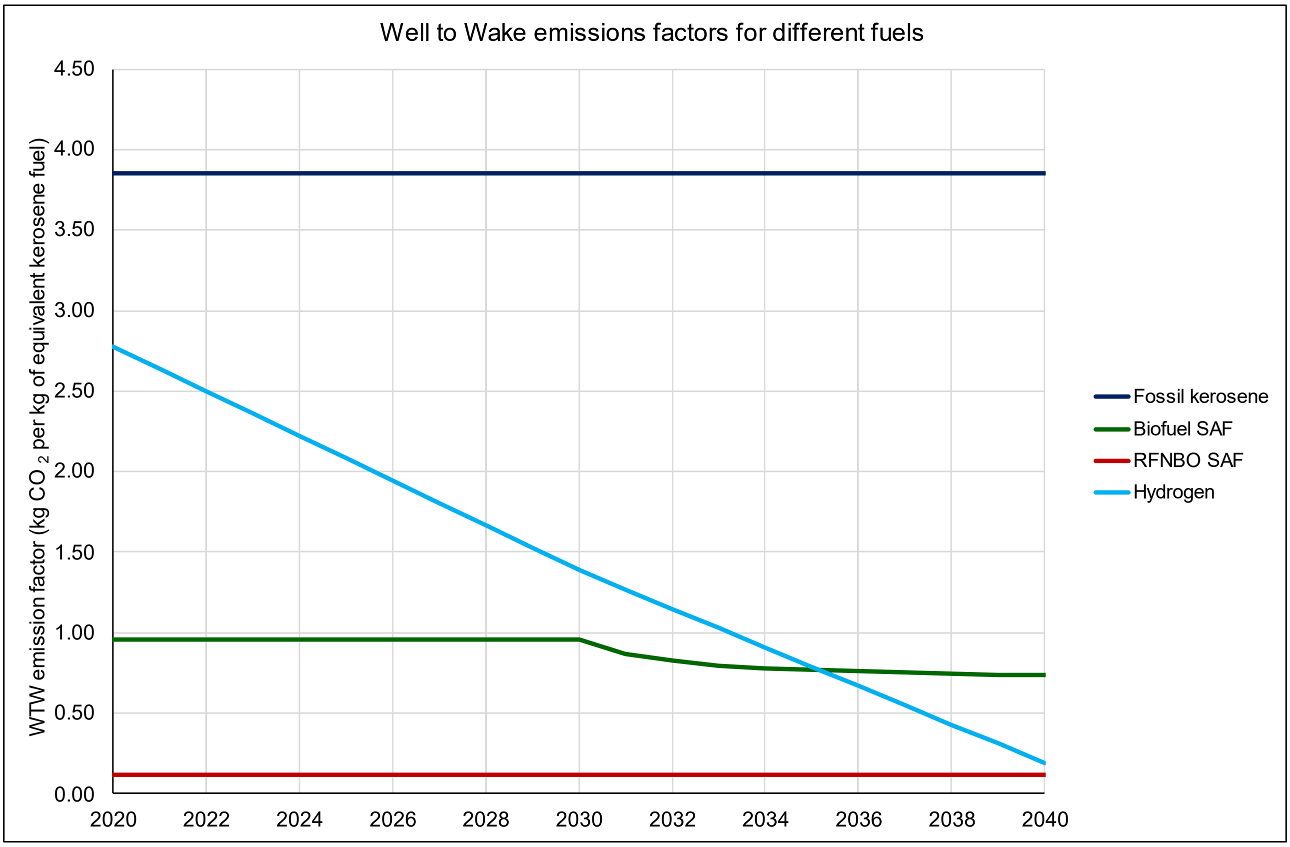


Figure 5-7: Fuel mix under Scenario 3 (FF55++)



As described above, the definition of the No DMan scenario was based on an increased use of RFNBO to deliver the same emissions as under the (capped demand) DMan scenario. The relevant emissions to consider in this case are “well-to-wake” (WTW) emissions, as the direct emissions in the engine exhaust (“tank-to-wake” or TTW) are the same for drop-in SAF as for fossil kerosene. The emissions reductions associated with SAF occur due to the negative emissions in the production process (due to the capture of atmospheric CO_2 by the plants that ultimately contribute to the biogenic wastes used for the production of SAF). Therefore, a full lifecycle, or WTW, approach to the calculation of emissions is required to capture the impacts of SAF on the total emissions for the aviation sector. Figure 5-8 shows the variations in WTW emissions factors used in these calculations, which were based on those used in the aviation Green Deal study for the European Parliament (Milieu Consulting and Ricardo, 2022).

Figure 5-8: Variations of WTW emissions factors used in emissions calculations



The emissions factors for fossil kerosene and biofuel SAF were taken from the ICAO CORSIA default lifecycle emissions values (ICAO, 2022), using the specific SAF types and pathways shown in Table 5-7. None of the pathways used here include any ILUC impacts; significantly higher overall emissions can occur for biofuel pathways that do include ILUC impacts.

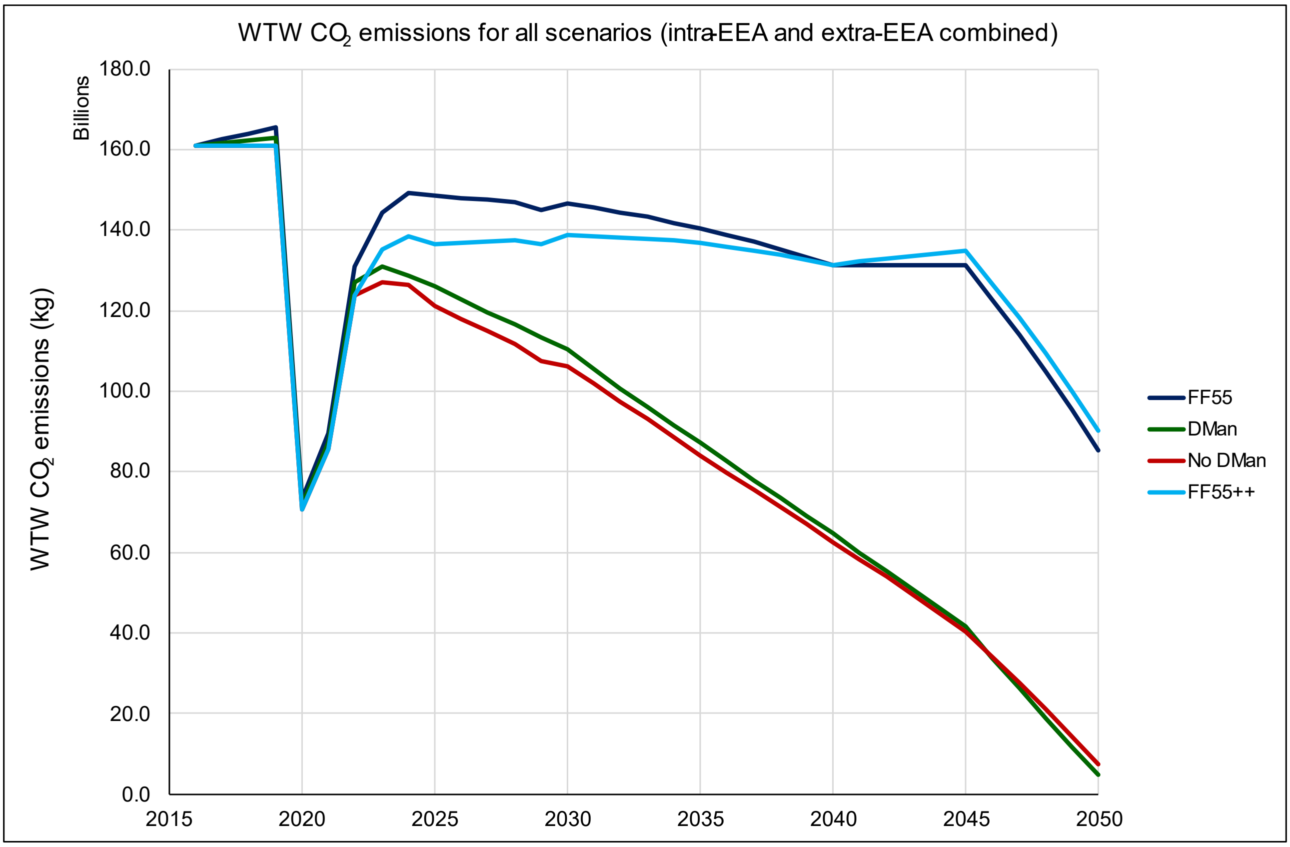
Table 5-7: WTW emissions factors

Pathway	**Feedstock**	**Emissions factor (kgCO$_2$/MJ)**
Conventional kerosene	n/a	89.0
Hydroprocessed Esters and Fatty Acids (HEFA)	Used Cooking Oil	13.9
Biomass Gasification + Fischer Tropsch (FT)	Forestry residues	8.3
Alcohol to Jet (AtJ)	Agricultural residues	23.8

The overall variation of emissions factor for biofuel SAF shown in Figure 5-8 was derived using the individual factors for the three types of biofuel shown in Table 5-7 and their relative proportions taken from the ReFuelEU Aviation Impact Assessment study (European Commission, 2021). The value used for RFNBO SAF applied the emissions reduction of e-diesel relative to conventional diesel (97% reduction) from a Concawe electrofuels study (Yugo & Soler, 2019) to the emissions factor for conventional kerosene. The factor for hydrogen was assumed to be the same as the emissions factor for electricity production (on the assumption that "green" hydrogen can be produced by the electrolysis of water with no additional emissions beyond those to produce the required electricity). These were based on projections to 2030 from the European Environment Agency (European Environment Agency, n.d.) (expressed as emissions per MJ, converted to emissions per equivalent kg of kerosene); the projections were extended to an assumed value of zero by 2050.

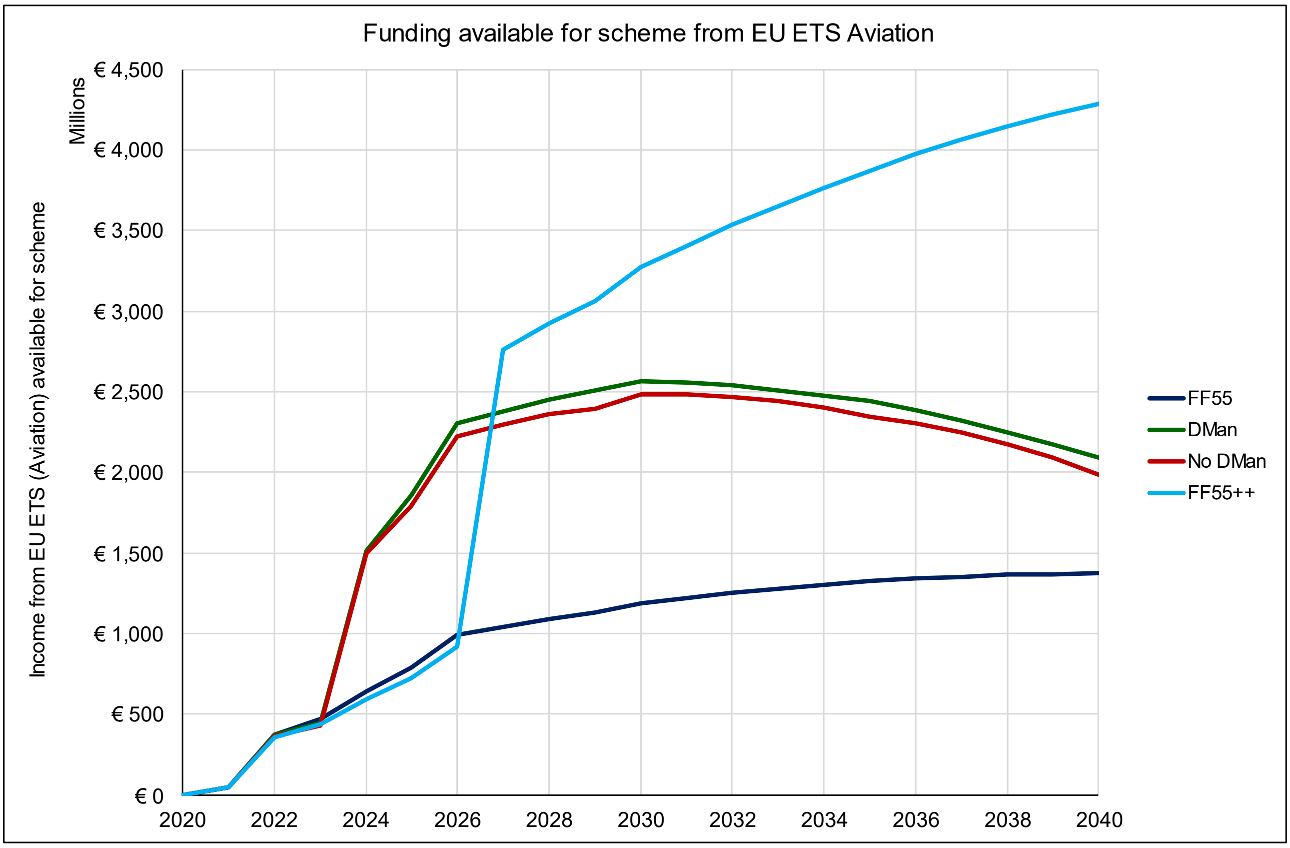
Figure 5-9 compares the calculated WTW emissions distributions for all four scenarios. It can be seen that the derived RFNBO penetration levels for No DMan have delivered very similar emissions (and hence reductions against a baseline) as DMan, in each case approaching zero emissions for the complete EEA aviation sector by 2050. In comparison, the two scenarios based on the ReFuelEU Aviation fuel mix (FF55 and FF55++) deliver emissions reductions of approximately 42% relative to 2019 levels. As shown in Figure 5-3, scenario FF55++ has lower fuel burn than FF55, particularly on extra-EEA flights, showing how the additional policies, in particular the extension of the EU ETS to all departing flights and the implementation of a fuel tax on intra-EEA flights, contributes to achieving the emissions reductions with lower levels of feedstock and energy consumption. This can provide significant advantages, in particular when considered against expected future competition for limited resources such as renewable electricity and green hydrogen.

Figure 5-9: Well-to-wake emissions for all Scenarios



The RFNBO support schemes being discussed in this report are all based on funding being available from EU ETS revenues. The analyses have assumed that 25% of the EU ETS revenues from the aviation sector would be available for this purpose. The revenues under the EU ETS depend on the emissions included which themselves depend on its scope (e.g. whether extra-EEA flights are included, known as "full scope", as under DMan, No DMan and FF55++ scenarios, or not as under FF55), the availability, or otherwise, of free allowances to operators and the proportion of SAF (for which airlines are not required to surrender allowances (i.e. it is "zero-rated") under the EU ETS)[26], which varies by scenario. Figure 5-10 shows the distribution of funding available for the support scheme, covering the period of relevance for the scheme (2025 to 2040).

Figure 5-10: Calculated funding available for RFNBO CfD scheme based on 25% of revenues from EU ETS



As described, the FF55 scenario does not include the extension of the EU ETS to extra-EEA flights, so the revenue collected, and hence the funding available, is significantly lower than under the other scenarios. The FF55++ scenario has the highest funding available (reaching approximately €4.3 billion per annum by 2040); The DMan and No DMan scenarios have very similar levels of funding available, lower than FF55++, as they are defined as having the same WTW emissions, achieved either through reduced demand (for DMan) or increased proportion of RFNBO (exempt from EU ETS) under No DMan. Although the EU ETS revenue is based on TTW emissions, the equivalence of WTW emissions under the two scenarios leads to similar consumption of fossil kerosene and, hence, similar TTW emissions.

The analyses of the ability of the CfD schemes to support the relevant uptake of RFNBO under the different scenarios, described below, are based on two auction periods, running from 2025 to 2034 (inclusive) and 2030 to 2039. In the overlapping period (from 2030 to 2034) it has been assumed that the funding available would be split equally between the two auctions. Table 5-8 shows the total funding available in each auction, and in total from 2025 to 2039, for each scenario.

Table 5-8: Funding available for CfD scheme under each scenario (billion euros)

Auction	FF55	DMan	No DMan	FF55++
Auction 1	€ 8.17	€ 17.83	€ 17.22	€ 19.22
Auction 2	€ 9.88	€ 17.90	€ 17.31	€ 29.11
Total	€ 18.05	€ 35.74	€ 34.52	€ 48.33

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[26] The requirement for airlines to surrender allowances under the EU ETS is based on their CO_2 emissions on relevant flights. These emissions are calculated as TTW emissions, but the lower WTW emissions of SAF are recognised through their associated emissions being excluded from the system.

The analysis of the quantities of RFNBO consumed under the different scenarios, the funding available and the quantity of RFNBO that can be supported under the CfD scheme (or the costs of the scheme in the event that funding available exceeds the cost of supporting all the RFNBO consumed) has considered two cases:

- A “basic scheme”, in which the RFNBO supported is that defined by the scheme (compliance with the relevant mandates for FF55 and FF55++, and those required by the definitions of the DMan and No DMan scenarios). The level of support provided is based on the price difference between RFNBO and biofuel-based SAF. This scheme is based on the existence in ReFuelEU Aviation (or scenario definition for DMan and No DMan) of a binding mandate on the use of RFNBO, which ensures a minimum RFNBO share within the total SAF use. As such, it can be viewed as a scheme in which the costs to airlines of compliance with the minimum RFNBO requirements are minimised, but no additional RFNBO is caused to be consumed. The effective reduction in price for RFNBO is the difference between the actual price and the price of biofuel SAF, equivalent to a price reduction of between 47% (in 2030) and 16% (in 2040).
- A scheme in which all mandated SAF can be RFNBO. The support given is again based on the price difference between RFNBO and biofuel-based SAF. The approach for this scheme is to increase the share of RFNBO within the overall SAF mandate as much as possible using the available funds. This, therefore, leads to the displacement of some, or all, of the biofuel-based SAF by RFNBO.

A further variation on the second scheme has also been included in the analysis. In cases where the funding available exceeds that required to support all mandated SAF being RFNBO, the excess funding is used to support further RFNBO consumption, leading to some displacement of fossil kerosene by RFNBO beyond the total SAF mandated to give the maximum support for RFNBO within the available funds. While the support for the RFNBO that displaces biofuel SAF is based on the price difference between those two fuels, to make the RFNBO competitive with fossil kerosene, the support for the additional displacement of kerosene by RFNBO is based on the price difference between RFNBO and fossil kerosene, also taking account of the additional costs for fossil kerosene (from the ETD and EU ETS) that are not incurred by SAF. Some results for this scheme variant are also included below[27].

The distribution of the quantity of RFNBO consumed on flights departing from EEA airports (and hence eligible for support) under the basic scheme is shown in Figure 5-11.

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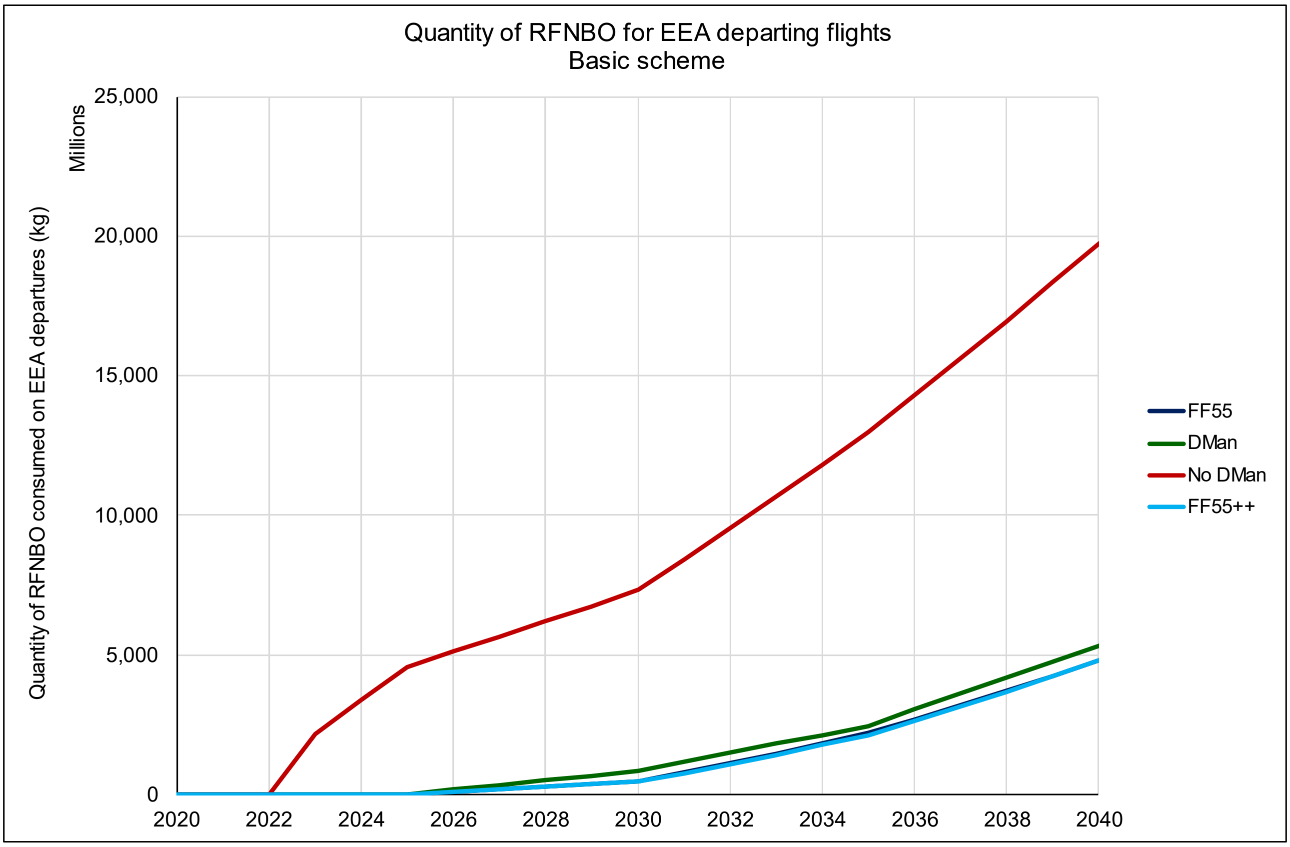
[27] A further option, in which all RFNBO was supported based on the price difference between RFNBO and fossil kerosene, was also considered. However, it was found that the funding available was insufficient to provide support for all SAF to be RFNBO, without any additional displacement of fossil kerosene, under this level of support during the period of the CfD scheme. Therefore, this option was not pursued further.

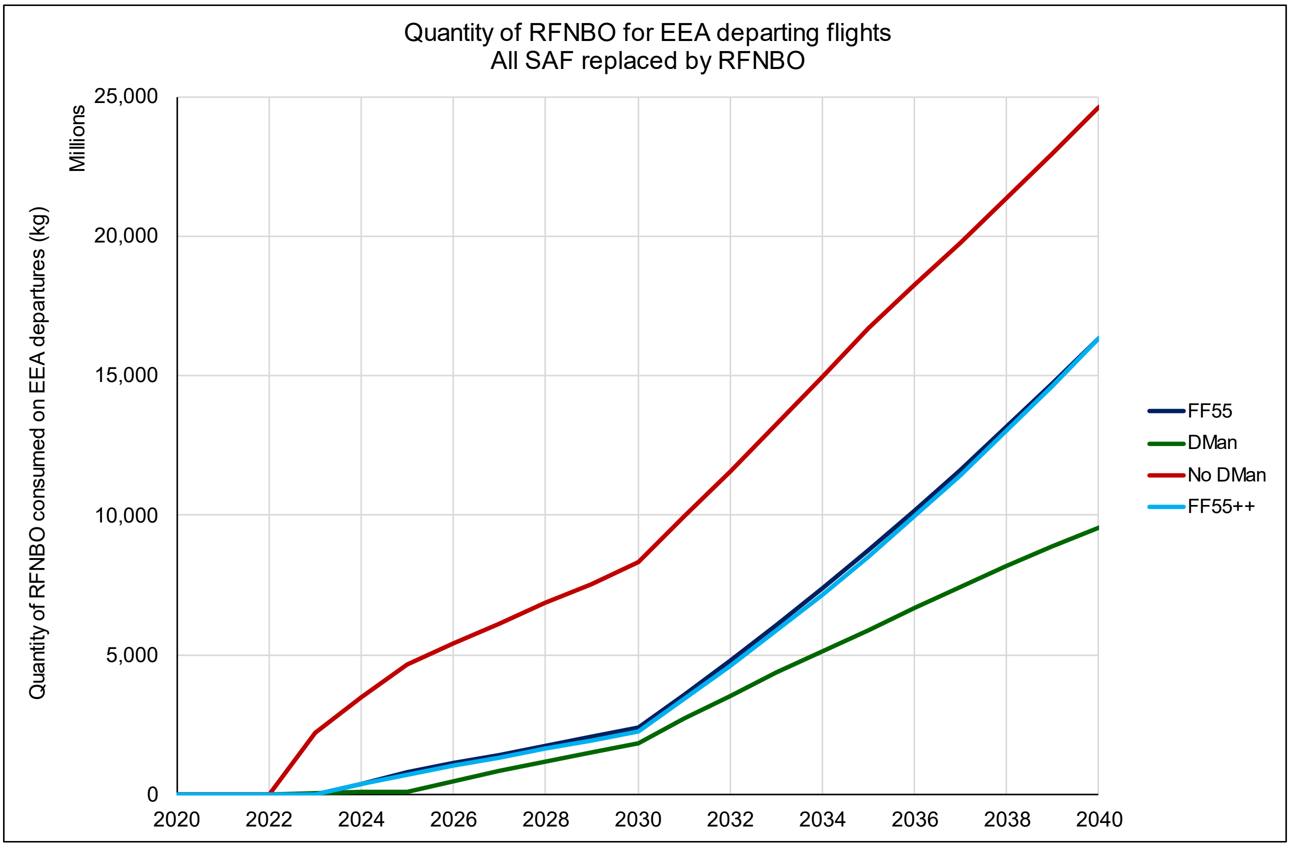
Figure 5-11: Quantity of RFNBO required for EEA aviation under the basic scheme (mandated RFNBO only)



Under the No DMan scenario, with its increased use of RFNBO to achieve the same emissions reductions as DMan, the RFNBO consumption reaches nearly 25 million tonnes by 2040. The consumption under the DMan scenario, with the capped demand, is significantly lower at 5.3 million tonnes, while that for the FF55 and FF55++ scenarios is lower still at just under 5 million tonnes by 2040. Although the total fuel consumption is substantially higher for FF55 and FF55++ than DMan (Figure 5-3), the proportion of RFNBO in the fuel mix for DMan is significantly higher, leading to an overall higher RFNBO consumption.

A similar analysis of the total RFNBO consumption, but for the scheme in which all mandated SAF is RFNBO, is shown in Figure 5-12.

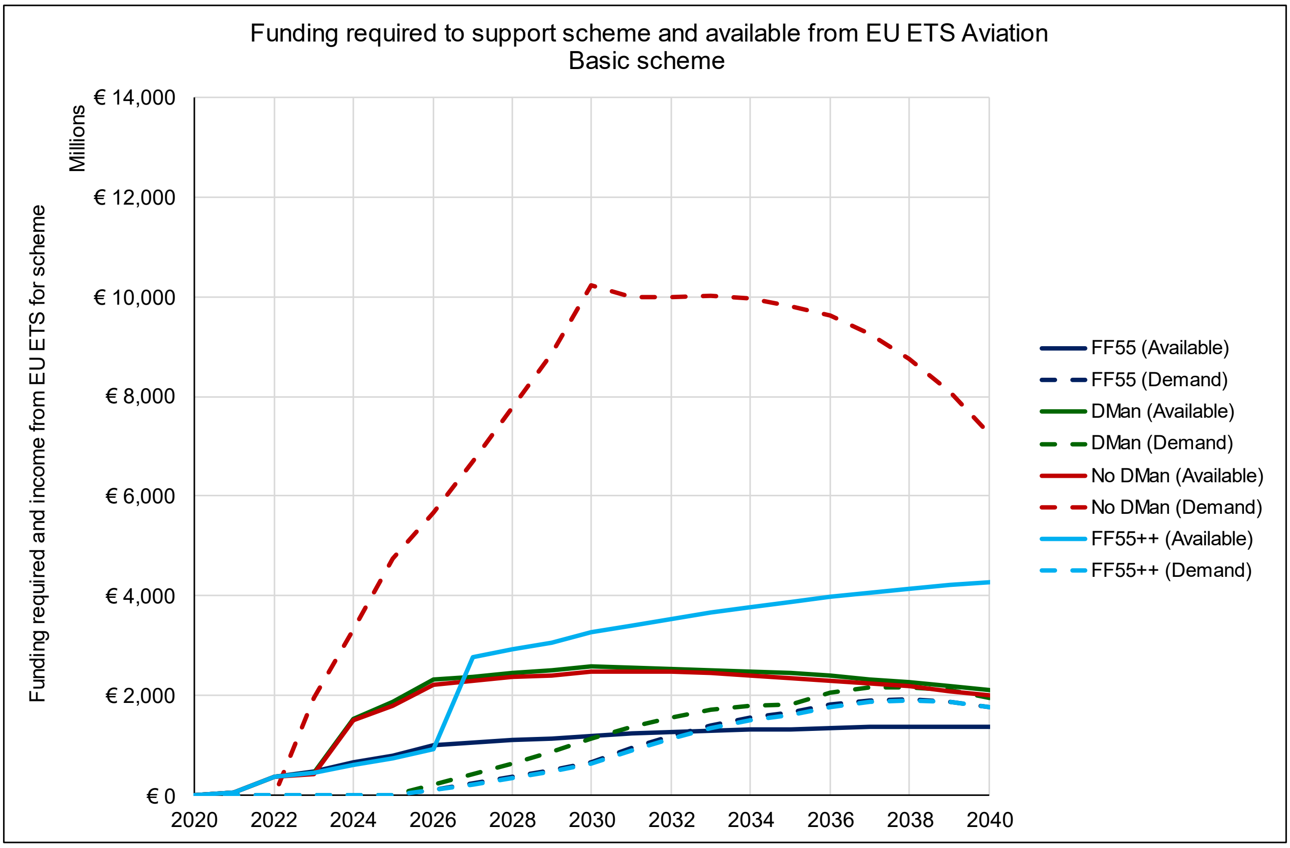
Figure 5-12: Quantity of RFNBO required for EEA aviation if all mandated SAF is RFNBO



The proportion of RFNBO required under the No DMan scenario (to deliver the same emissions reductions as DMan) already substantially exceeds the SAF mandates being considered under the other scenarios; therefore, the results shown for this scenario in Figure 5-12 are no different to those in Figure 5-11. The quantities of RFNBO required under the other three scenarios are increased significantly relative to the case in which only the mandated RFNBO is included. The FF55 and FF55++ scenarios both reach approximately 16 million tonnes by 2040, while DMan reaches nearly 10 million tonnes by the same date.

The quantities of RFNBO used under the different scenarios, as shown in the figures above, have been used to derive the level of funding that would be required for a CfD support scheme on the assumption that all the RFNBO consumption shown would be supported at 100% of the price difference between RFNBO and biofuel-based SAF. The funding available (as shown in Figure 5-10) is then compared with the funding required in Figure 5-13 (for the basic scheme) and Figure 5-14 (for the case with all SAF being RFNBO).

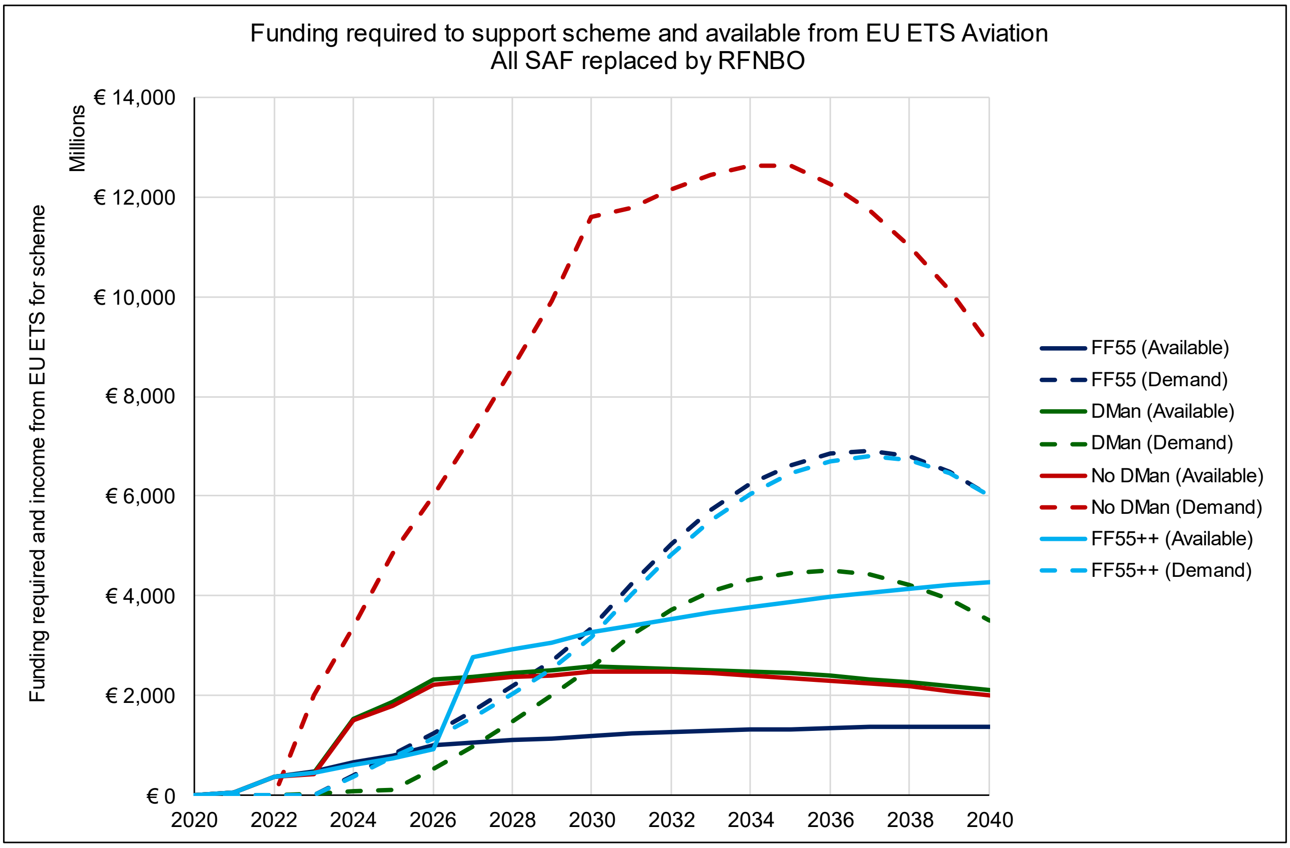
Figure 5-13: Funding available from EU ETS revenues and required to support RFNBO uptake under the basic scheme



In Figure 5-13, the solid lines represent the funding available in each year, while the dashed lines represent the funding that would be required to support all the SAF consumed. The funding required for the FF55 and FF55++ scenarios are almost identical.

Under the FF55 scenario, the funding available exceeds that required by the scheme up to 2031, after which the available funding would be insufficient to support all RFNBO used at 100% of the price difference. Under the FF55++ scenario, the available funding is increased, while that required is essentially the same as under FF55, so all RFNBO consumed could be supported at 100% of the price difference. Although the funding available under the DMan scenario is lower than under FF55++ after 2026, the quantity of RFNBO required is only slightly higher, and all RFNBO required can be funded under the scheme. The higher RFNBO consumption required for the No DMan scenario results in the available funding being insufficient to support all RFNBO consumed in all years of the proposed scheme.

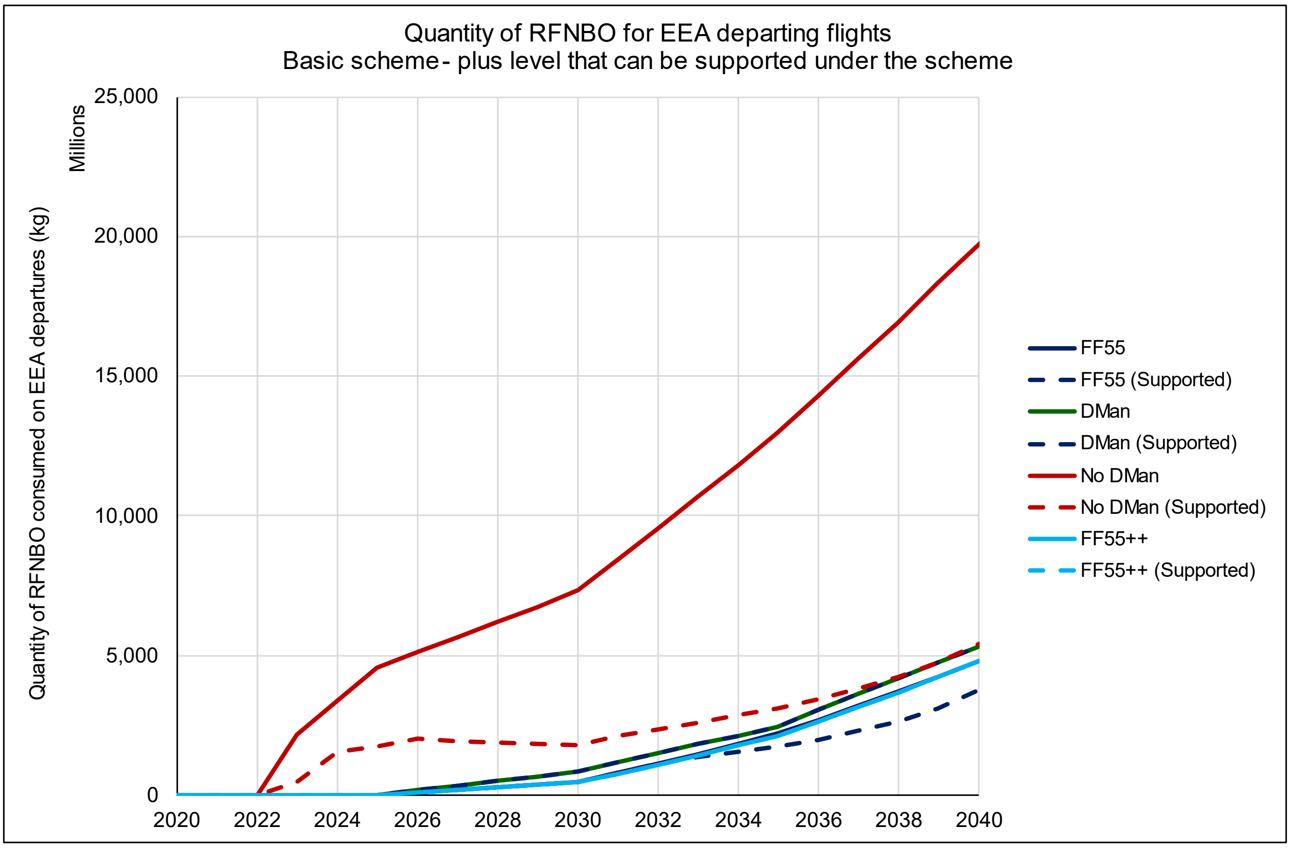
Figure 5-14: Funding available from EU ETS revenues and required to support RFNBO uptake if all SAF is RFNBO



Under the case where the aim is to support all mandated SAF to be RFNBO, the costs of the support are increased for all scenarios except No DMan. Under the FF55 scenario, the costs of the scheme exceed the available funding before 2025 (i.e., before the CfD auctions would commence), while for the DMan and FF55++ scenarios, this occurs by 2030.

From the previous two figures, it can be seen that the ability to support RFNBO use by a CfD scheme (based on 100% of the price difference between RFNBO and biofuel-based SAF) is limited when the aim is to reduce the costs of compliance with the RFNBO mandates in force, and very limited in the case where the aim is to increase the displacement of biofuels by RFNBO through making the latter cost-competitive with the former. Figure 5-15 and Figure 5-16 illustrate the quantities of RFNBO that can be supported under the CfD scheme, compared with the total RFNBO consumed under each scenario.

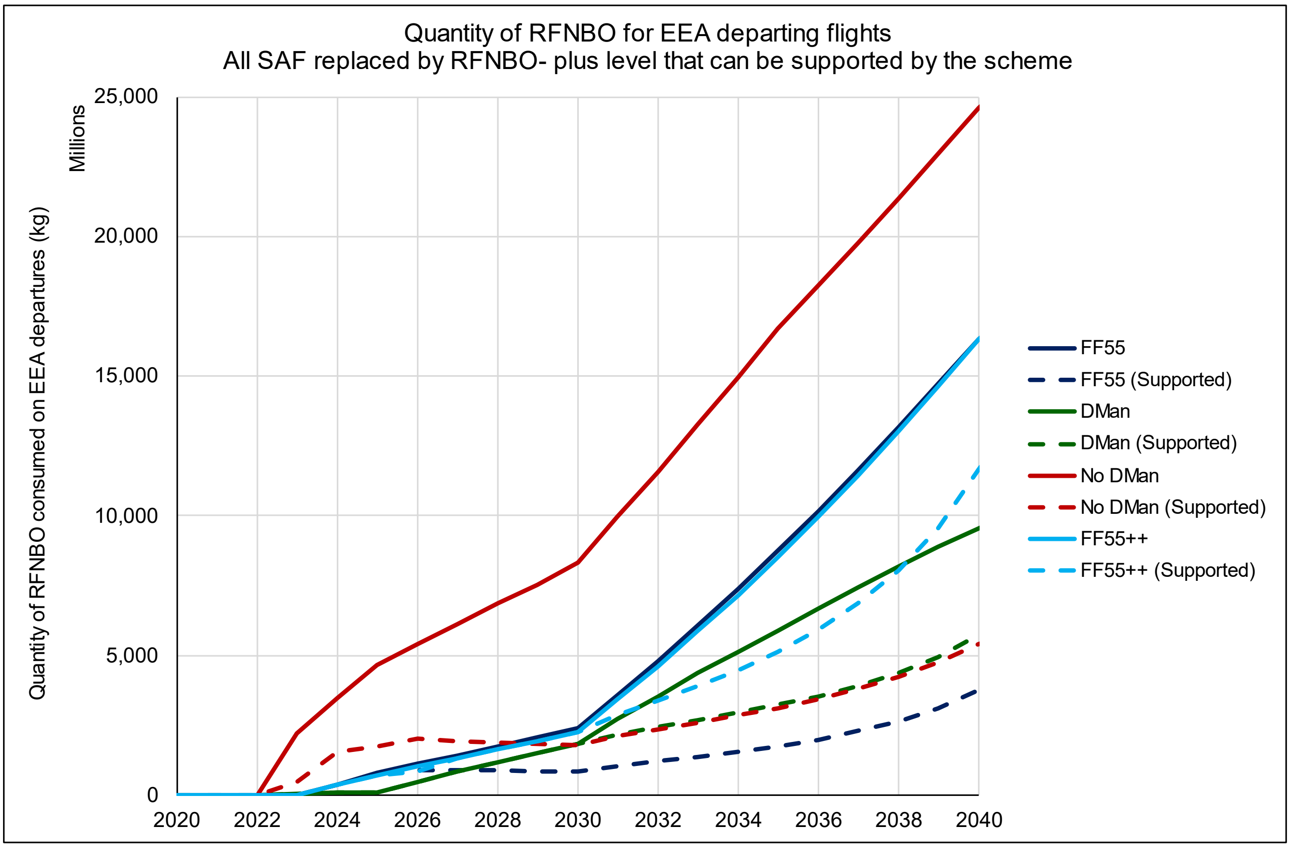
Figure 5-15: Quantity of RFNBO required for basic scheme (mandated RFNBO only) and that which can be supported under the scheme



Under the basic scheme, the funding available is sufficient to cover all RFNBO use under the FF55 scenario up to 2032, after which the quantity that can be supported (the dashed line) starts to diverge from the total use. By 2040, approximately 78% of all RFNBO consumed can be supported under the scheme. Under the DMan and FF55++ scenarios, the funding available is sufficient to support all RFNBO consumed in all years from 2025 to 2040. Under the No DMan scenario, the total consumption of RFNBO is increased substantially, and the funding available is insufficient to support all RFNBO consumed in any year. The quantity that can be supported under the scheme is between 19% and 35% of total consumption, depending on the year..

The above comparisons are based on the assumption that, while the auctions may each last for 10 years, the funding available in each year would be limited to 25% of the revenues from the EU ETS and it would not be possible to carry any excess funding forwards to future years. A different design of the auction scheme, allowing carry over of excess funding to later years, could allow support for increased quantities of RFNBO to be achieved. Over the period 2025 to 2040, the excess funding (if allowed to be carried over to subsequent years) could support an additional 3.2 Million tonnes of RFNBO under the FF55 scenario, corresponding to a 17.9% increase over the quantity supported if carry over is not allowed. Under the DMan scenario, the additional quantity of RFNBO that can be supported would be 12.8 million tonnes (47.3% increase), while under the FF55++ scenario the additional quantity would be 38.1 million tonnes (172.2% increase). Under the No DMan scenario, no additional RFNBO uptake can be supported. Evidently, a significant increase in RFNBO uptake over that mandated under the ReFuelEU Aviation Regulation would be feasible under the FF55 and FF55++ scenarios (and over the specified uptake under the DMan scenario).

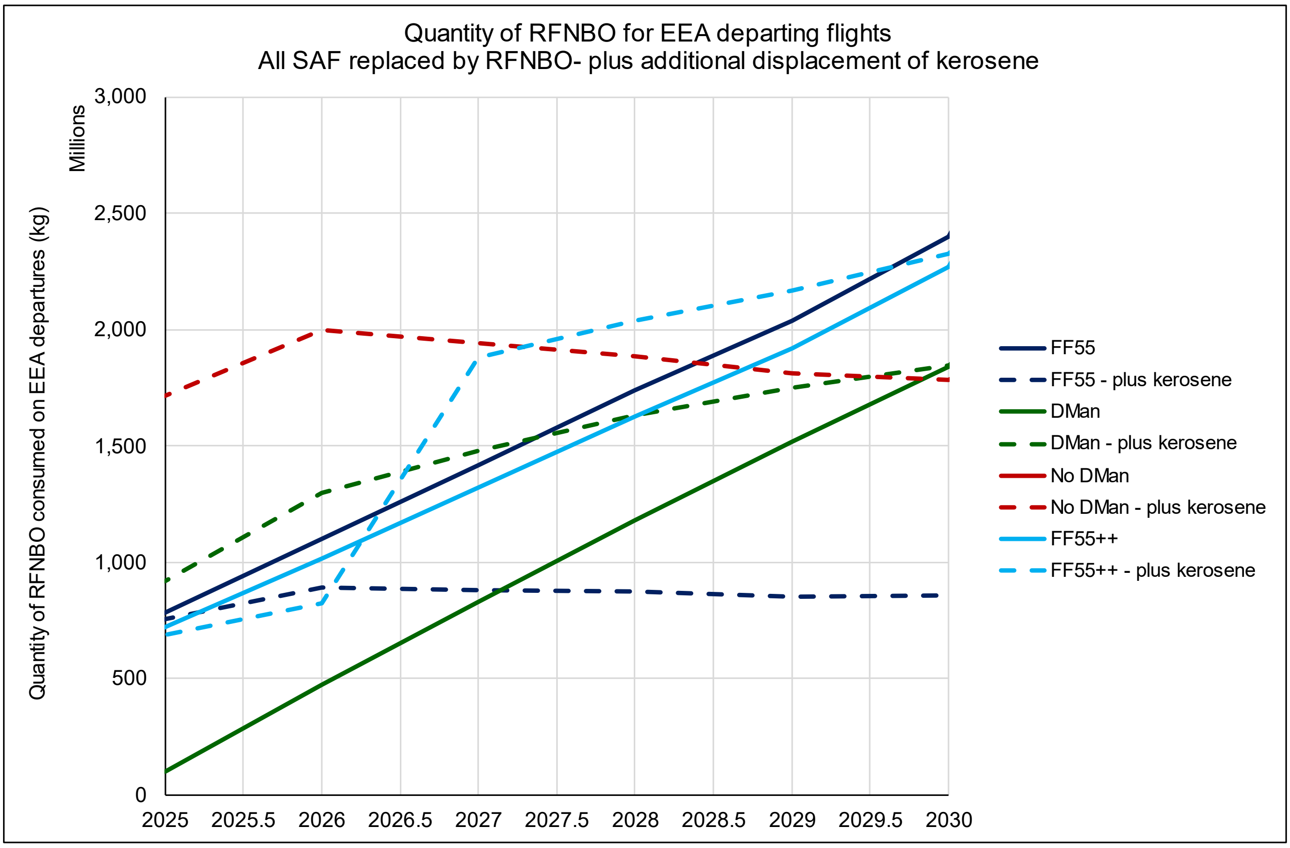
Figure 5-16: Quantity of RFNBO required if all SAF is RFNBO and that which can be supported under the scheme



Under the scheme with all SAF being RFNBO, the quantity of RFNBO consumed is significantly higher (except for the No DMan scenario, as explained previously), with the result that the funding available is insufficient to support all RFNBO consumed under the FF55 scenario from 2025 (the start of the proposed CfD scheme). By 2040, 23% of all RFNBO consumed can be supported (at 100% of the price difference) under this scenario. Under the DMan scenario, the point at which the funding is no longer sufficient to support all RFNBO is delayed to 2030; by 2040, 60% of RFNBO can be supported. The position for No DMan is the same as under the basic scheme, while for FF55++, all RFNBO consumed can be supported up to 2028; by 2040, 71% of all RFNBO consumed can be supported under this scenario.

As noted previously, consideration has also been given to the extent to which the CfD scheme could also support additional RFNBO uptake, leading to displacement of fossil kerosene beyond the mandated total SAF level. As expected from Figure 5-16, the ability to do so is limited to the early years of the scheme. Figure 5-17 provides a comparison of the RFNBO consumed is all mandated SAF is RFNBO and the quantity that can be supported under the scheme (with any RFNBO use beyond the SAF mandate being supported at 100% of the price difference between RFNBO and fossil kerosene) focussing on the period from 2025 to 2030. Regions in which the dashed line is above the relevant solid line show where additional RFNBO displacement of fossil kerosene could be supported.

Figure 5-17: Quantity of RFNBO required if all SAF is RFNBO, plus additional displacement of kerosene, and that which can be supported under the scheme



It should be noted that the scale on the vertical axis in Figure 5-17 is such that the solid red line (consumption of RFNBO for No DMan) is above the axis maximum and hence does not appear on the chart. For DMan, an additional 818 million kg (818 thousand tonnes) of RFNBO could be supported in 2025, displacing an equivalent quantity of fossil kerosene. This quantity that can be supported reduces over time, reaching zero by 2030. Under the FF55++ scenario, the scheme is not able to support additional RFNBO until 2027, when 558 thousand tonnes of RFNBO can be supported; again, it reduces over time, reaching zero by 2030.

The scheme under which all supported to be RFNBO (including additional displacement of fossil kerosene when feasible) uses all available funding in year and, as such, essentially captures the same use of the funds as was described above as the use of excess funding under the basic scheme by allowing carry over. Therefore, under this funding scheme, there is no need to allow for carry over of excess funds.

5.2.2 Maritime

The methodological approach to building the maritime model differs from the aviation model as there was no comparative software to AERO-MS available for use in this study. The approach taken instead looks to build up the picture of current and expected fuel use from the present through to 2050 and apply this to the expected fuel uptake scenarios as defined in the scenarios presented in Table 5-3. The starting point for the model was to obtain data on the global shipping fleet, this was supplied by DNV (Ricardo & DNV, 2022) and contains a breakdown of activity (Gt-miles/yr) per year for different vessel types. Vessel types include crude oil tankers, oil tankers, gas carriers, bulk carriers, container ships and other cargo vessels. From this dataset of historic and predicted global activity EU activity was estimated. This was conducted by comparing the total emissions from the EU maritime sector (Fourth Annual Report from the EC on CO_2 emissions from Maritime Transport) to global maritime emissions. Emission from EU activity equates for between 15-21% based on recent historic data (between 2018-2021) and an average of this value was used within the model.

The activity was then converted to annual fuel consumption per vessel type using a weighted average fuel consumption. From past Ricardo work for Concawe various fuel consumption data for different vessel types and sizes was collected. The weighting was based upon the number of vessels in service of each size, each with a respective fuel consumption. The annual fuel consumption was then converted to an annual energy requirement to carry out the required level of activity based upon a fuel's specific energy properties (Table 5-9).

Table 5-9: Summary of marine fuel properties

Value	HFO	FAME	e-diesel	LNG	Bio-LNG	e-LNG	Bio-Methanol	e-Methanol	e-Ammonia
Specific energy (MJ/kg)	40.9	37.1	43.2	48.6	48.6	48.6	19.9	19.9	23
Density (kg/m3)	991	880	846	428	428	428	791	791	696

**Specific energy obtained from the Engineering Toolbox 'Fuels – Higher and Lower Calorific Values'*
***FAME density from ETIP Bioenergy factor sheets*

To account for expected improvement in emission intensity of fuels over time Ricardo sourced data on estimated emission factors for marine fuels to include within the model. This is a key consideration when addressing RFNBOs as the overall emission intensity is largely dictated by the emission intensity of electricity consumption during the step of electrolysing water to produce hydrogen.

Table 5-10: WTW emission factor for fuel types per year (gCO_2e/MJ)

Year	HFO	FAME	e-diesel	LNG	Bio-LNG	e-LNG	Bio-Methanol	e-Methanol	e-Ammonia
2020	96	13.8	5.76	84.5	29.3	11.9	12.6	1.1	1.4
2025	96	13.8	5.46	79.2	21	11.6	10.4	0.8	1
2030	96	13.8	5.25	78	16.9	11.4	8.4	0.5	0.7
2035	96	13.8	5.1	77.9	13.9	11.3	6.6	0.4	0.5
2040	96	13.8	5.0	77.8	11.1	11.2	4.8	0.3	0.3
2045	96	13.8	4.93	76.7	7.3	11.1	3	0.2	0.2
2050	96	13.8	4.88	76.7	4.7	11.1	1.3	0.1	0.2

**All emission factors were obtained from the MMMCZCS position paper on WTW emission for marine fuels*

Under each of the examined scenarios exists expected fuel uptake values per year. This data was provided by T&E from a previous model (Transport & Environment, 2023) and serves as an input value to this work. Data was provided in 5-year intervals which Ricardo linearly interpolated to provide granularity on an annual basis. The fuel uptake values are shown in Figure 5-18 and Figure 5-19. The uptake scenarios for FEUM + efficiency and DE_DK + efficiency are identical to their respective base cases with the only difference being the level of energy efficiency improvements in these scenarios. This has the effect of reducing the overall fuel consumption in each of these scenarios, leading to lower costs of fuel required.

Figure 5-18: Fuel uptake under FEUM scenario

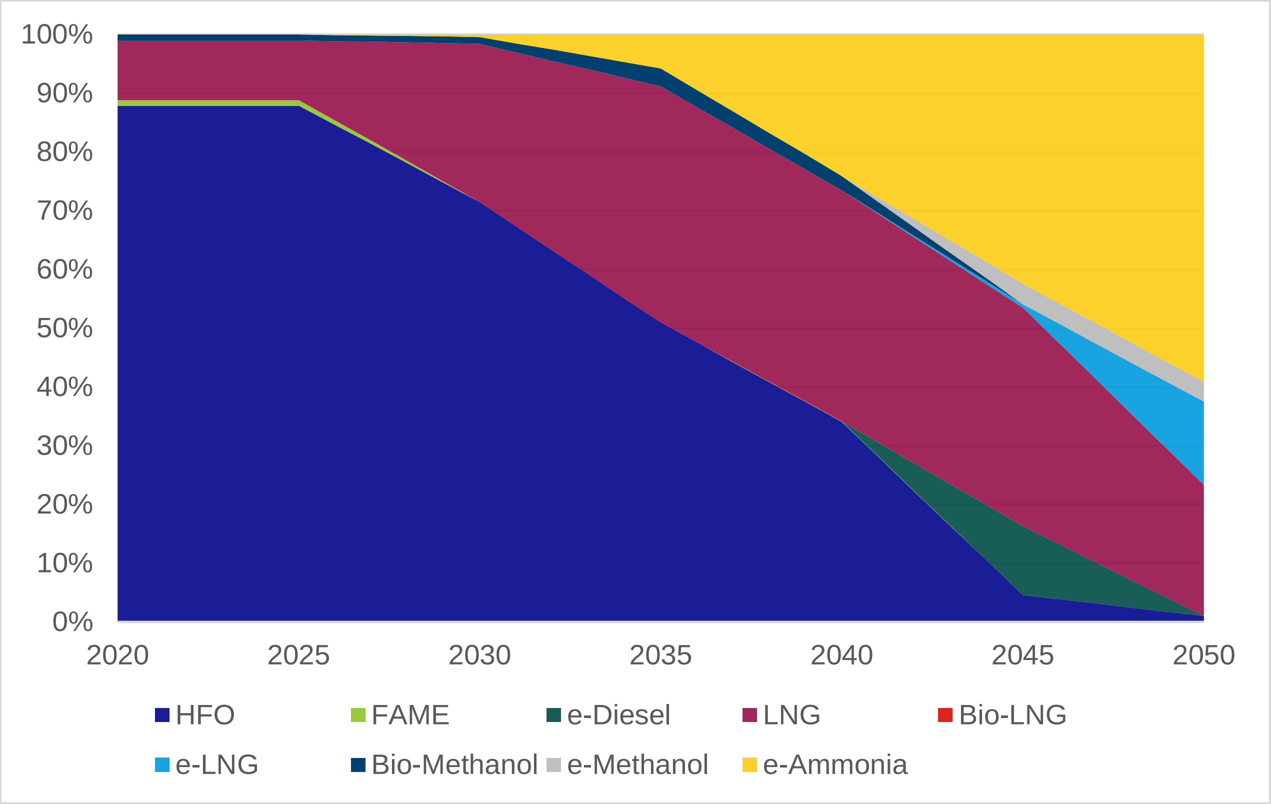
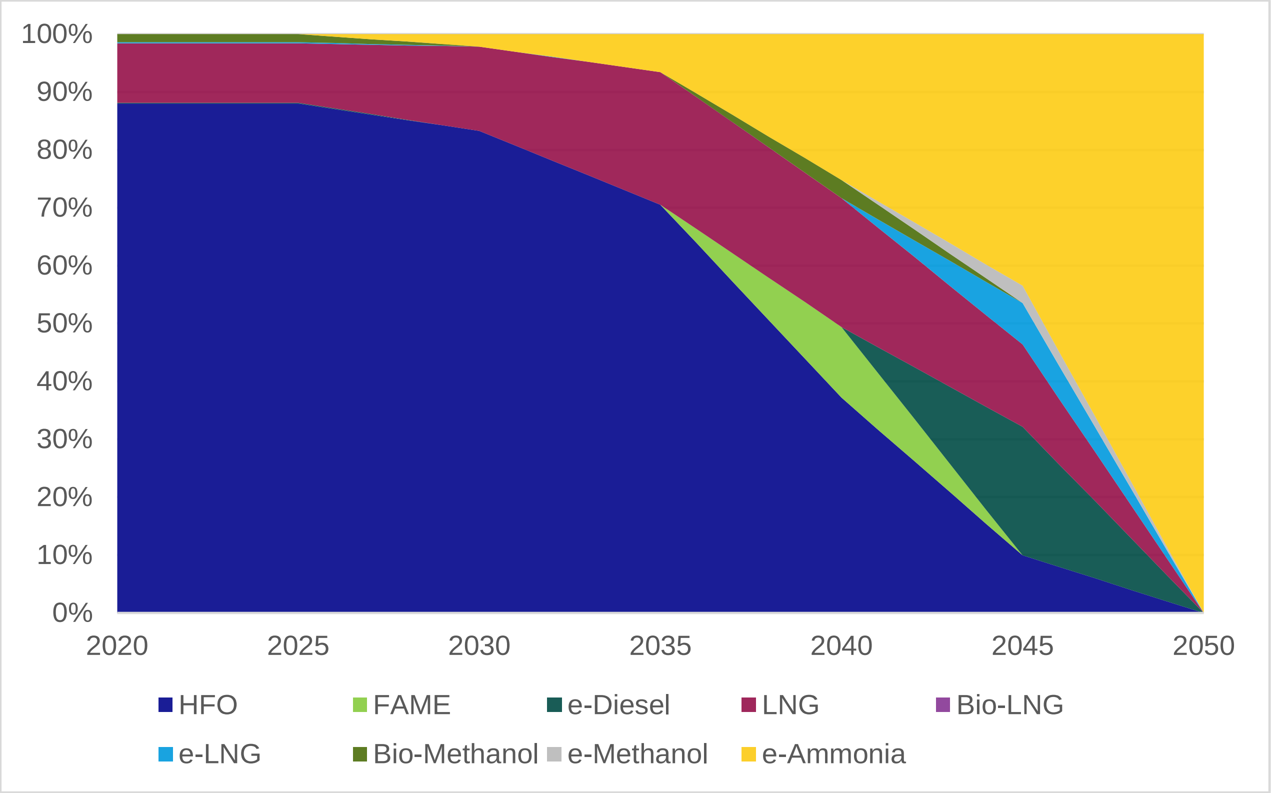


Figure 5-19: Fuel uptake under DE_DK scenario



These uptake scenarios combined with the energy requirements and fuel cost form the basis of the maritime model. Figure 5-20 shows the total cost of fuel estimated to be consumed in the maritime sector based upon the expected fuel uptake scenarios. It is the expectation that the DE_DK scenario is more expensive owing to the higher volume of more expensive RFNBOs consumed over time which is confirmed in Figure 5-20 although there is a brief period where the FEUM scenario is marginally more expensive. The cost of implementation of the DE_DK scenario is driven by the higher RFNBO sub-targets and, as RFNBOs are more expensive than fossil and biofuels, this scenario is more costly. Table 5-11 shows a breakdown in the uptake of fossil, bio and e-fuels over time per scenario.

Table 5-11: Split of fossil, biofuel and RFNBO over time

Year	**FEUM**			**DE_DK**		
	Fossil	Biofuel	RFNBO	Fossil	Biofuel	RFNBO
2020	98.1%	1.9%	0%	98.2%	1.5%	0.2%
2025	98.1%	1.9%	0%	98.2%	1.5%	0.2%
2030	98.4%	1.2%	0.4%	97.8%	0%	2.2%
2035	91.2%	3.1%	5.8%	93.5%	0%	6.5%
2040	73.4%	2.5%	24.1%	59.4%	15.4%	25.2%
2045	41.8%	0%	58.2%	24.1%	0%	75.9%
2050	23.4%	0%	76.6%	0%	0%	100%

Without any form of intervention, the cost involved with implementing the fuel uptake scenarios, on a European level, is outlined in both Figure 5-20 (per year) and Figure 5-21(cumulatively).

Figure 5-20: Annual cost of total fuel consumption in Europe by scenario during proposed auction periods

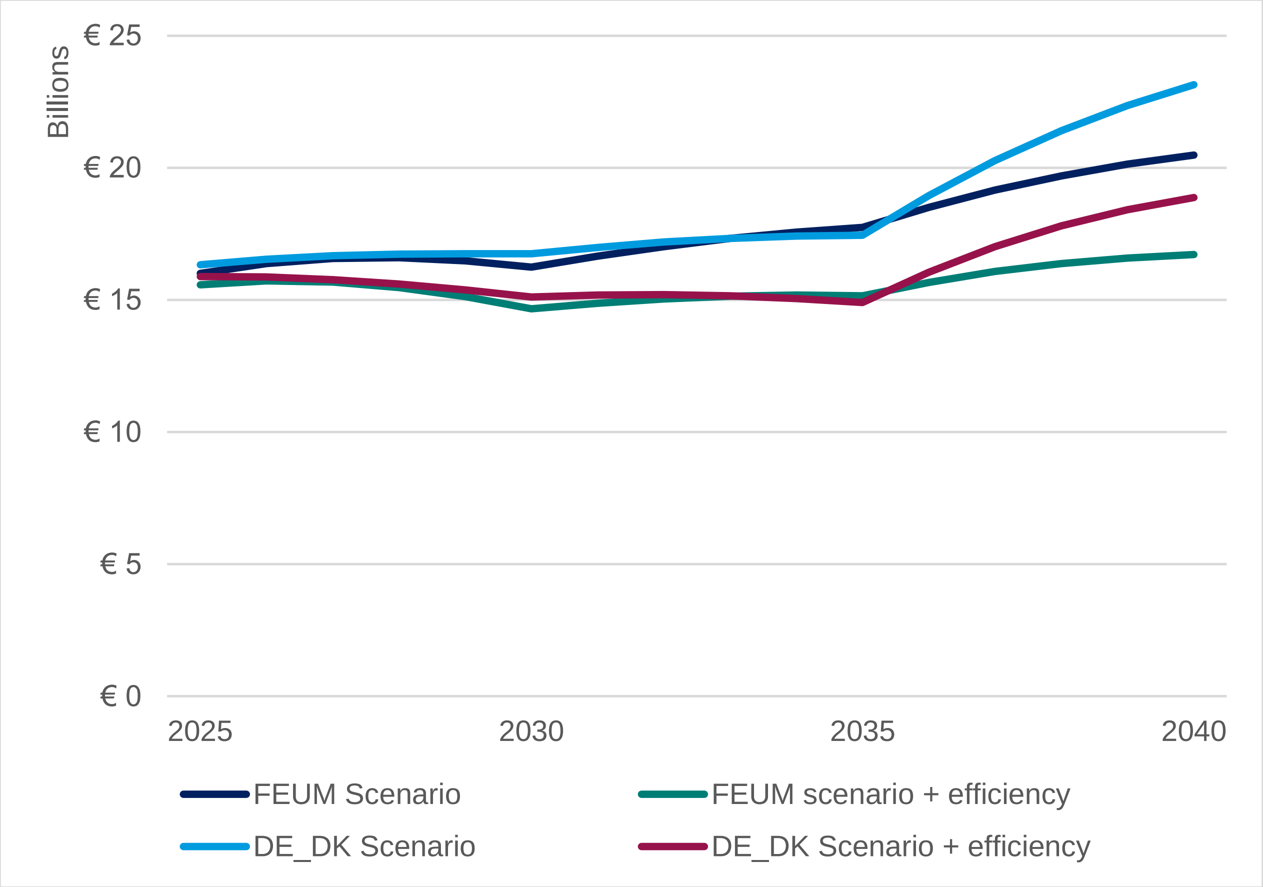


Figure 5-21: Cumulative cost of fuel uptake in Europe per scenario during proposed auction period

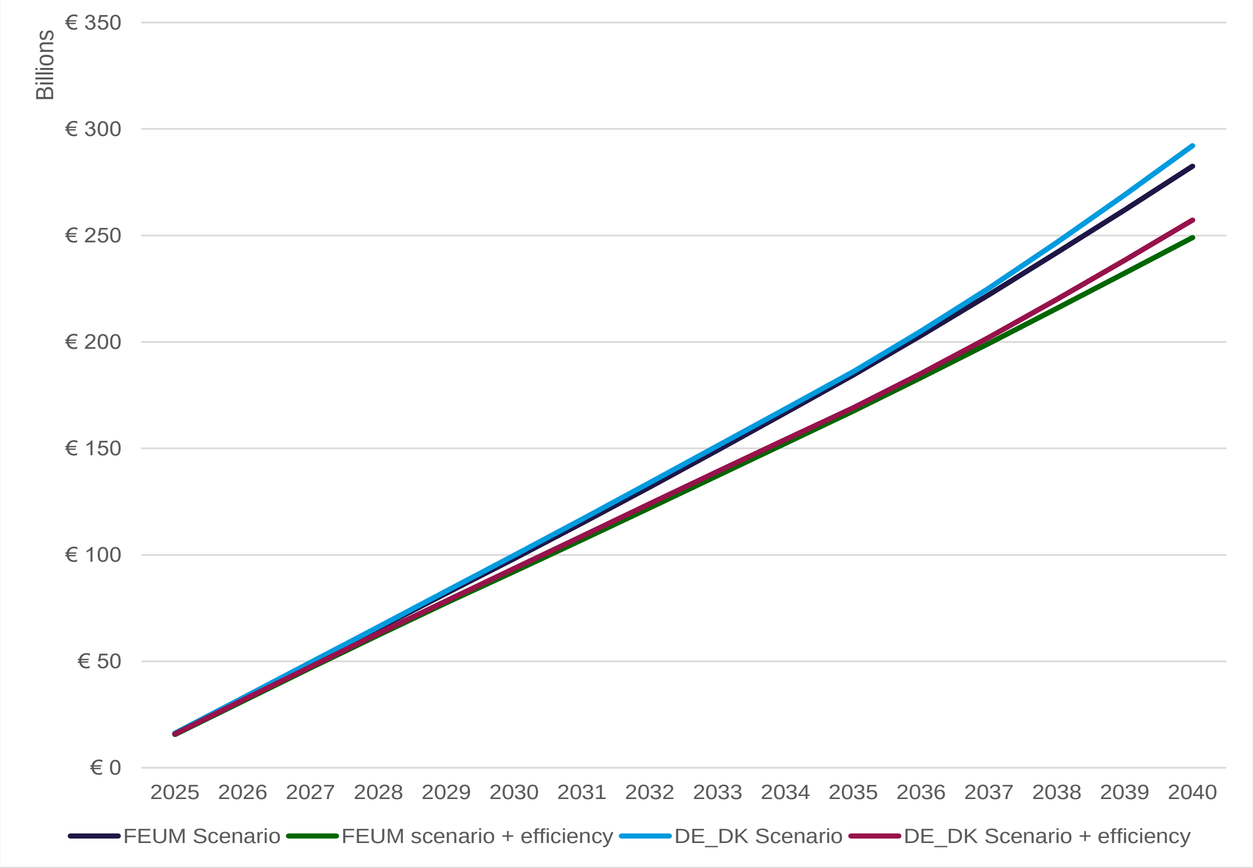


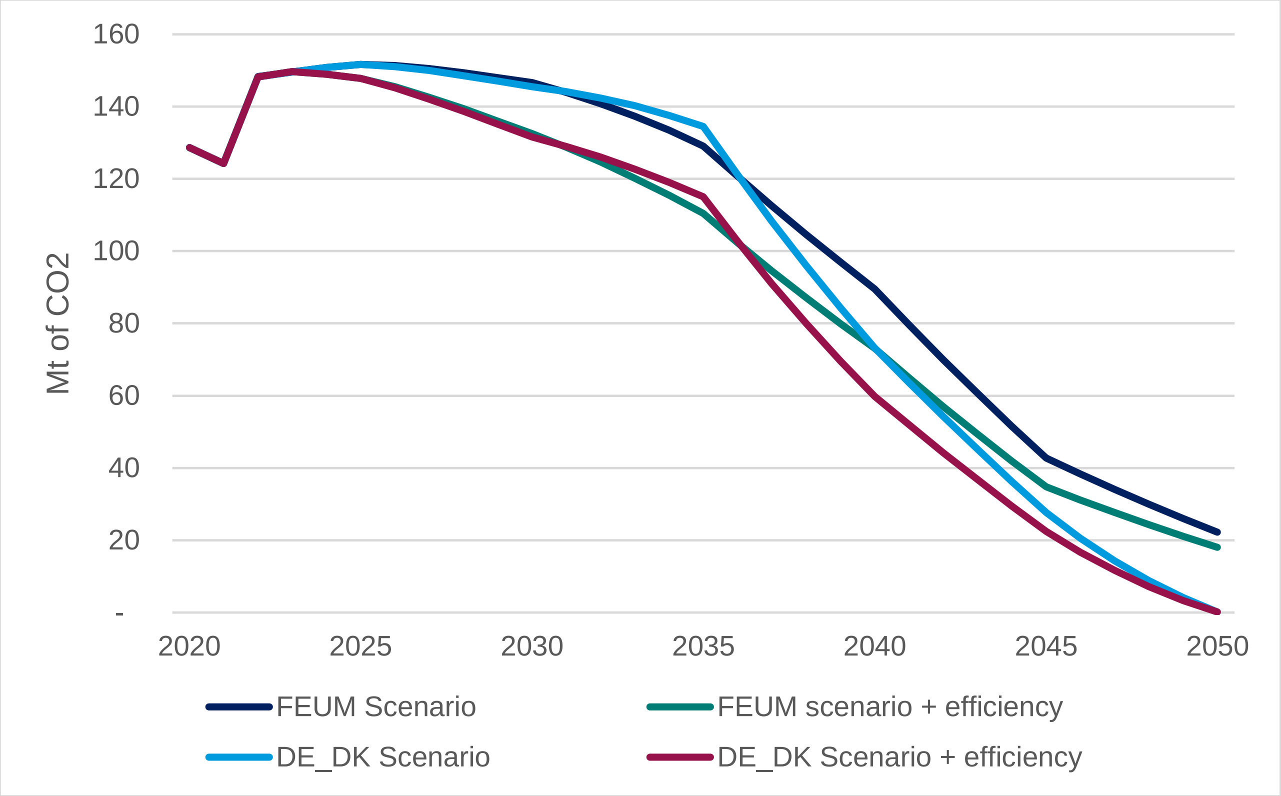
Figure 5-22 shows the total WTW emissions per scenario based on the expected fuel uptake levels. To calculate the total emissions associated with European shipping for the years 2017-2021 Ricardo took historical data from the Fourth Annual CO_2 report for Maritime. From 2021 onwards an assumption was made that European contribution to global shipping emissions does not change and an average value was taken forward.

Table 5-12: European contribution to global shipping emissions

Year	European share of global emissions
2017	21%
2018	19%
2019	19%
2020	16%
2021	15%
2022 onwards	18%

It was noted that in the FEUM and DE_DK scenarios emissions are not expected to peak until 2026 whereas in the scenario with additional efficiency the peak is expected to happen in 2023 (unlikely to be realistic). An interesting observation from this modelling work shows that none of the modelled scenarios are currently aligned to the recent IMO objectives to achieve a 20% reduction (striving for 30%) by 2030 or 70% reduction (striving for 80%) by 2040 (IMO, 2023b) However, the two DE_DK scenarios do broadly align with the objective to reach net zero on or around 2050. In 2050 within the FEUM scenario and FEUM + efficiency scenario there remains 22m and 18m tonnes CO_2eq respectively.

Figure 5-22: European shipping emissions over time by scenario



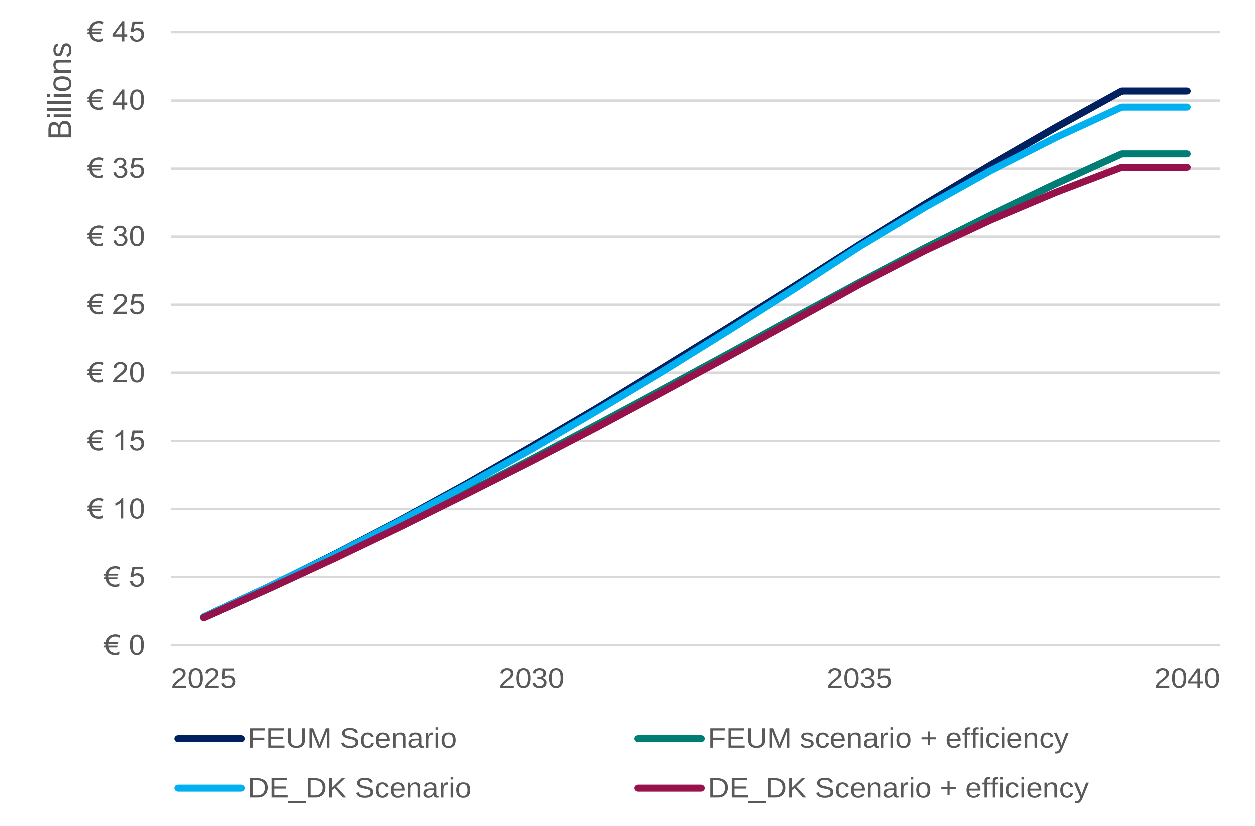
To understand the level of funding available through potential schemes, estimates were developed of the CO_2 emissions generated under each scenario. WTW emissions factors expressed in tCO_{2eq}/GJ (Table 5-10 taken from (Maersk McKinney Moller Center for Zero Carbon Shipping, 2022)) of fuel were combined with the calculated fuel consumption in each scenario. Under the EU ETS voyages starting or ending outside of the EU have 50% of their emissions covered whereas voyages that occur between two EU ports and when ships are in EU ports 100% of emission are covered. To calculate the total volume of emissions that fall within scope of the ETS historical emission data was used (European Commission, 2023f). It was found that the average share of emissions by journey type over 2018-2021 that fell within scope and thus eligible to pay into the ETS was 68% as per Table 5-13.

Table 5-13: Percentage of voyages within scope of the EU ETS weighted by actual emissions

Voyage	2018	2019	2020	2021	Average
Extra-EEA (incoming)	32.7%	31.8%	33.2%	34.9%	33%
Extra-EEA (outgoing)	29.4%	28.9%	30.8%	32.7%	30%
Intra-EEA	32.2%	32.6%	29.7%	26.0%	30%
At berth	5.7%	6.8%	6.3%	6.4%	6%
Share of voyages in scope					**68%**

The TTW emissions generated which are in-scope were combined with projected ETS allowance prices. This enabled the calculation of revenue projections under the schemes, within each scenario. This is displayed in Figure 5-23, showing that during the auction periods a total of between €40-50 billion will be generated under the EU ETS across the different scenarios. For the purpose of the modelling, it was assumed that revenue generated in a given year was utilised within the same year; in practice this may differ from how the CfD scheme would be administered. It was also assumed that in the years where the two CfD auction rounds overlap (2030-2034) the ETS revenue was available for the CfD scheme was capped at 25%. For these years the revenue was split equally over the two auction rounds. The ETS revenue in the model beyond 2039 (end of second auction period) was not considered further during this study but there would be expected further revenue generation, on a decreasing level, beyond this time frame.

Figure 5-23: Cumulative ETS revenue for auction period years (2025-2039)



For the purpose of establishing a CfD scheme, this study explores utilisation of 25% of all available ETS revenue to be available to support RFNBO uptake[28]. As expected, the available revenue from the ETS (at 25%) is not sufficient to fully subsidise the cost differential. This should not be the purpose of the CfD scheme, but it bears for an interesting comparison to show to what extent support could be partially subsidised, under the theory that increased subsidisation will lead to greater uptake. The following graphs for each scenario show the cost of fuel uptake i.e., how much does it cost to purchase fuel under this scenario against the available revenue from the EU ETS at 25% and 100%. This is shown on an annual basis and cumulative basis across the period where the CfD auctions are active. show for each scenario.

In a hypothetical situation, it is observed from Figure 5-24 allocating a greater level of EU ETS revenue to support the uptake of RFNBOs that between the periods 2030 and 2035 could fully subsidise the cost of all European shipping fuel. Practically this would not be implemented but it is interesting to compare the expected levels of EU ETS revenue against the cost of fuel uptake. It should be noted that ETS revenue generation begins before the start of the first CfD auction in 2025. From 1 Jan 2024 ships above 5,000 GT onwards must acquire and surrender allowances as defined in Section 3.1.2.

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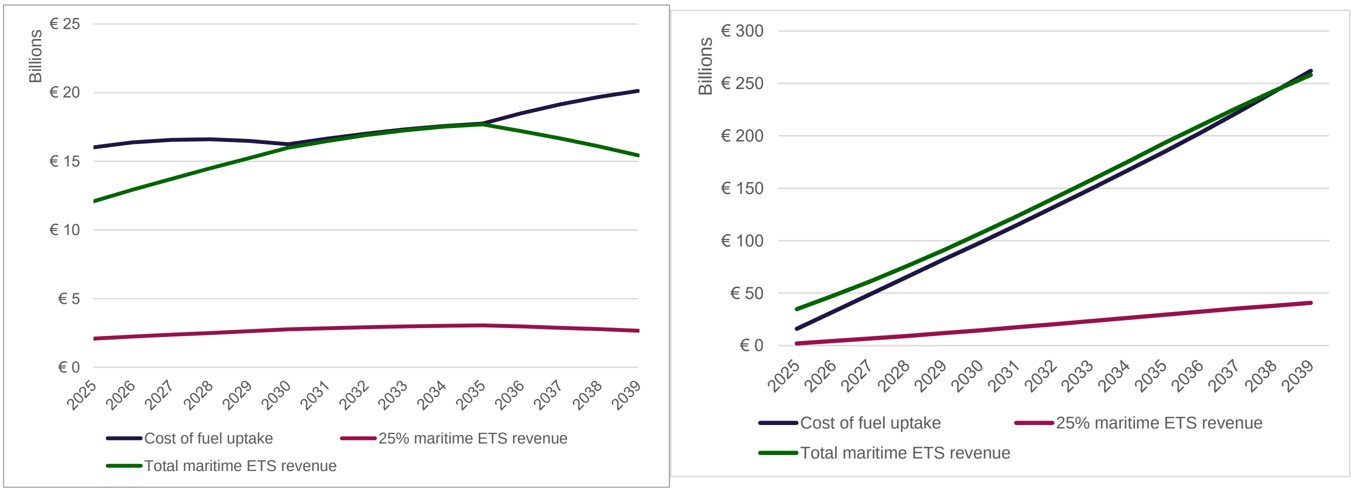
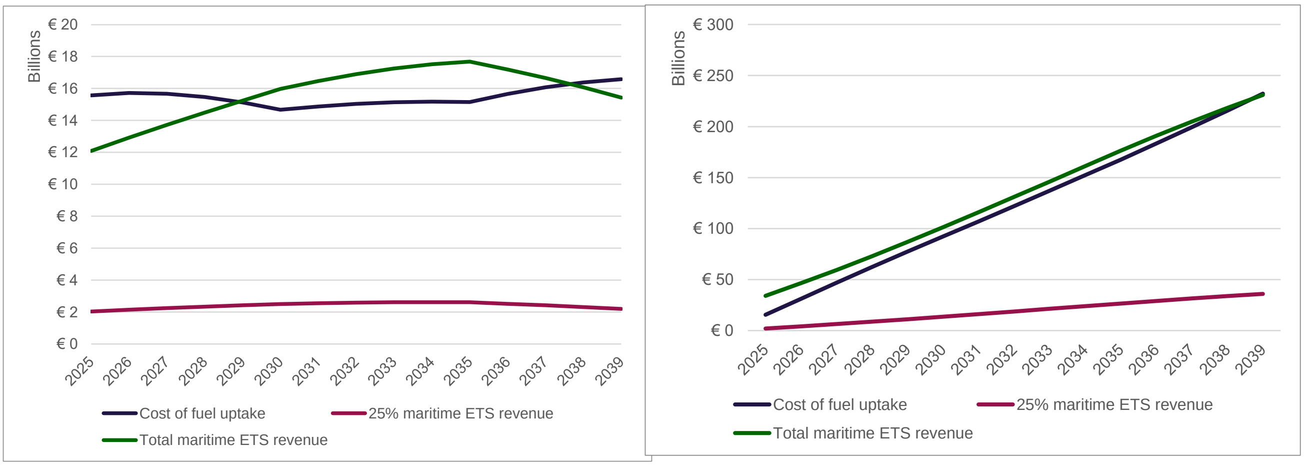
[28] For the purposes of this study, 25% of ETS revenue usage was explored at the request of T&E.

Figure 5-24: Allocation of ETS revenue during auction period FEUM scenario (annual left and cumulative right)



A similar trend is observed for the FEUM scenario with additional efficiency measures noting that the overall cost of fuel uptake in this scenario is less as the added measures reduce the total expected fuel consumption.

Figure 5-25: Allocation of ETS revenue during auction period FEUM + efficiency improvements scenario (annual left and cumulative right)



For both the DE_DK and DE_DK + efficiency scenarios the same observations are made. However, in these scenarios the periods where 100% of ETS revenue could theoretically subsidise the entirety of fuel uptake is between 2033 and 2035.

Figure 5-26: Allocation of ETS revenue during auction period DE_DK scenario (annual left and cumulative right)

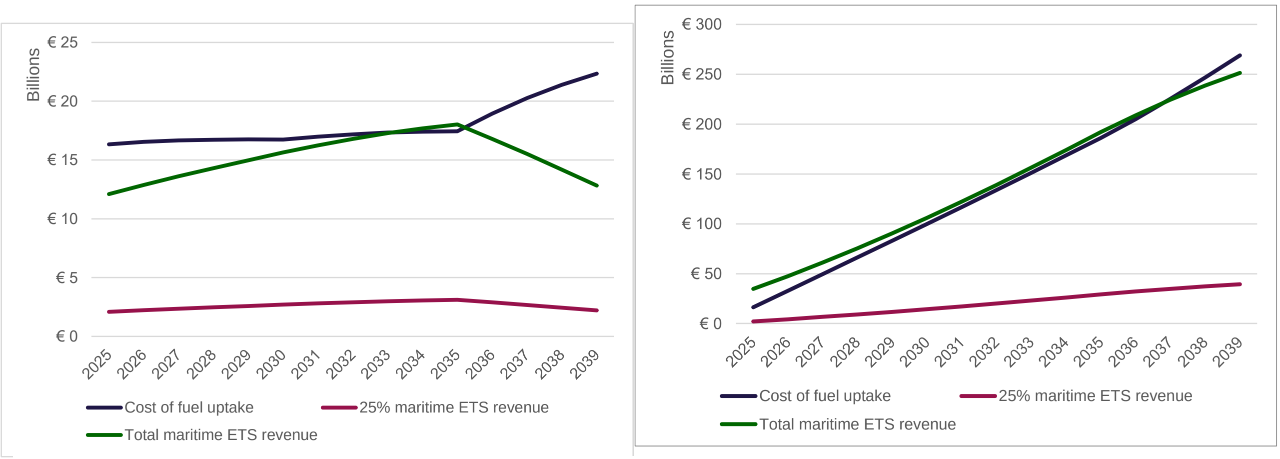


Figure 5-27: Allocation of ETS revenue during auction period DE_DK + efficiency improvements scenario (annual left and cumulative right)

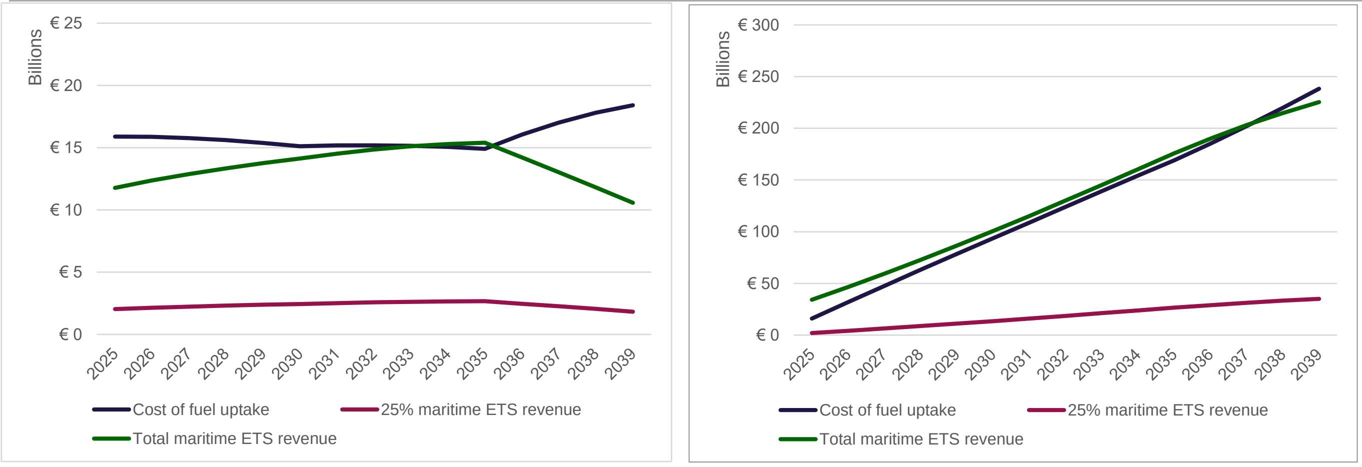
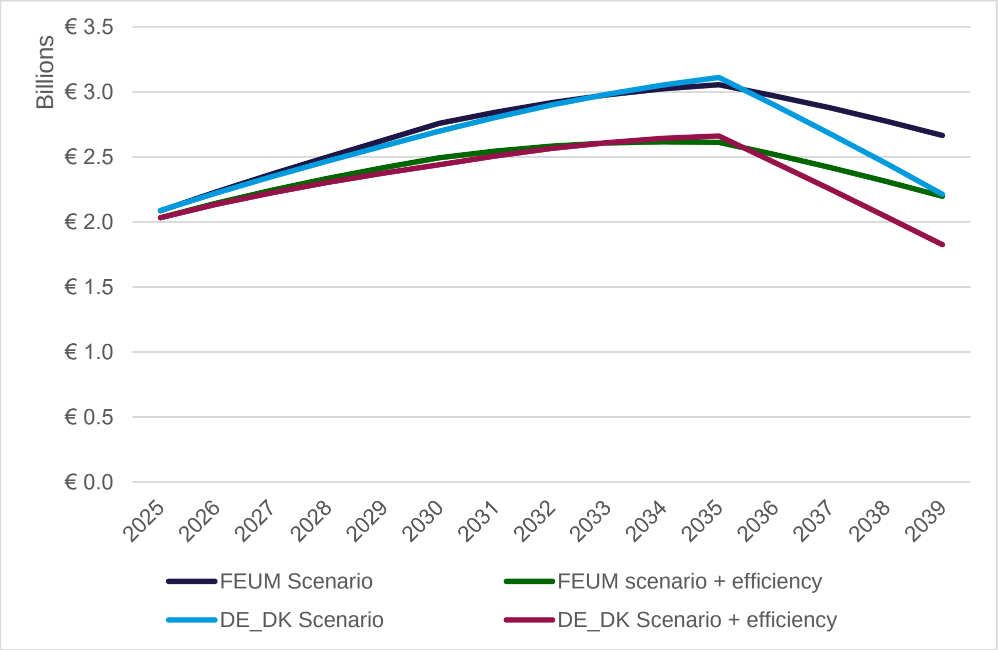


Figure 5-28: Comparison between scenarios of annual EU ETS revenue generated (at 25% of total) during auction periods



It can be seen from Figure 5-28 that the peak in-year revenue from the EU ETS (at 25% of total ETS revenue generation) is approximately €3bn. There is broadly a similar level of revenue generation between the FEUM and DE_DK scenarios up until 2035, after which point revenue generated from the DE_DK scenario drops due to the increased uptake of RFNBOs. RFNBOs are zero-rated under the EU ETS therefore their use provides an exemption from paying into the ETS being collected.

5.3 LEVEL OF RFNBO SUPPORTED

5.3.1 Aviation

Taking the information presented on the annual quantities of RFNBO that can be supported under the CfD scheme presented in Section 5.2.1, an analysis has been made of the total quantities that could be supported under two auction periods, running from 2025 to 2034 and 2030 to 2039, respectively. In the overlap period (2030 to 2034), it has been assumed that the available funding would be split equally between the two auctions, to avoid the total funding exceeding the 25% of EU ETS revenues specified for the scheme.

The costs for the scheme have been calculated using the passenger demand and fuel consumption described in Section 5.2.1. The design of the "basic scheme" allows airlines to meet the mandated RFNBO uptake at a lower cost (i.e., at the same cost that would be incurred if RFNBO were the same price as biofuel SAF)[29]. This provides an effective subsidy for RFNBO that varies over time, depending on the prices for biofuel SAF and RFNBO, from €1,040 per tonne (35%) in 2025 to €370 (16%) in 2040.

As noted above, in calculating the values presented in these charts, it has been assumed that the available funding, and the ability to use it to support RFNBO uptake through a CfD scheme, is an annual scheme, with no ability to carry excess funding over to a future year[30]. Different designs of the CfD scheme could allow such a carry-over of excess funds and hence enable the support of more RFNBO. The following charts include additional results (in the hatched areas) to give an indication of the potential of greater support under different scheme designs. Figure 5-29 presents the quantities that can be supported under the basic scheme, while

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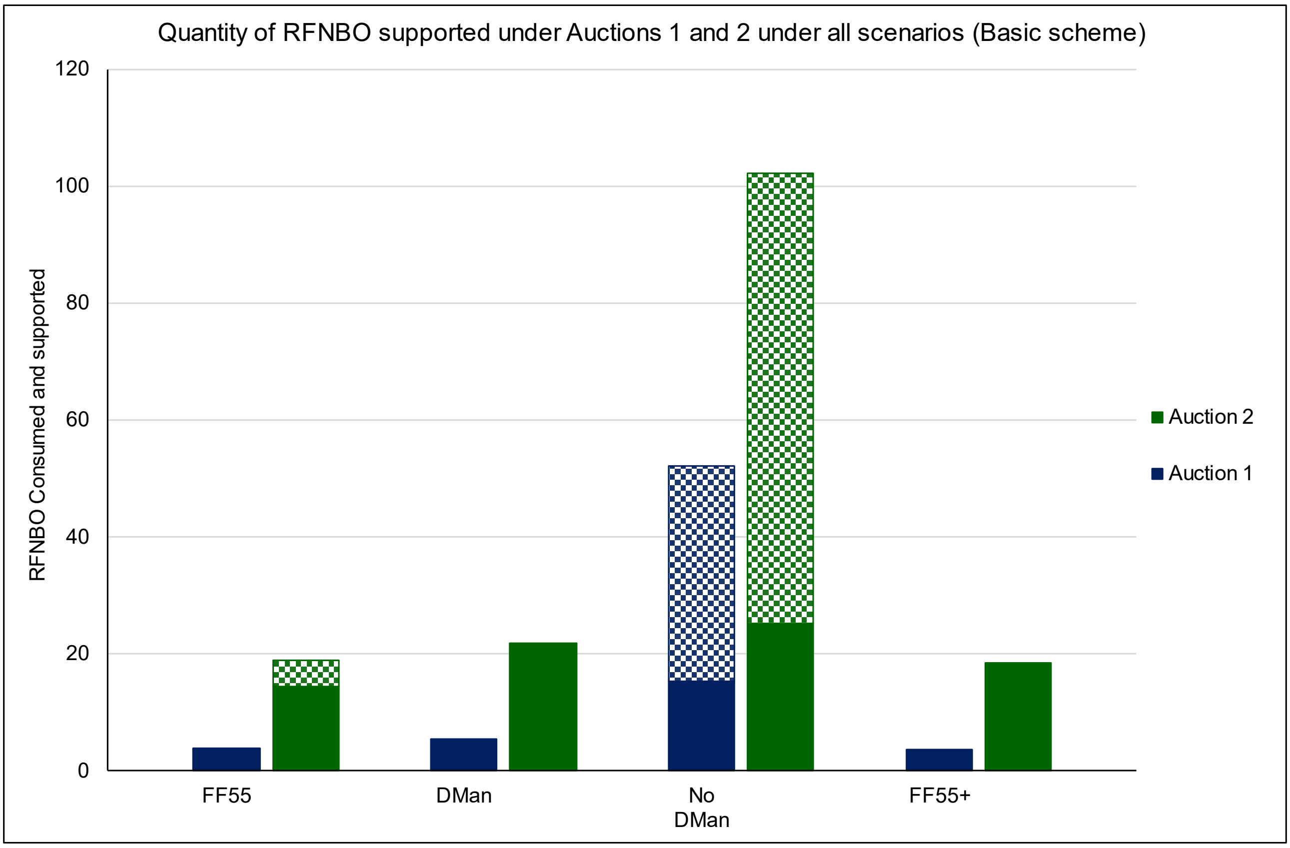
[29] This would be likely to lead to a reduction in ticket prices (compared to the case in which the same quantity of RFNBO was used at the full RFNBO price) and hence an increase in demand (and a further increase in RFNBO consumption). The RFNBO consumption and scheme costs presented do not take this iteration step into account; they are based on the demand calculated assuming the full RFNBO cost is incurred.

[30] Or to anticipate additional funding from a future year, although as RFNBO uptake rises faster than EU ETS revenues, that is a less likely scenario.

Figure 5-30 presents the quantities that can be supported under the scheme with all mandated SAF being RFNBO.

Figure 5-29: Quantity of RFNBO supported and unsupported under the two auction periods under the Basic scheme

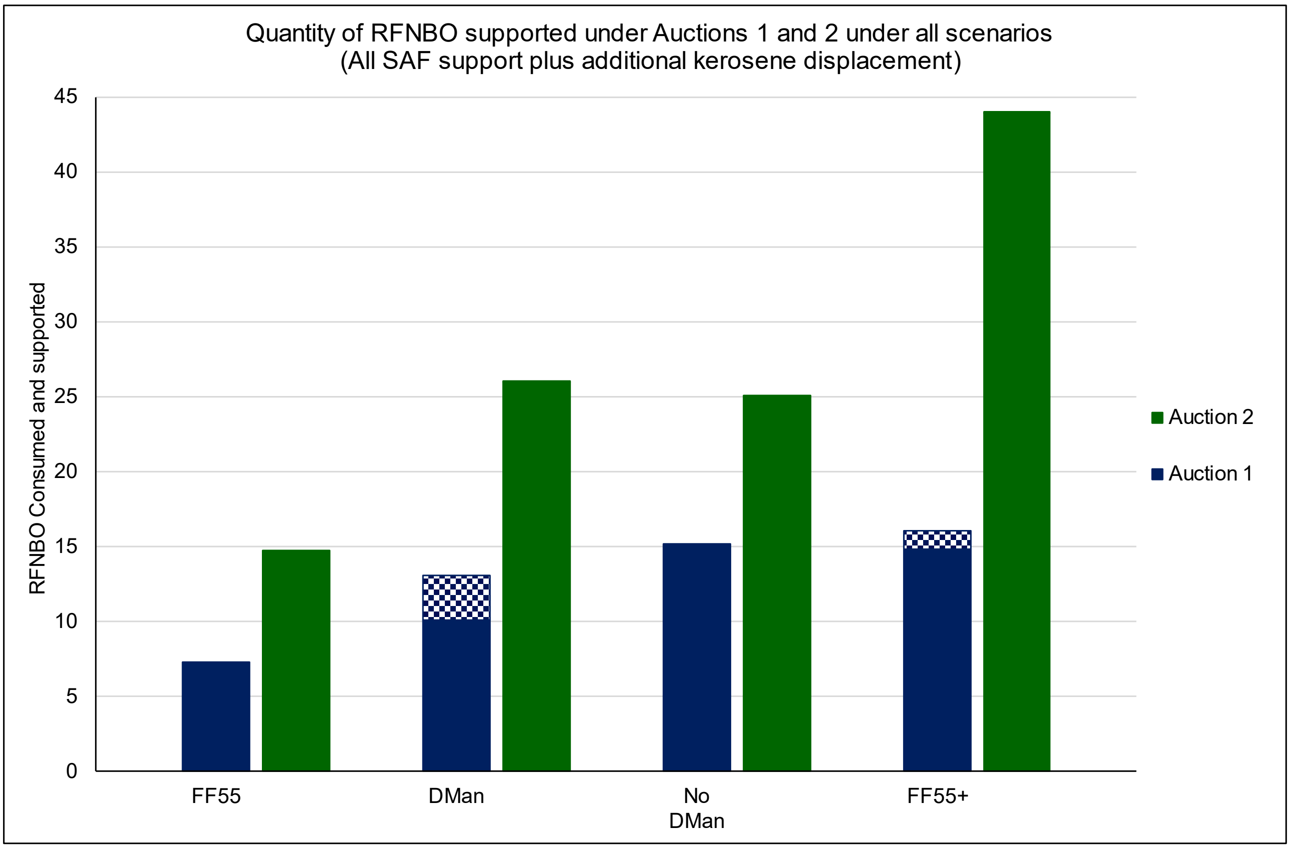


Notes: The solid areas show the quantities of RFNBO supported under the auctions; the hatched areas show the additional RFNBO consumed, but not supported under the scheme.

Because of the increased consumption of RFNBO over time, the increase in funding available from EU ETS revenues and the reducing price difference between RFNBO and biofuel-based SAF, the quantities of RFNBO that can be supported under the basic scheme are substantially higher for the second auction period than for the first. The total quantity that can be supported is highest under No DMan (although the proportion of total consumption that can be supported under this scenario is significantly lower than under other scenarios, the total quantity included is higher). This reaches 15.1 and 25.8 million tonnes of RFNBO supported under auction periods 1 and 2, respectively. Based on the total demand for RFNBO, this leaves 46.5 and 103.8 million tonnes of unsupported RFNBO during the two auction periods. The quantities that can be supported under the other scenarios are rather lower, particularly for auction period 1. For example, under FF55 (the lowest), 3.6 million tonnes of RFNBO are supported under auction period 1 and 14.5 million tonnes under auction period 2. The proportion of total RFNBO demand that is supported is higher under the other scenarios, with no unsupported demand under the DMan and FF55++ scenarios.

Comparing the results of the DMan and No DMan scenarios, which are defined to deliver the same emissions reduction, shows the significant quantity of unsupported RFNBO that needs to be consumed to deliver the required emissions reduction. The DMan scenario, based on the T&E roadmap with passenger demand capped at 2019 levels to deliver carbon neutrality by 2050, achieves the same emissions reduction while enabling the required RFNBO uptake to be supported under the scheme.

Figure 5-30: Quantity of SAF that can be supported under the two auction periods (if all SAF is RFNBO) (with case in which additional kerosene is also displaced)



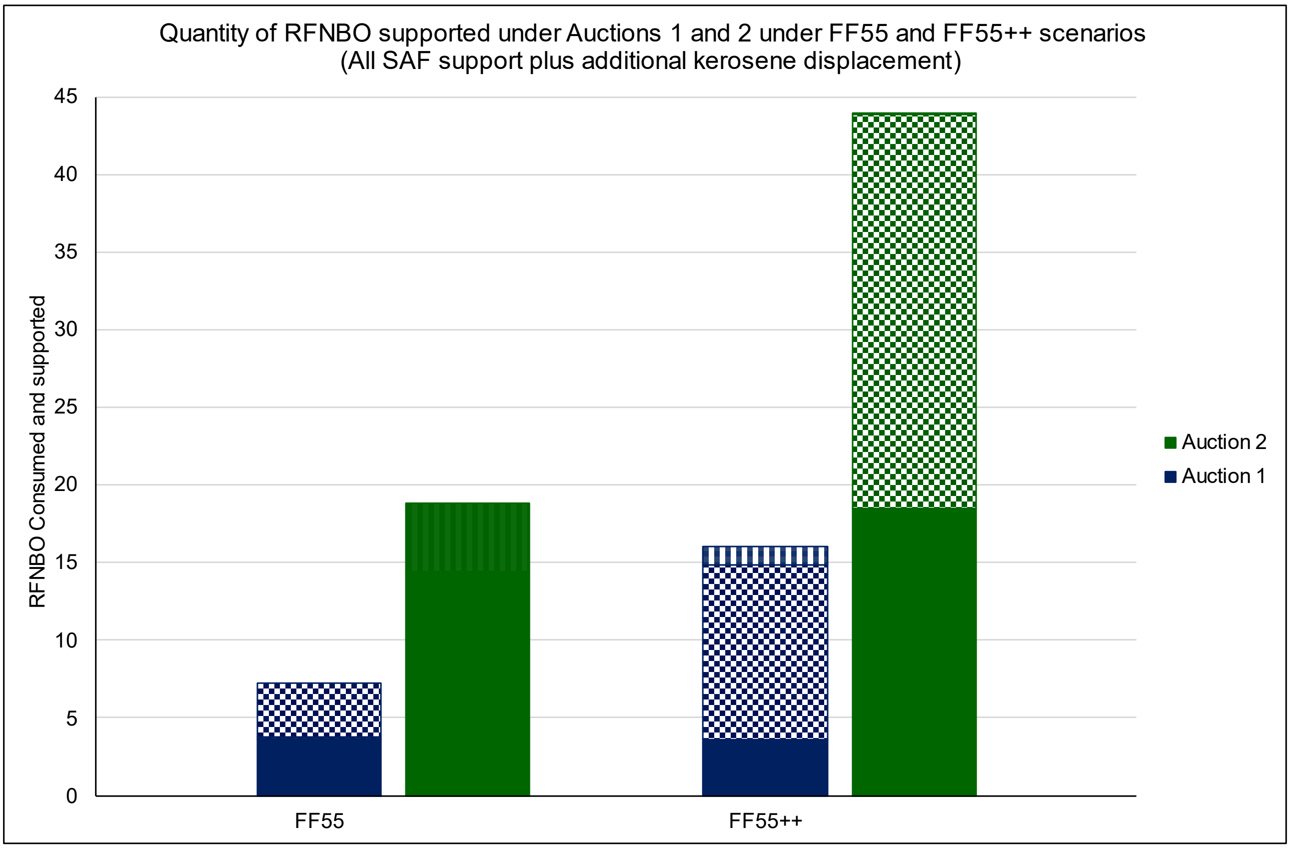
Notes: The solid areas show the quantities of RFNBO within the relevant SAF mandate supported under the auctions; the hatched areas show the additional RFNBO supported, displacing fossil kerosene consumption beyond the mandate.

As for previous figures, the results for the No DMan scenario are unchanged as the RFNBO required already exceeds the total SAF mandate. The FF55 scenario shows a small increase in the RFNBO supported by auction 1, but a negligible change in auction 2. The DMan scenario also shows small increases over the basic scheme. In contrast, the FF55++ scenario shows substantial increases, with the quantity of RFNBO supported under auction 1 rising from 3.6 million tonnes to 14.8 million tonnes, and from 18.5 million tonnes to 43.8 million tonnes under FF55++.

Also included in Figure 5-30 are the results for cases in which any remaining funds are used to support further uptake of RFNBO, leading to displacement of fossil kerosene beyond that required by the mandates. As was shown previously, this is only feasible during the period covered by auction 1, and Figure 5-30 shows small increases in RFNBO covered under this auction for DMan (rising from 10.0 to 13.0 million tonnes) and FF55++ (rising from 14.8 to 16.0 million tonnes). Note that Figure 5-29 showed that the scheme was not able to support all RFNBO uptake under FF55 (auction period 2) and No DMan (both auction periods). While the scheme is able to support some additional displacement of biofuel SAF during auction period 1 of FF55, it is not able to support any additional displacement of fossil kerosene under either of the auction periods for both these two scenarios (the unsupported RFNBO shown in Figure 5-29 is not included in Figure 5-30).

Further details of the total use of RFNBO in, and beyond, the context of the ReFuelEU Aviation mandate during the period of the CfD scheme are shown for scenarios FF55 and FF55++ in Figure 5-31. The figure separates the total RFNBO use into that which is mandated under ReFuelEU Aviation and supported by the scheme (solid areas), that which is mandated, but not supported (for example, the upper area on FF55 under Auction 2), that which is beyond the RFNBO sub-mandate but displaces biofuel SAF (for example, the upper area on FF55 under Auction 1) within the overall mandate and that which displaces fossil kerosene beyond the SAF mandate (for example, the upper area on FF55++ under Auction 1).

Figure 5-31: RFNBO use in scope of ReFuelEU Aviation, including supported and unsupported use under the CfD scheme, for FF55 and FF55++ scenarios



Notes: The solid areas show the quantities of RFNBO within the ReFuelEU Aviation mandate supported under the auctions; the vertical barred areas show the mandated RFNBO that is not supported by the scheme; the hatched areas show the additional RFNBO supported displacing biofuel SAF within the overall mandate; the dotted areas show further RFNBO supported, displacing fossil kerosene consumption beyond the mandate.

The impacts of the support scheme in increasing the consumption of RFNBO beyond the mandated level is clearly evident under both scenarios during the period of Auction 1, and under the FF55++ scenario during the period of Auction 2. The is particularly significant under Scenario FF55++, increasing the consumption by factors of 4.4 and 2.4 compared to the mandated quantity. This reflects the increased capacity of the scheme to support the uptake of RFNBO resulting from the increased scope of the EU ETS under the scenario.

The changes in the mix of different fuel types resulting from the support of the CfD scheme are shown for scenarios FF55 and FF55++ in Table 5-14. The results for the case without CfD support are the same for both scenarios as they reflect the impacts of the SAF mandate, including the RFNBO sub-mandate. With the support from the CfD scheme, there is a noticeable switch from biofuel SAF to RFNBO SAF in the earlier years of the scheme under FF55 (up to 2030), but no observable impact from 2035 onwards as the income to the scheme is insufficient to support the full mandated RFNBO. Under Scenario FF55++, the switch from biofuel SAF to RFNBO continues through to 2040, with the small displacement of fossil kerosene also visible in the results for 2030. As for Figure 5-31, this shows the significantly increased capability of the CfD scheme to support RFNBO uptake with the EU ETS extended to all departing flights.

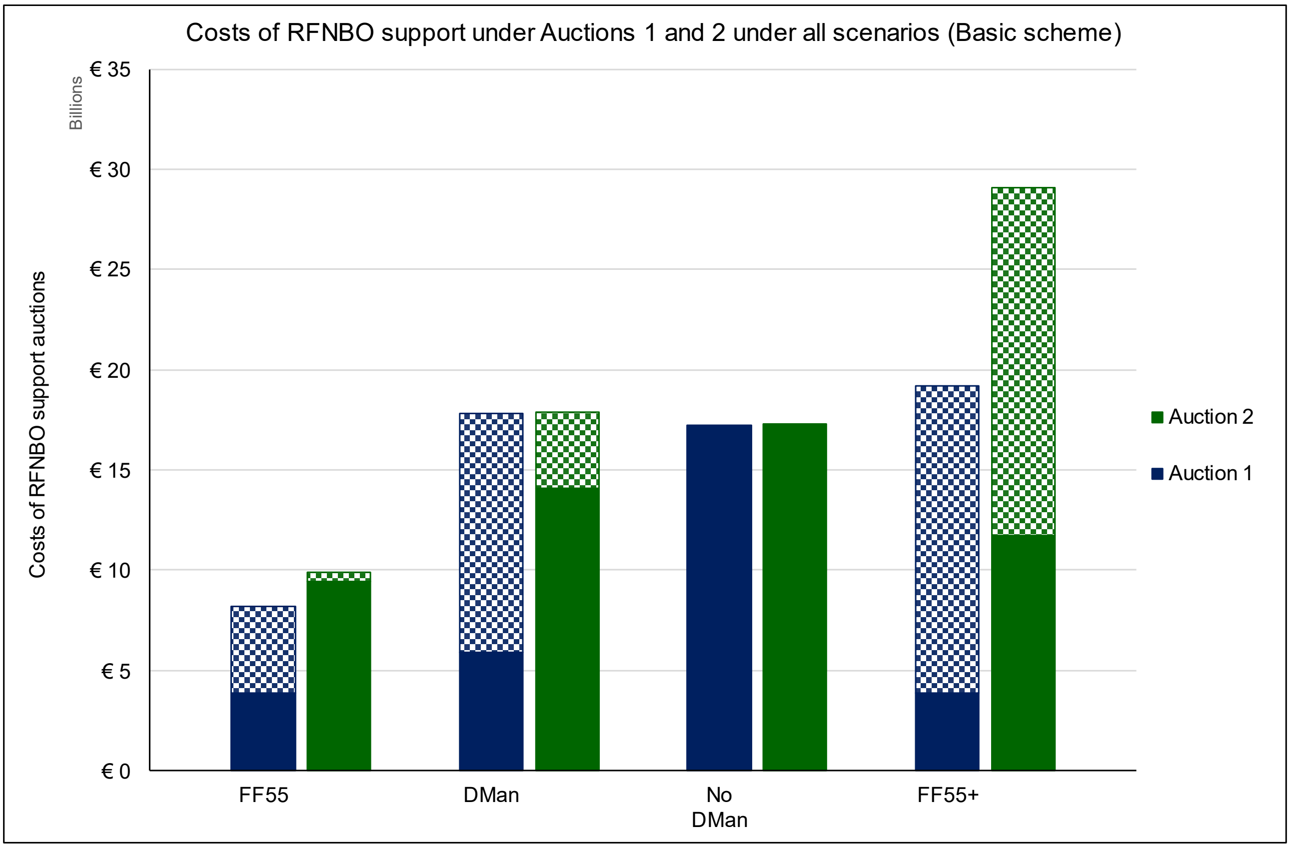
Table 5-14: Fuel mix under scenarios FF55 and FF55++, under the ReFuelEU Aviation policy without CfD and with the impact of the CfD scheme

		2025	2030	2035	2040
FF55 Scenario					
Without CfD					
	Kerosene	98.0%	94.0%	80.0%	66.0%

		2025	2030	2035	2040
	RFNBO	0.0%	1.2%	5.0%	10.0%
	Biofuel SAF	2.0%	4.8%	15.0%	24.0%
With CfD					
	Kerosene	98.0%	94.0%	80.0%	66.0%
	RFNBO	1.9%	2.1%	5.0%	10.0%
	Biofuel SAF	0.1%	3.9%	15.0%	24.0%
FF55++ Scenario					
Without CfD					
	Kerosene	98.0%	94.0%	80.0%	66.0%
	RFNBO	0.0%	1.2%	5.0%	10.0%
	Biofuel SAF	2.0%	4.8%	15.0%	24.0%
With CfD					
	Kerosene	98.0%	93.9%	80.0%	66.0%
	RFNBO	1.9%	6.1%	12.0%	24.3%
	Biofuel SAF	0.1%	0.0%	8.0%	9.7%

The figures above have shown the quantities of fuel supported under the two auctions for the two schemes; Figure 5-32 and Figure 5-33 show the costs associated with this support under the two auctions.

Figure 5-32: Costs of RFNBO support scheme for two auction periods under the Basic scheme, plus excess funding available



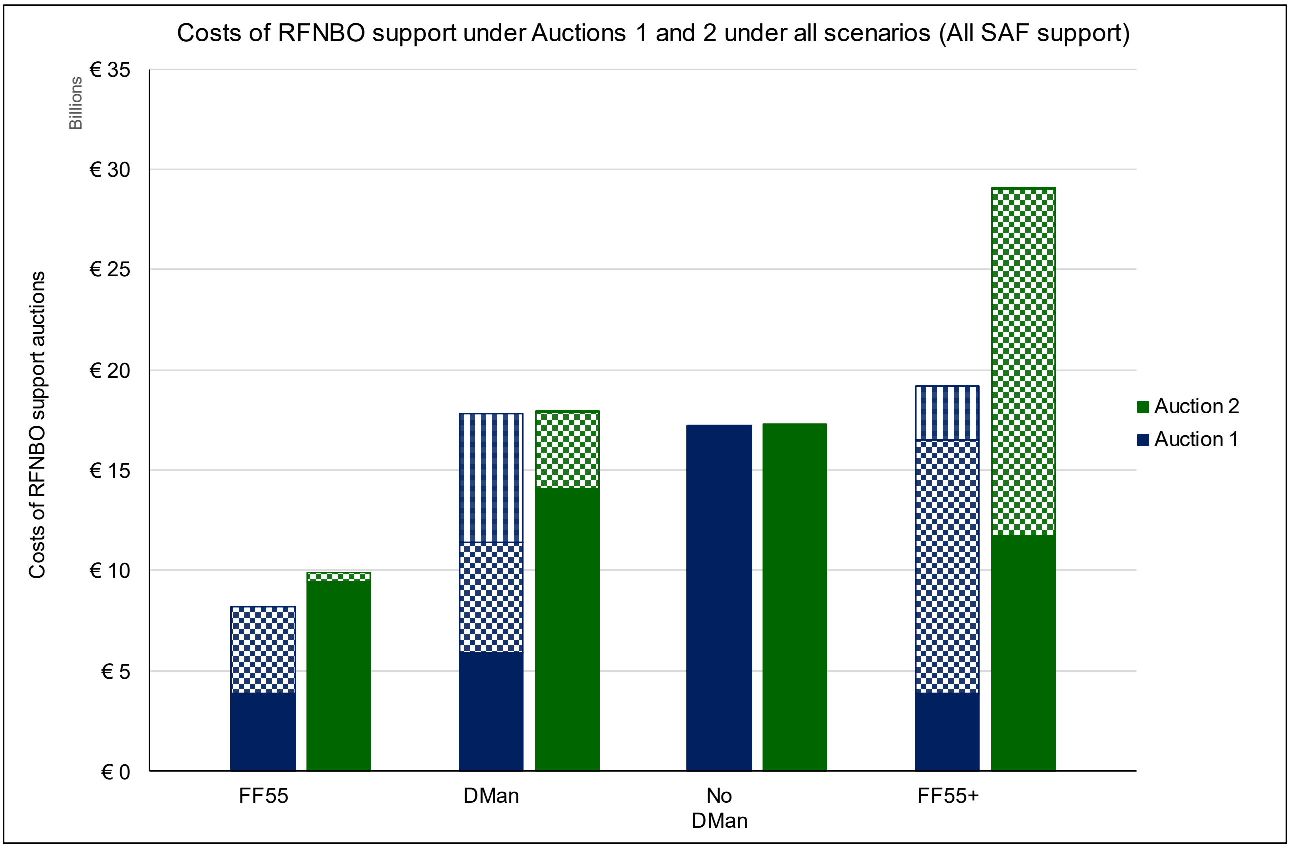
Notes: The solid areas show the costs of supporting RFNBO under the two auctions. The hatched areas show the available funding that exceeds that required for the auctions.

Under the basic scheme, the costs largely follow the same distribution as the quantities of RFNBO supported, except that the greater price difference (between RFNBO and biofuel-based SAF) in the early years of the scheme leads to the costs of auction 1 being greater relative to those for auction 2 than is the case for the quantities of RFNBO. This is most noticeable for No DMan, which also has the highest costs of any of the scenarios, with total costs of €17.1 billion and €17.7 billion for auctions 1 and 2, respectively.

Comparing Figure 5-32 and Figure 5-29, under the FF55 scenario, there is both unsupported RFNBO and excess funding during auction period 2. As seen previously (Figure 5-13), during the early part of auction period 2 (2030 to 2033), the available funding exceeds that required to support all mandated RFNBO (so there is some excess funding), while between 2033 and 2040, it is insufficient, so there is some unsupported RFNBO. As noted previously, a design of the CfD scheme that allowed excess funds to be carried over to subsequent years could allow the excess funds from the early years to support come of the unsupported RFNBO after 2033. As described in the context of Figure 5-15, an ability within the CfD scheme to carry excess funds over to subsequent years could allow an additional 3.2 million tonnes of RFNBO to be supported under the FF55 scenario, 12.8 million tonnes under DMan and 38.1 million tonnes under FF55++.

The cost results for the case in which all SAF is RFNBO (Figure 5-33) are separated by the costs associated with supporting the mandated RFNBO (dark colours), the additional costs of supporting all mandated SAF to be RFNBO (medium colours), and the costs of additional displacement of fossil kerosene (light colours). The results are aligned with those for the quantity of RFNBO supported. During auction period 1, the costs under No DMan are the same as in the basic scheme at €17.1 billion, with those for FF55++ being slightly lower at €16.5 billion when considering the case of supporting all mandated SAF to be RFNBO, or €19.1 billion when supporting additional displacement of kerosene. During auction period 2, there is very little ability to support additional displacement of fossil kerosene; the costs of supporting all SAF to be RFNBO are now highest under FF55++ at €29.0 billion. Also evident in Figure 5-33 is that the difference in costs for the cases in which additional RFNBO (beyond the SAF mandate) is supported are greater (relative to the costs without the additional RFNBO) than for the quantities of RFNBO (Figure 5-30). This is expected, as the additional RFNBO is supported at the price difference between RFNBO and fossil kerosene, rather than between RFNBO and biofuel-based SAF.

Figure 5-33: Costs of RFNBO support scheme for two auction periods (all SAF is RFNBO), including case with additional displacement of fossil kerosene



Notes: Solid areas show the costs of supporting mandated quantities of RFNBO; hatched areas show the costs of supporting the displacement of biofuel SAF by RFNBO; dotted areas (only applicable to Auction 1 here) show the costs of additional displacement of fossil kerosene by RFNBO.

5.3.2 Maritime

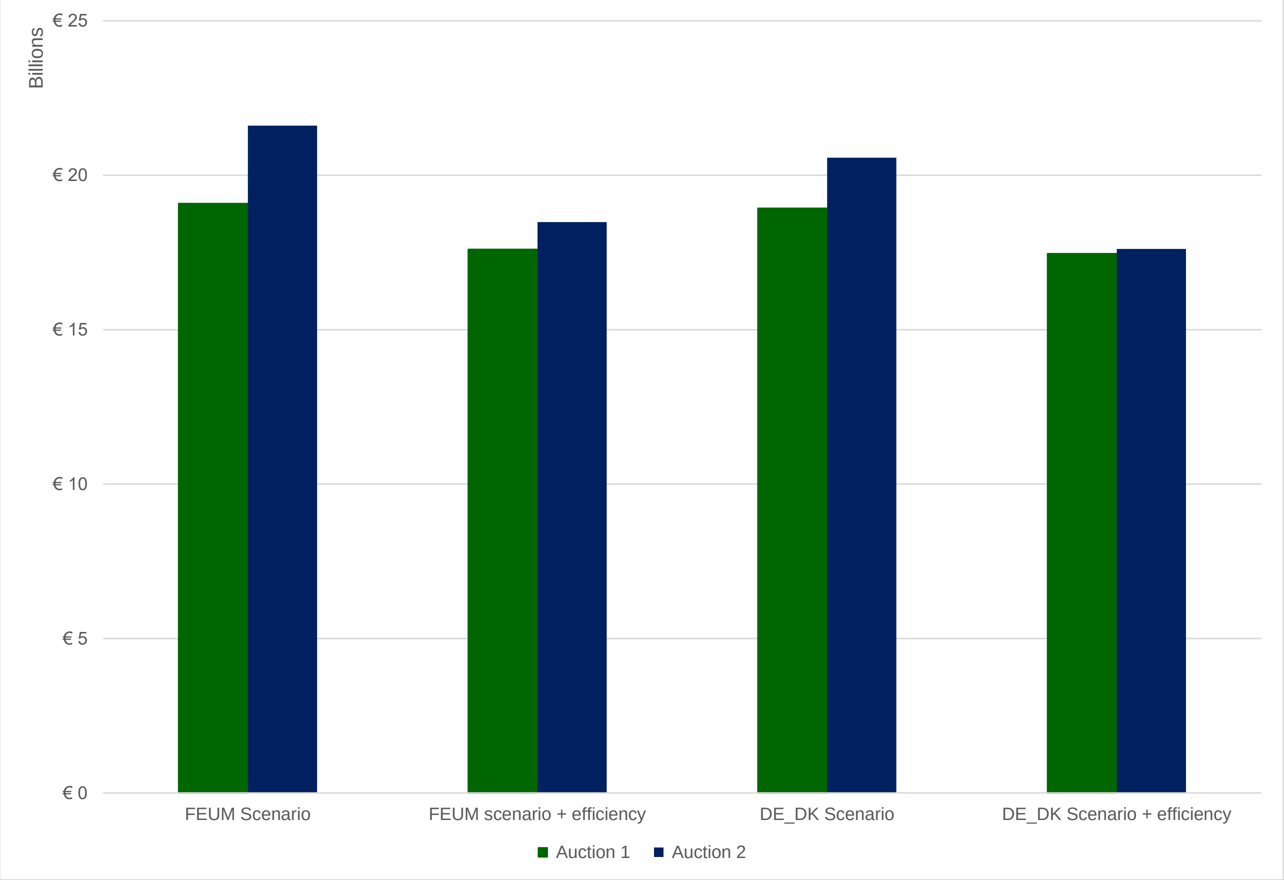
Figure 5-34 details the revenue generated from the EU ETS, assuming 25% of the total is available, during the two auction rounds. This is the level of funding that is available to subsidise the difference in cost between HFO, as the dominant fossil fuel source, and RFNBOs. Two CfD rounds were considered, the first running from 2025-2034 and the second from 2030-2039 (10 years each in duration). For the period of overlap between 2030 and 2034 it has been assumed that the revenue will be split equally across both auctions. The design and administration of the CfD scheme is outside the scope of this study and in the maritime context it has been assumed that any in-year EU ETS revenue generated is utilised in the same year to support RFNBO production/supply with no ability to carry over funding. It has also been assumed that all generated revenue is utilised every year. Further work could explore different designs of the CfD schemes, such as inclusion of a flexibility mechanism, allowing carry-over of excess funds. This could be particular useful early on in the CfD scheme as RFNBOs will still be in a status of commercial immaturity, having the ability to accumulate ETS revenue funds into a collective RFNBO support pool could enable fuel which reach maturity later on in the CfD scheme to receive more support.

Greater revenue is available during the second auction period for all scenarios as by this point in time the carbon price is expected to be much higher, this in combined with the relatively high fossil fuel usage in each scenario leads to more revenue during the second auction period.

Table 5-15: Average carbon prices during auction periods

	Auction 1 **2025-2034**	**Auction 2** **2030-2039**
Average carbon price	€ 125 per t CO_2	€ 167 per t CO_2

Figure 5-34: Revenue available through two schemes collecting 25% of ETS revenue



Funding was allocated in several different ways to observe how much fuel (in tonnes) could theoretically be supported. The first level of allocation was a proportional allocation based upon the expected fuel uptakes scenarios. All revenue was allocated to encourage the uptake of RFNBOs i.e., biofuels and fossil-based fuels were excluded. Figure 5-35 shows the proportional allocation per scenarios. Perhaps unsurprisingly e-ammonia is the most supported fuel type for each scenario given that it is the dominant RFNBO type expected to be used.

When proportionally allocating ETS revenue under both the FEUM and FEUM + efficiency scenarios there is no expected uptake of any other RFNBOs besides e-ammonia during the two auction periods. Shown in Table 5-16.

In the DE_DK and DE_DK + efficiency scenarios there is some uptake of e-LNG and e-diesel across both auctions, but the values are relatively small in comparison to ammonia. Table 5-17 provides more granularity on the amount of fuel that can be supported under these two scenarios.

Table 5-16: Fuel supported under FEUM and FEUM + efficiency scenarios via proportional allocation.

	FEUM		**FEUM + efficiency**	
Fuel supported (tonnes)	Auction 1	Auction 2	Auction 1	Auction 2
e-ammonia	34.5 million	43.2 million	31.8 million	36.9 million

Table 5-17: Fuel supported under DE_DK and DE_DK + efficiency scenarios via proportional allocation

	DE_DK		**DE_DK + efficiency**	
Fuel supported (tonnes)	Auction 1	Auction 2	Auction 1	Auction 2
e-ammonia	27.2 million	40.9 million	24.8 million	35.0 million

	DE_DK		DE_DK + efficiency	
e-LNG	1.03 million	0.12 million	0.99 million	0.11 million
e-diesel	0.27 million	0	0.26 million	0
Total	28.5 million	41 million	26 million	35 million

It is observed between the base line scenarios (FEUM and DE_DK) and the scenarios with additional efficiency measures (FEUM + efficiency and DE_DK + efficiency) that less absolute volume RFNBO can be supported via a publicly funded CfD scheme overall which is to be expected as the total fuel consumed by the maritime sector under these scenarios is lower. This is due to the additional efficiency measures reducing the overall fuel consumption in these scenarios. Less fuel consumption leads to less revenue being generated under the EU ETS and thus meaning less funding is available to support RFNBO uptake. However, proportional to the total fuel consumed by the maritime sector, the same percentage of RFNBOs can be supported under the scenarios with additional efficiency.

Comparing the FEUM and DE_DK scenarios Figure 5-35 shows that, even with the more ambitious RFNBO mandates outlined in the DE_DK scenario as a result of specific RFNBO sub-quotas, a comparable level of RFNBOs can be supported despite less ETS revenue being available.

Figure 5-35: RFNBOs supported by scenario and auction round with proportional allocation by fuel type (tonnes)

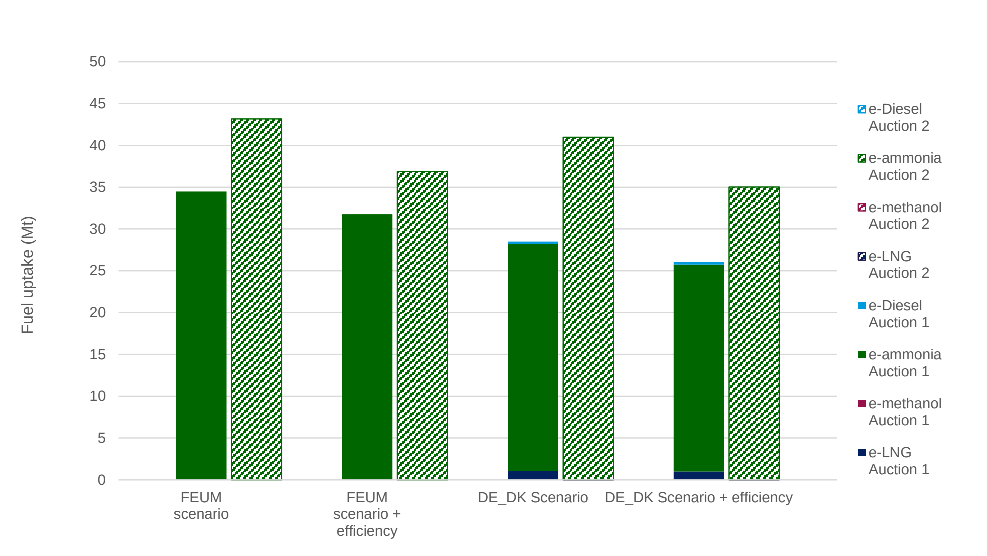


Figure 5-36 explores the situation where the available ETS revenue is split out equally among all the different RFNBO types (25% each between e-ammonia, e-LNG, e-diesel and e-methanol). On a mass (Figure 5-36) and energy (Figure 5-37) basis e-ammonia is again the most widely supported RFNBO which is due to a combination of factors.

i. The primary driver is the price differential between e-ammonia and HFO. This is only €23/GJ on average across the auction period between HFO and ammonia. Compared to lower compared to both e-methanol (€42.17/GJ), e-diesel (€125.41/GJ) and e-LNG (€43.74/GJ])

ii. The specific energy (how much energy is contained within a unit mass) for ammonia is approximately half that of e-LNG and e-diesel but comparable to methanol.

Over each scenario a total of >15 million tonnes of RFNBOs can be supported per auction round.

Figure 5-36: RFNBOs supported by scenario and auction round with equal allocation by fuel type (tonnes)

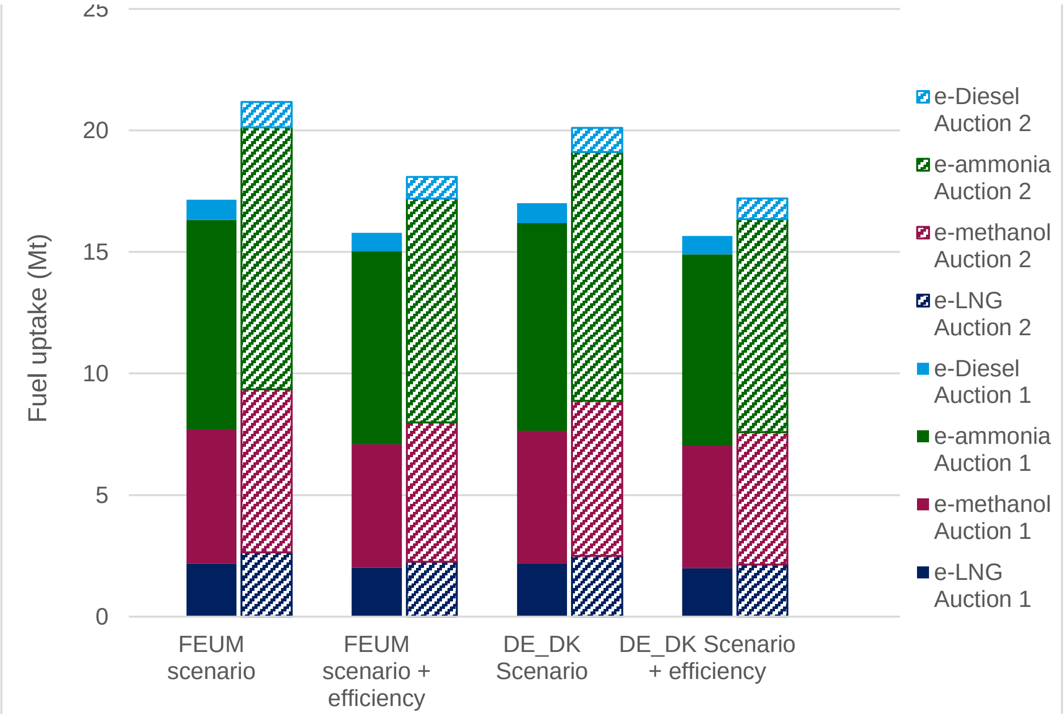
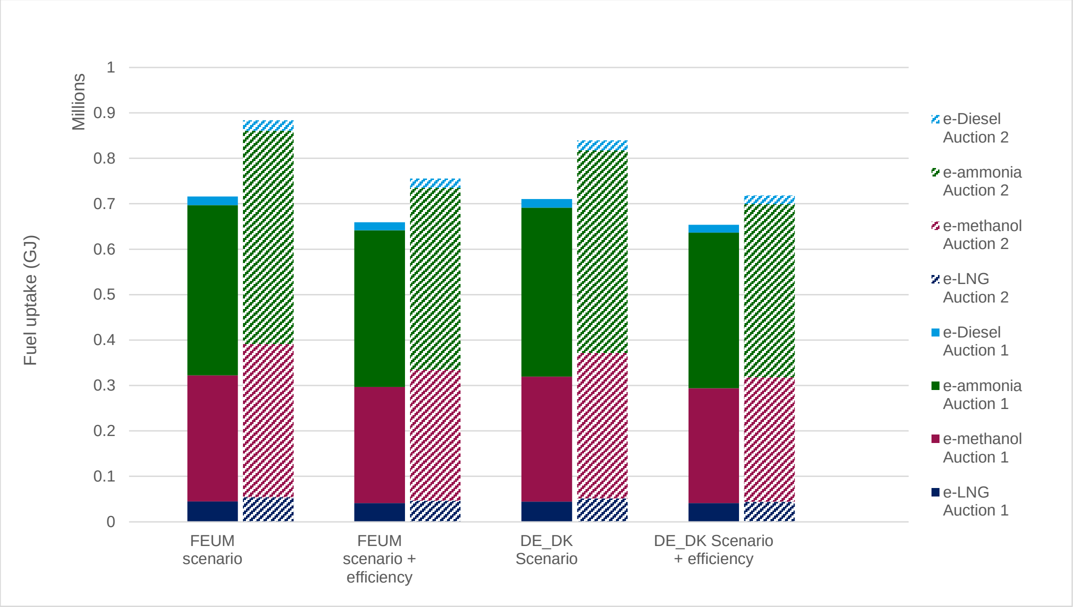
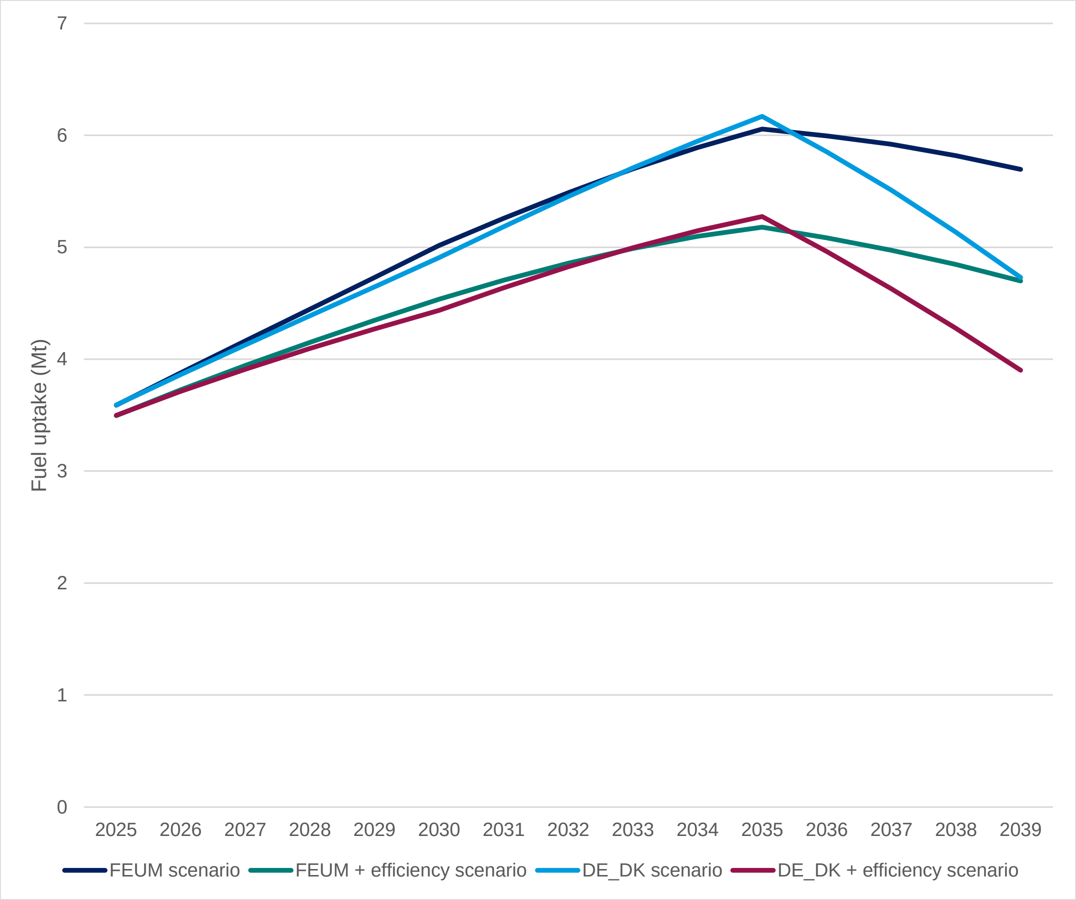


Figure 5-37: RFNBOs supported by scenario and auction round with equal allocation by fuel type (million GJs)



A final revenue allocation type was explored to determine how much of e-ammonia only could be supported through distributing ETS revenue across each scenario. This is presented in Figure 5-36 on an annual basis. The total amount of e-ammonia supported under each scenario is 77.6 million tonnes of e-ammonia could be supported under the FEUM scenario, 68.6 million under FEUM + efficiency, 75.2 million under DE_DK and 66.6 million under DE_DK + efficiency.

Figure 5-36: RFNBOs supported on an annual basis with 100% ammonia subsidy allocation (million tonnes)



Returning to the proportional allocation of ETS revenue Figure 5-37 shows over time the level of RFNBOs that are expected to be utilised in the FEUM scenario (dashed lines) alongside the level of RFNBOs that could be supported under the proposed CfD scheme (solid lines). The y-axis in this case is the percentage of RFNBOs in the total fuel mix. It can be seen that prior to 2036 sufficient ETS revenue (at 25%) is available to support more RFNBOs (only e-ammonia in this scenario) than is expected to be utilised. This is overwhelmingly a positive result as earlier available support could lead to an earlier uptake of RFNBOs compared to that defined in the initial FEUM scenario. This in turn could lead to further positive benefits that the price to produce RFNBOs will reduce at an earlier period making them more competitive which in turn leads to greater levels of emission reduction.[31] This results also clearly highlights the ease in which the sub-target of 2% RFNBO from 2034 onwards in FuelEU Maritime could be achieved through the proposed CfD scheme as under this scenario the amount of e-ammonia that could be supported is approximately 8% of the total fuel consumed. It also helps meet the IMO targets of 5% of fuels to be zero or near zero by 2030 but doesn't achieve the ambition required to meet the higher target of 10%.

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[31] No feedback loop is included in the model so only expected qualitative impacts have been explored

Figure 5-37: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under FEUM scenario (proportional ETS funding allocation)

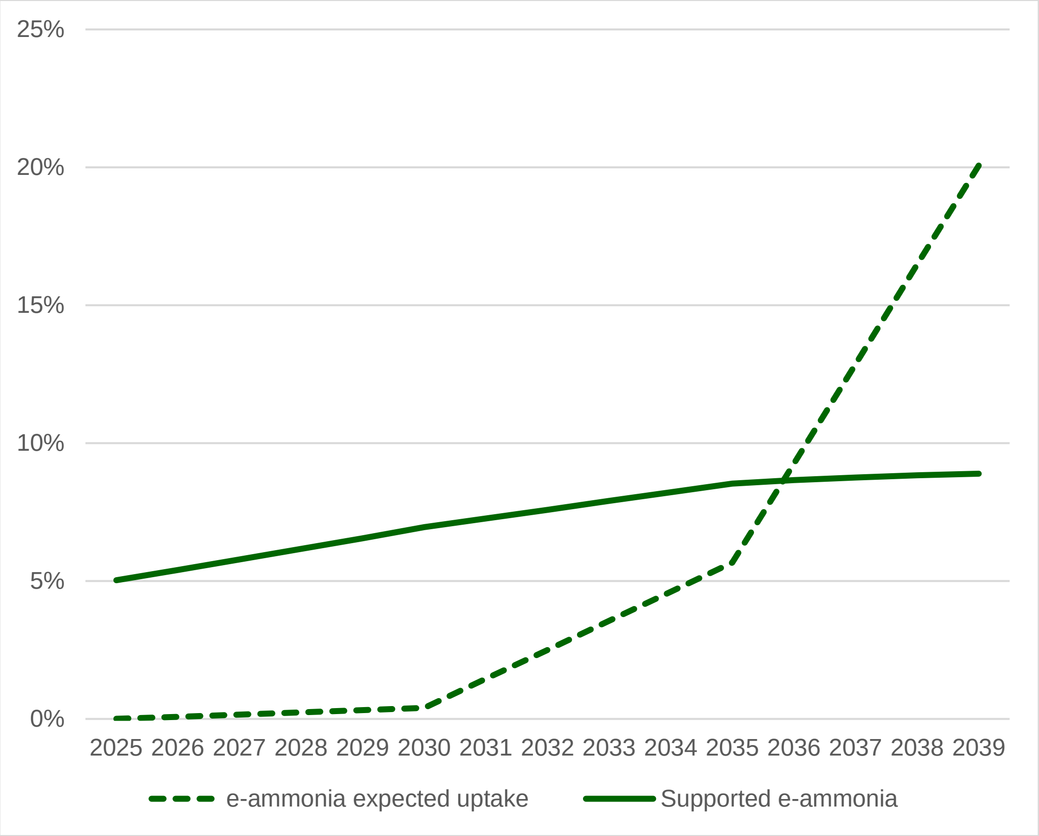


Figure 5-39 highlights a similar observation for the DE_DK scenario, in this scenario prior to 2036 there is sufficient ETS revenue being generated in a given year to subsidise all the expected e-ammonia and additional volumes of e-ammonia beyond the expected uptake. To contextualise this result expected uptake of e-ammonia was calculated independently as per the scenario defined in Table 5-3. In reality if a CfD scheme was able to subside greater than expected volumes of e-ammonia under this scenario it would be expected that the uptake of e-ammonia would accelerate further, this has not been implemented in this study as there is no feedback loop contained within the model to adjust for increase fuel uptake.

In the DE_DK scenario there is some expected uptake of other RFNBOs which are not clear from Figure 5-39. Figure 5-38 presents an insert showing e-LNG and e-diesel only. From this figure it is clear that sufficient revenue is available to fully support the uptake of e-LNG throughout the auction period, which could stimulate further uptake. Prior to 2027 there is sufficient revenue to support beyond the expected level of e-diesel uptake and after this point the revenue available aligns closely to the expected uptake.

Figure 5-39: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario (proportional ETS funding allocation)

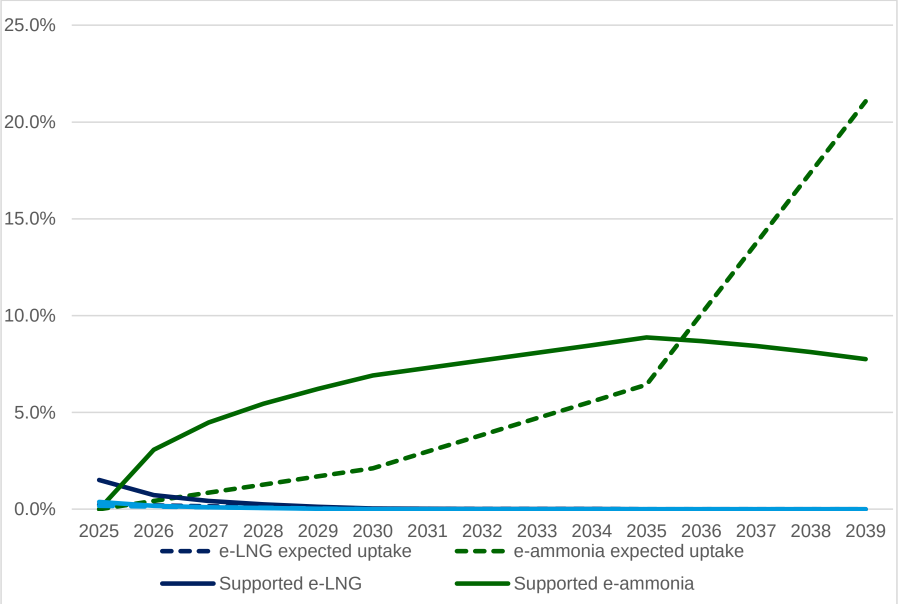


Figure 5-38: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario excl. e-ammonia (proportional ETS funding allocation)

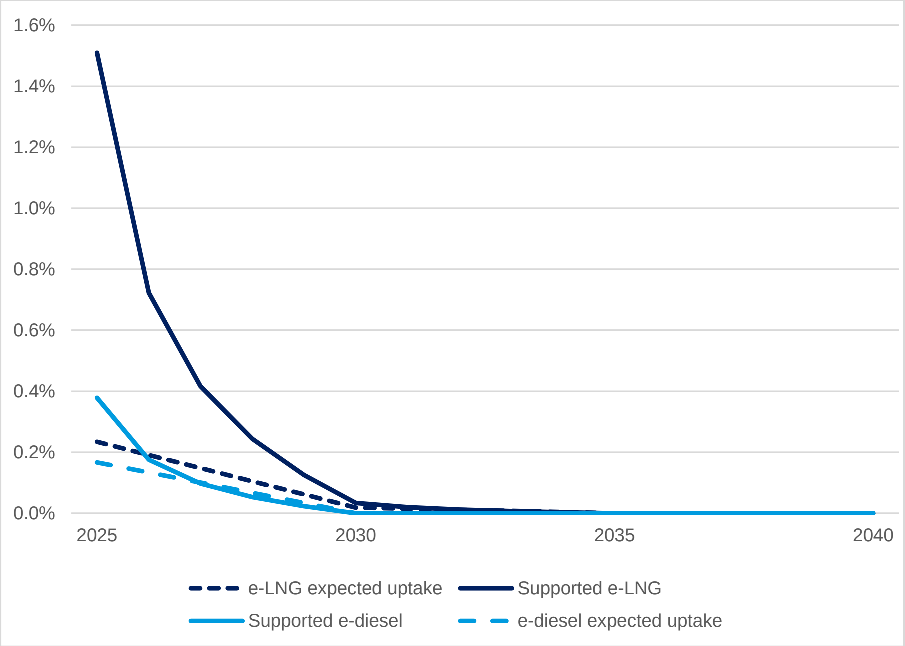


Figure 5-40 shows the results of equally allocating ETS revenue across the FEUM scenario. It is found that prior to 2032 there is sufficient revenue generated to support more e-ammonia than is expected to be utilised by the industry. Figure 5-41, examines the available support for other RFNBOs under this scenario, here there is no expected uptake of other RFNBOs beside ammonia therefore there is sufficient revenue generation to support up to a peak of ~1% of the total EU shipping fuel consumed by the maritime sector for e-methanol and e-LNG and a peak of 0.4% for e-diesel. Collectively across all RFNBO types there is enough RFNBO that can be supported to meet the FuelEU RFNBO sub-target. The sum of all RFNBOs ~3% of the total fuel consumed by the EU maritime sector.

Figure 5-40: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under FEUM scenario (equal ETS funding allocation)

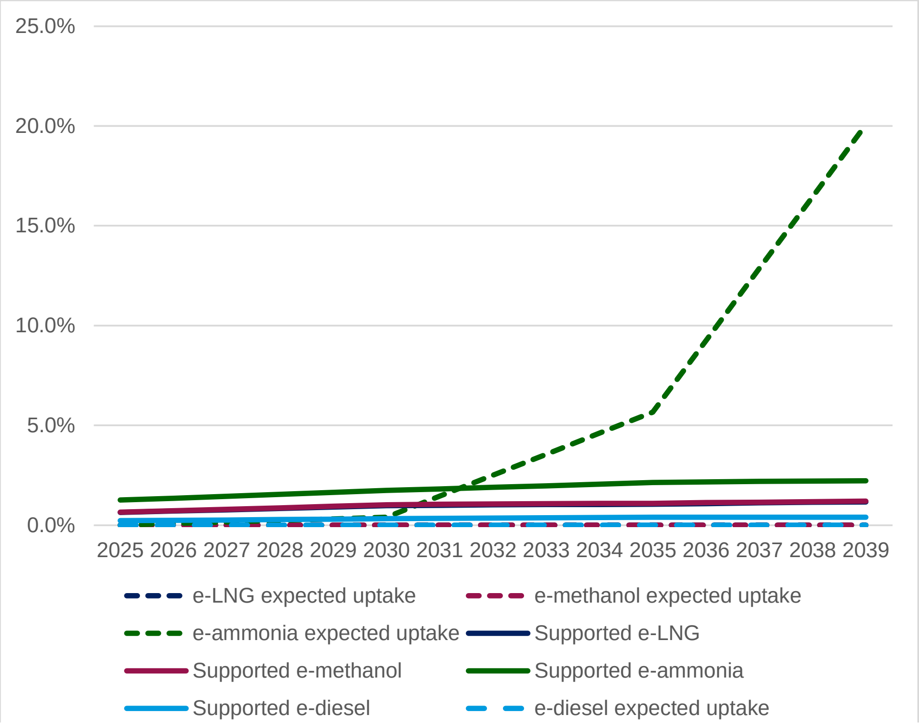


Figure 5-41: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under FEUM scenario excl. e-ammonia (equal ETS funding allocation)

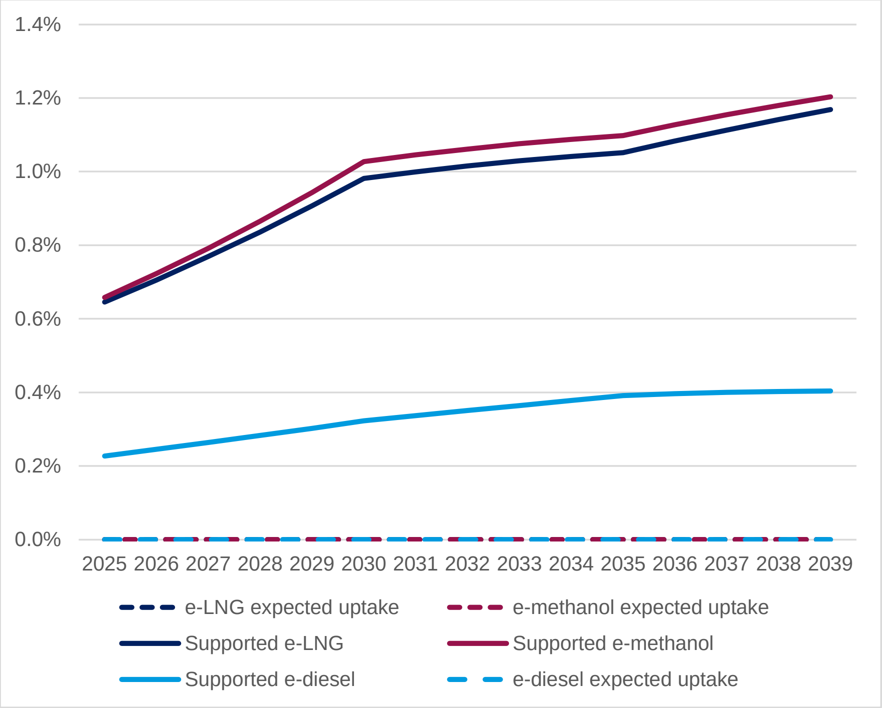


Figure 5-42 shows same results for the DE_DK scenario. In this case it was found that case, prior to 2029 there is sufficient revenue generated to support more e-ammonia than is expected to be utilised by the industry. It is also the case that for e-LNG, e-diesel and e-methanol more support is available than demand for these fuels across the entire CfD scheme period (Figure 5-43), **Error! Reference source not found.**which could stimulate further uptake of these RFNBOs. Compared to the FEUM scenario more RFNBO can be supported under the DE_DK scenario with equal allocation of ETS revenue across all RFNBO types. The total amount of RFNBO that can be supported represents ~4.5% of the total fuel consumption. This is unsurprising given the higher RFNBO targets in the DE_DK scenario.

Figure 5-42: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario (equal ETS funding allocation)

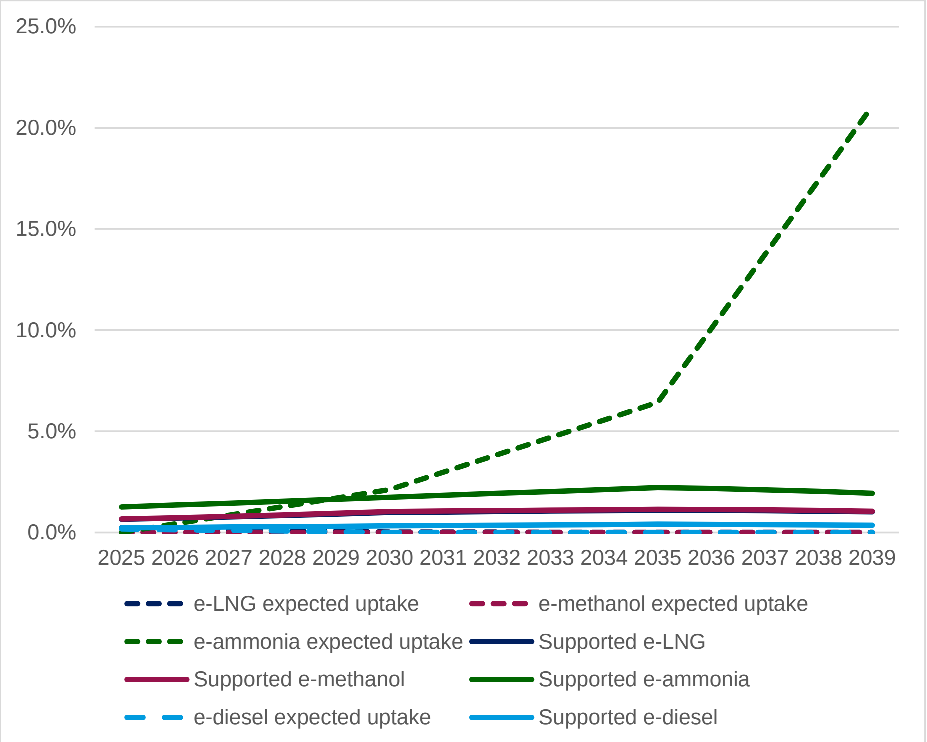
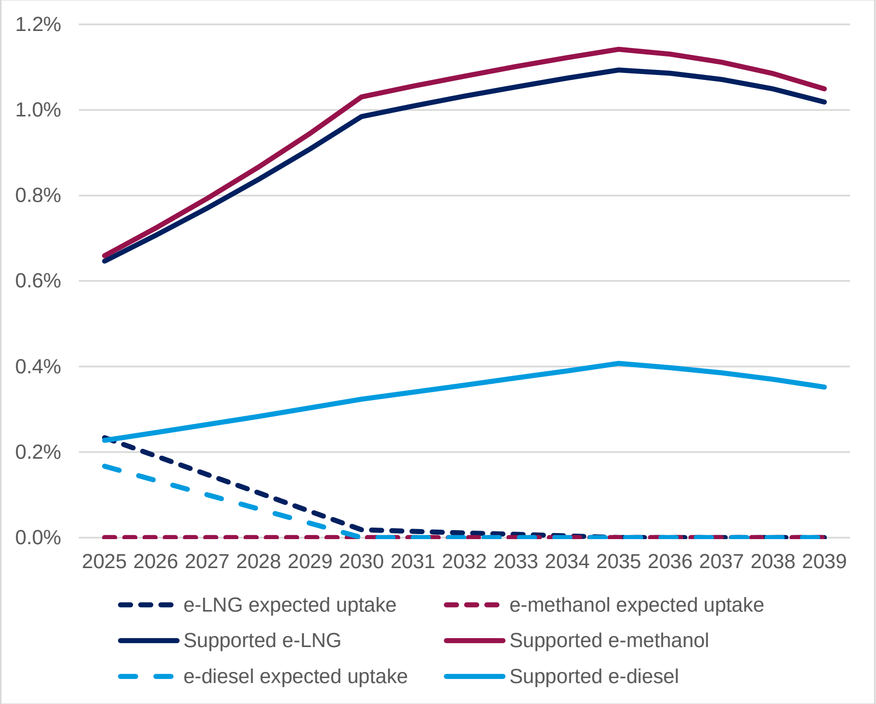


Figure 5-43: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario excl. e-ammonia (equal ETS funding allocation)



5.4 ROUTE SELECTION

5.4.1 Aviation

To gain further insight into the impacts of the support scheme on airlines and passengers, analyses have been made of fuel consumption and costs on some example flights, as shown in Table 5-18.

Table 5-18: Selected routes for analysis

Route	Distance	Typical Aircraft Type	Typical Number of Seats[32]
Paris – Stockholm	1,540 km	Airbus A320neo	155
Athens – Reykjavik	4,208 km	Airbus A321neo	200
Rome – Beijing	8,146 km	Airbus A350-900	325

The calculation of fuel consumption on flights on these routes using these aircraft types was made using the EMEP/EEA "Aviation master emissions calculator" (Annex 1.A.3.a to the 2023 EMEP/EEA Guidebook (European Environment Agency, 2023)).

The results of these calculations for total fuel consumption for these flights (at 2023 technology levels) are shown in Table 5-19.

Table 5-19: Fuel consumption on routes (for 2023 technology levels)

Route	Fuel consumption
Paris – Stockholm	4,524 kg
Athens – Reykjavik	13,010 kg
Rome – Beijing	56,611 kg

To calculate the costs for these flights, and hence the reduction in costs that would occur with the support from the CfD scheme, the fuel consumption was projected over the period of the scheme (to 2040) with the same annual improvement in fuel efficiency as seen in the AERO-MS results (e.g. see Figure 5-3), DMan for illustration of reducing fuel consumption with constant RPK). The same fuel mixes under the different scenarios as presented in section 5.1.1 were used to derive fuel consumption by type. While it is not clear whether an airline would be likely to use both biofuel-based SAF and RFNBO SAF on the same flight (blended with fossil kerosene), they would certainly not use hydrogen fuel on the same flight as the liquid hydrocarbon fuels; therefore, the results of the fuel mix calculations should be seen as an average taken across multiple flights (potentially by different operators) on the same route[33].

The support costs per flight have been calculated using the fuel consumption results described above, together with the same fuel price data shown in Figure 5-1. They have been calculated for both the basic scheme (in which the CfD scheme is used to offset the costs of compliance with the mandated levels of RFNBO) and the scheme in which all SAF is supported to be RFNBO. To provide context, Table 5-20 shows the increase in fuel costs for the flight due to the adoption of RFNBO under the mandate (relative to continuing to use fossil kerosene), then Table 5-21 shows how much of this additional cost can be offset through the support scheme.

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[32] The typical numbers of seats are based on the mid-point of the range of typical seat numbers given on the relevant page on the Airbus website for the aircraft type (e.g. https://aircraft.airbus.com/en/aircraft/a350-clean-sheet-clean-start/a350-900#:~:text=As%20the%20cornerstone%20member%20in,18%2C000km)%20non%2Dstop.)

[33] Assuming airlines would take a mix of biobased SAF and RNFBO SAF.

Table 5-20: Additional fuel costs per flight for selected years due to the adoption of the relevant percentage RFNBO replacing conventional kerosene (as result of mandate or scenario definition)

	FF55	DMan	No DMan	FF55++
Route 1: Paris – Stockholm				
Basic Scheme				
2030	€ 111	€ 250	€ 1,920	€ 111
2035	€ 368	€ 640	€ 2,554	€ 368
2040	€ 565	€ 1,170	€ 2,824	€ 565
Scheme with all SAF being RFNBO				
2030	€ 555	€ 564	€ 2,179	€ 555
2035	€ 1,470	€ 1,558	€ 3,289	€ 1,470
2040	€ 1,921	€ 2,114	€ 3,519	€ 1,921
Route 2: Athens – Reykjavik				
Basic Scheme				
2030	€ 319	€ 718	€ 5,522	€ 319
2035	€ 1,057	€ 1,839	€ 7,346	€ 1,057
2040	€ 1,625	€ 3,364	€ 8,121	€ 1,625
Scheme with all SAF being RFNBO				
2030	€ 1,595	€ 1,622	€ 6,267	€ 1,595
2035	€ 4,228	€ 4,482	€ 9,460	€ 4,228
2040	€ 5,526	€ 6,078	€ 10,120	€ 5,526
Route 3: Rome – Beijing				
Basic Scheme				
2030	€ 1,388	€ 3,123	€ 24,031	€ 1,388
2035	€ 4,599	€ 8,003	€ 31,964	€ 4,599
2040	€ 7,072	€ 14,639	€ 35,337	€ 7,072
Scheme with all SAF being RFNBO				
2030	€ 6,941	€ 7,056	€ 27,270	€ 6,941
2035	€ 18,398	€ 19,501	€ 41,163	€ 18,398
2040	€ 24,045	€ 26,450	€ 44,036	€ 24,045

Table 5-21: Amount (and percentage) of the additional costs due to using RFNBO in place of conventional kerosene that can be reduced through the CfD support scheme

	FF55	DMan	No DMan	FF55++
Route 1: Paris – Stockholm				
Basic Scheme				
2030	€ 70 (63.4%)	€ 158 (63.4%)	€ 293 (15.4%)	€ 70 (63.4%)

	FF55	DMan	No DMan	FF55++
2035	€ 122 (32.9%)	€ 264 (41.2%)	€ 253 (9.9%)	€ 152 (41.2%)
2040	€ 109 (19.3%)	€ 290 (24.8%)	€ 196 (6.8%)	€ 140 (24.8%)
Scheme with all SAF being RFNBO				
2030	€ 127 (22.7%)	€ 358 (63.4%)	€ 293 (13.6%)	€ 352 (63.4%)
2035	€ 122 (8.2%)	€ 352 (22.6%)	€ 253 (7.7%)	€ 364 (24.8%)
2040	€ 109 (5.7%)	€ 313 (14.8%)	€ 196 (5.5%)	€ 339 (17.7%)
Route 2: Athens – Reykjavik				
Basic Scheme				
2030	€ 202 (63.4%)	€ 455 (63.4%)	€ 842 (15.4%)	€ 202 (63.4%)
2035	€ 350 (32.9%)	€ 758 (41.2%)	€ 728 (9.9%)	€ 436 (41.2%)
2040	€ 314 (19.3%)	€ 833 (24.8%)	€ 564 (6.8%)	€ 403 (24.8%)
Scheme with all SAF being RFNBO				
2030	€ 364 (22.7%)	€ 1,029 (63.4%)	€ 842 (13.6%)	€ 1,012 (63.4%)
2035	€ 350 (8.2%)	€ 1,013 (22.6%)	€ 728 (7.7%)	€ 1,047 (24.8%)
2040	€ 314 (5.7%)	€ 899 (14.8%)	€ 564 (5.5%)	€ 976 (17.7%)
Route 3: Rome – Beijing				
Basic Scheme				
2030	€ 881 (63.4%)	€ 1,981 (63.4%)	€ 3,662 (15.4%)	€ 881 (63.4%)
2035	€ 1,523 (32.9%)	€ 3,299 (41.2%)	€ 3,169 (9.9%)	€ 1,896 (41.2%)
2040	€ 1,368 (19.3%)	€ 3,626 (24.8%)	€ 2,453 (6.8%)	€ 1,752 (24.8%)
Scheme with all SAF being RFNBO				
2030	€ 1,584 (22.7%)	€ 4,476 (63.4%)	€ 3,662 (13.6%)	€ 4,403 (63.4%)
2035	€ 1,523 (8.2%)	€ 4,406 (22.6%)	€ 3,169 (7.7%)	€ 4,556 (24.8%)

	FF55	DMan	No DMan	FF55++
2040	€ 1,368 (5.7%)	€ 3,913 (14.8%)	€ 2,453 (5.5%)	€ 4,248 (17.7%)

The levels of support cost per flight, equivalent to the reduction in fuel costs to the airline compared to a case without the CfD support scheme (but the same uptake of RFNBO) range from €70 to €4,556, depending on the scenario and the distance flown, with the latter representing approximately 60% of the additional costs to the airline for consuming RFNBO rather than conventional kerosene. It is unlikely that the lower end of the values would have much impact on an airline's operations; however, the higher values on Route 1, up to around €360 (representing 60% of the additional costs of using RFNBO), would be more likely to have an impact, particularly as such short, intra-EU, routes are often flown by low-cost carriers, which typically operate with lower margins than traditional "network" carriers and are more sensitive to cost increases. On the longer routes, the support costs are in the thousands of euros per flight. This level of support, offsetting some of the increase in fuel costs associated with the specified uptake of RFNBO, would be expected to have a significant impact on airline operating costs.

Using the costs per flight from Table 5-20, together with the seat numbers from Table 5-18 and an assumed passenger load factor of 87.7% for European flights, as recently reported by IATA (IATA, 2023d) and assumed to be constant over the period of the analysis, the costs per passenger have also been calculated, as shown in Table 5-22.

Table 5-22: Support costs per passenger on the different routes for selected years

	FF55	DMan	No DMan	FF55++
Route 1: Paris – Stockholm				
Basic Scheme				
2030	€ 0.52	€ 1.16	€ 2.15	€ 0.52
2035	€ 1.11	€ 1.94	€ 1.86	€ 1.11
2040	€ 0.80	€ 2.13	€ 1.44	€ 1.03
Scheme with all SAF being RFNBO				
2030	€ 0.93	€ 2.63	€ 2.15	€ 2.59
2035	€ 0.89	€ 2.59	€ 1.86	€ 2.68
2040	€ 0.80	€ 2.30	€ 1.44	€ 2.50
Route 2: Athens – Reykjavik				
Basic Scheme				
2030	€ 1.16	€ 2.60	€ 4.81	€ 1.16
2035	€ 2.00	€ 4.33	€ 4.16	€ 2.49
2040	€ 1.80	€ 4.76	€ 3.22	€ 2.30
Scheme with all SAF being RFNBO				
2030	€ 2.08	€ 5.88	€ 4.81	€ 5.78
2035	€ 2.00	€ 5.79	€ 4.16	€ 5.98
2040	€ 1.80	€ 5.14	€ 3.22	€ 5.58
Route 3: Rome – Beijing				
Basic Scheme				
2030	€ 3.09	€ 6.95	€ 12.85	€ 3.09

	FF55	DMan	No DMan	FF55++
2035	€ 5.34	€ 11.58	€ 11.12	€ 6.65
2040	€ 4.80	€ 12.72	€ 8.61	€ 6.15
Scheme with all SAF being RFNBO				
2030	€ 5.56	€ 15.71	€ 12.85	€ 15.45
2035	€ 5.34	€ 15.46	€ 11.12	€ 15.99
2040	€ 4.80	€ 13.73	€ 8.61	€14.90

Assuming that airlines would pass on fuel price increases to passengers through increased ticket prices at 100% pass-through, and that they would pass on lower fuel prices similarly, the support costs per passenger in Table 5-18 can also be seen as a reduction in ticket price due to the CfD scheme (compared to a situation with the same RFNBO uptake but no support scheme). Again, the changes in ticket prices identified range from levels that would be very unlikely to have any impact on demand (around €1 or less) to those that could have a more significant impact (up to €16), although the price of a ticket on the Rome-Beijing route was identified at approximately €2,200[34], so this price reduction would correspond to less than 1% of the ticket price.

5.4.2 Maritime

This section seeks to quantitatively and qualitatively explore the costs associated with switching to alternative fuels for a standard journey on three specific maritime routes for different fuel types as shown in Table 5-23, compared to using HFO. The maritime model built as part of this study uses global shipping activity as the primary input. It therefore provides an indication into the level of financial support that would be needed, via a CfD or other scheme, to help transition to alternative fuels for these voyage types. Where possible an indication on the expected transport cost increases have been provided.

Table 5-23: Selected maritime routes for analysis

Route	Distance	Typical Vessel type	Fuel type
#1 Shanghai to Valencia	18,596 km	Container	e-Methanol
#2 Santos to Rotterdam	12,499 km	Bulk Carrier	Ammonia
#3 Kristiansand to Hirtshals	228 km	Ferry (Ro-Ro)	Hydrogen

Box 3.1 describes the expected impact both quantitatively, where possible, and qualitatively on Route 1. Within the assessment fuel costs as well as vessel and infrastructure costs and considerations have been made as well as a general commentary on potential effects on container rates.

Box 3.1: Impact on Route 1

- Cost of fuel switch (2020)– €55.25/GJ fuel more expensive than HFO (700% greater cost)
- Cost of fuel switch (2050) – €24.19/GJ fuel more expensive than HFO (300% greater cost)
- Cost of new vessel – 16,000 TEU cost between $180m to $210m (dual fuel) (The Maritime Executive, 2023)
- Cost of infrastructure – Installation costs of a small methanol bunkering unit have been estimated at around € 400,000 (FCBI Energy, 2015)
- CO_2 emission reduction - ~35 tCO_2e/kg fuel WTW basis

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[34] Air China flight 940, operating on 21 November 2023 from Rome Fiumicino to Beijing Capital International Airport. Price identified via online travel agent Expedia, 7 November 2023.

Analysis conducted by the American Bureau of shipping calculated that for an Asia-Europe route the cost for vessels running on green methanol could be as high as $1,945/TEU, assuming no additional energy efficiency measures were applied to the vessel and no slow steaming. Factoring in these additional measures this could be reduced to $1,214/TEU however, this is still ~20% more than a vessel operating on VLSFO (Loadstar, 2023). Methanol is currently stored in over 100 ports worldwide and bunkering does not require significant modification to existing infrastructure.

The levels of support required under the proposed CfD scheme per voyage under Route 1 is likely to be substantial. On an energy basis methanol has the greatest cost differential compared to HVO (in comparison to ammonia and hydrogen), therefore more support is required to support a lower volume of fuel. Also, the distance travelled under this route is the largest across all routes explored again requiring greater volumes of fuel. Given that fuel costs dominate the operational costs of a vessel it is clear that the impact on freight rates could well be in excess of those quoted above without a CfD scheme in place to mitigate the dramatic increase in fuel costs associated with using methanol as a fuel.

China to Europe is a popular trade route and a CfD scheme could be well-served decarbonising this heavily trafficked route. Shanghai and Valenca, as key ports are likely to rapidly install the necessary infrastructure to meet the demand from vessels running on alternative fuels which could also propagate methanol use by other vessels trading out of these ports. So although CfD funds may not be able to support large quantities of methanol use along this route there could be wider benefits to the sector. Support for methanol along this route would also reduce CO_2 emissions by the greatest amount across all 3 routes examined (assuming methanol is sourced from DACC).

Box 3.2 describes the expected impact both quantitatively, where possible, and qualitatively on Route 2. Within the assessment fuel costs as well as vessel and infrastructure costs and considerations have been made. There is less literature data available and price breakdown for bulk cargo rates so a more generalised commentary on expected impacts has been provided.

Box 3.2: Impact on Route 2

- Cost of fuel switch (2020)– €26.66/GJ fuel more expensive than HFO (350% greater cost)
- Cost of fuel switch (2050) – €18.95/GJ fuel more expensive than HFO (200% greater cost)
- Cost of new vessel – Average cost $49.6m + $22m for ammonia-ready status (Navigation, 2023) (Lloyds List, 2022)
- Cost of infrastructure - No ammonia bunkering facility in operation
- CO_2 emission reduction - ~27.5 tCO_2e/kg fuel WTW basis

The lower cost per kg of ammonia and lower WTW GHG emissions compared to other fuel types makes it a highly suitable candidate for support through a CfD scheme as the ETS revenue generated can go further and have a higher degree of impact. Applying that to a bulk carrier, where traditionally build costs are lower than other vessel types it could be a sign of encouragement for vessel owners to further invest in upgrading their fleets to run off ammonia as the TCO costs are lower compared to other combinations of vessel and fuel types.

The levels of support required under the proposed CfD scheme per voyage under Route 2 will be lower than that required for Route 1. On an energy basis ammonia has a lower cost differential to HFO compared to methanol therefore support via a CfD can be utilised to support a greater volume of fuel. From the analysis conducted in Section 5.3.2 it was modelled that there would be enough support for ammonia beyond the expected uptake so further support could be extended to other vessels operating on this route or out of these two port locations.

Santos and Rotterdam are strategic regional ports and support via a CfD scheme for vessels operating on ammonia between these 2 ports could help the formation of a green shipping corridor to support the trade of mineral and vegetable products.

Box 3.3 describes the expected impact both quantitatively, where possible, and qualitatively on Route 3. Within the assessment fuel costs as well as vessel and infrastructure costs and considerations have been made. In the Scandinavian context the governments in that part of the world have been very supportive of adopting zero emission infrastructure (Cox, 2021; Valeur, 2024; Invest in Denmark, 2022) and a commentary has been provided on this alongside some recommendations on appropriateness for a CfD scheme along this route.

Box 3.3: Impact on Route 3

- Cost of fuel switch (2020)– €30.97/GJ fuel more expensive than HFO (400% greater cost)
- Cost of fuel switch (2050) – €8.67/GJ fuel more expensive than HFO (100% greater cost)
- Cost of new vessel – $78m for existing vessel, from external modelling expect hydrogen vessel to cost 26% more (Aarskog, et al., 2020)
- Cost of infrastructure – although several ports have hydrogen refuelling systems limited public information is available on installation costs however, capital costs estimates for new fuelling stations in California varied between $1,200 and 3,000 per kilogram hydrogen dispensed per day (kg/day) (US Department of Energy, 2021).
- CO_2 emission reduction - ~3 tCO_2e/kg fuel WTW basis

Given the significantly higher fuel costs of running the ferry service, the additional cost of purchasing a hydrogen powered vessel and additional costs of installing new fuelling infrastructure it is almost certain passengers travelling along this route would experience a cost increase without outside intervention. A fuel only CfD scheme would go some way towards mitigating cost increases for the passenger but owing to vessel and infrastructure costs there would still be an overall increase in ticket prices unless further support for infrastructure costs was obtained from national governments in Norway and Denmark.
In terms of maximising the impact of the CfD scheme, this route has the lowest overall GHG impact, due to the short distance. However, as the cost differential between hydrogen and HFO is the lowest (across methanol, ammonia and hydrogen) and decreases significantly over time there is the ability to support many small routes such as Route 3 via a CfD scheme which collectively could have a larger GHG saving potential.

In comparison to methanol and ammonia the cost of hydrogen on an energy basis is slightly more expensive than ammonia yet cheaper than methanol in 2020. Over time towards 2050 hydrogen becomes the cheapest fuel on an energy basis. A consideration for the implementing the CfD scheme is which fuels to support and at which point in time. The scheme could be used to subsidise routes or fuels with the largest cost differential thus mitigating economic impacts being passed on to consumers or it could be used to support fuels with the lowest cost differential thus allowing more volume of fuel to be supported. This would create a demand for such fuels and through economies of scale of production the cost of these fuels would reduce over time to a point where a CfD scheme may no longer be necessary.

5.5 EFFECTS OF ECONOMY OF SCALE

A high-level review has been made of the potential for reductions in the production costs, and hence prices, of RFNBO as a result of the increased uptake due to the support scheme (i.e., economies of scale effects). This review has focussed on the available literature on future developments of RFNBO production, including costs reductions over time.

CRU have studied the costs of producing green ammonia (CRU Group, 2022), and the potential for reducing those costs. They note that the main costs involved are the costs of renewable electricity, the electrolyser capital cost and its efficiency. The application of a “credible set of sensitivities”, reflecting technological improvements (and thus economies of scale), but also economic factors (reduction in discount rate applied, tax breaks, etc.) gave a significant reduction in costs (by about 35% relative to their base case), although the price for green ammonia remained above that for “grey” ammonia.

The dependence of the costs of producing green ammonia on the costs of renewable electricity and electrolysers is important, as these elements are included in the production of all RFNBO fuels. In another study on the production of green ammonia, Ravi and Makepeace (Ravi & Makepeace, 2022) note that, unlike the production of hydrogen from fossil fuel, the production by electrolysis of water (using renewable energy) does not benefit from economies of scale. This is because electrolysers are modular in nature and well suited to small scale production.

On the other hand, in 2020, the Hydrogen Council (Hydrogen Council, 2020) noted that production costs for green hydrogen could reduce by 60% by 2030 due to a combination of manufacturing scale, learning rate, technological improvements and increased module size. The main contributions to this are the widescale deployment of electrolysis capability and significant results in the cost of renewable electricity from offshore wind.

A key feature of the above reports, particularly that from the Hydrogen Council, is that the reductions in cost arise from massive investments in renewable electricity generation capability that are required for the wider society, not just transport fuels. The extent to which support for an increased uptake of RFNBO in the aviation or maritime sector would further increase this, and hence further reduce the costs of producing green hydrogen and hence RFNBO fuels, is not clear but is likely to be a relatively small effect. When considering the potential impact that the scheme could have on fuel prices in the context of the results presented in this study, it should also be noted that the prices for RFNBO obtained from the sources used for these calculations already show price reductions over time, which are likely to take into account assumptions of the impacts of economies of scale on production costs.

To add more insight into the price reductions already included in the sources used, the information on fuel costs in the ReFuelEU Aviation study (the primary source for SAF prices for aviation) was examined (European Commission, 2021d). The study report confirmed that “*in the model logic prices derive from the equilibrium of demand and supply*” and “*The analysis of the costs of plants for fully commercialised technologies (Nth plant analysis) also expects capital investments and related costs (e.g., maintenance) to be a driver of cost reduction compared to pioneer plants*”. Thus, the ReFuelEU Aviation study assumed that the uptake of alternative fuels, driven by the mandate, would lead to reductions in production costs and price.

In the aviation context, it is important to note that these cost reductions (and associated fuel price reductions) are already included in the results of the analysis and are driven by the increased uptake in SAF due to the mandate. In the ReFuelEU Aviation study, continued increases in SAF uptake do not lead to further reductions in fuel costs after the initial learning phase and, therefore, it is not clear that additional uptake of RFNBO due to the CfD support would lead to further reductions in RFNBO prices beyond the expectations for the initial reduction due to increasing demand (noting that, as described in this report, only the “All SAF being RFNBO” scheme leads to additional RFNBO uptake; the Basic Scheme does not support additional RFNBO uptake beyond the mandate).

In the maritime context, it is assumed that within the literature values obtained for the RFNBO prices over time some consideration has already been made to account for the effects of economies of scale and thus indirectly included into the maritime model already. It may be the case that introduction of the CfD scheme further drives the uptake of RFNBOs in the maritime sector and subsequently improves the effect of economies of scale beyond the original literature price projections. Given that the production of hydrogen is a key limiting factor in scaling RFNBO production from a cost perspective, from the literature analysis conducted upon economies of scale it is predicted that introduction of a CfD may not have a substantial additional effect beyond what is indirectly included in the fuel pricing.

6. SUMMARY AND CONCLUSIONS

This report has assessed the different possibilities of using support mechanisms such as CfDs, CCfDs and fixed premiums to incentivise production and uptake of RFNBO fuels in the maritime and aviation sector. The main findings are:

- Public support schemes can provide the necessary incentives to accelerate the uptake of RFNBOs in the aviation and maritime sector, which are currently struggling to decarbonise at pace.
- The types of schemes analysed in this report (CfDs, CCfDs and fixed premiums) are alternative options to meet this goal. Based on the assumptions outlined in earlier sections, we find that:
    - Supply-side CfDs provide certainty to producers and could be used to promote the scaling up of RFNBOs. Based on experience from other sectors (e.g. renewable electricity generation), CfDs can be a flexible and relatively administratively-light instrument to implement. We recommend that CfDs for both sectors are based on technology-specific auctions to determine the appropriate strike-price.
    - Demand-side CfDs can be introduced to support the deployment of fuels which require dedicated infrastructure and retro-fitting of engines on board vessels and aircraft (e.g. ammonia). In this case, a demand-side CfD can coexist alongside a supply-side CfD in a given sector, provided that any distortions are limited at policy design stage.
    - Alternatively, regulators may wish to design the support scheme by hedging the strike-price against the value of carbon credits – in the EU, this would be the case of a CCfD pegged against the EU ETS scheme. Whilst the potential benefit of the scheme is that it would provide certainty of rewards for producers who abate emissions, it could be less effective at targeting GHG reductions given its link with carbon (not fuel) prices, and would be harder to set up and administer.
    - Fixed premiums act, instead, as a fixed subsidy and would generally be easier to implement than CfDs. However, the burden of administering a subsidy scheme can increase exponentially as commodity prices fluctuate and adjustments are needed to ensure that distortions are limited. This renders fixed premiums less effective in the market for fuels, where prices are likely to vary significantly over the next few years.
- For all public support schemes, it is imperative that the design features consider interactions with existing policy and regulatory frameworks. An example of the latter is the potential interaction between supply-side CfD schemes and the mandates for alternative, low-carbon fuels under aviation at EU level. In the case of aviation, the existence of a mandate for a minimum uptake of SAF, including a sub-mandate for RFNBO, under the ReFuelEU Aviation Regulation, ensures that a certain level of RFNBO will be used. In this case, a demand-side CfD may provide improved benefits, as it incentivises airlines to increase the proportion of RFNBO that they use. In the absence of a firm mandate for the maritime sector, implementation of a CfD scheme could serve as basis to increase the level of ambition of this mandate as upon the basis of the maritime modelling work conducted under this study a CfD scheme could easily facilitate RFNBO uptake far beyond the requirements of FuelEU.

6.1 COMPARISONS OF SUPPORT SCHEME DESIGN

Table 6-1 and Table 6-2 below outline the pros and cons of different public support schemes for the aviation and maritime sectors, respectively.

Table 6-1. Pros and cons of public support schemes for Aviation

Support scheme	Pros	Cons
Supply-side Contracts for Difference schemes	Supply-side CfDs provide a stable revenue per unit e-kerosene sold on the market that can reduce investor risk. A set quantity of e-kerosene procured can ensure the industry mobilises quickly enough and at the scale needed.	As the reference price for a supply-side CfD for e-kerosene is the biofuels price, a drop in the biofuels price will increase the cost to the CfD counterparty. Conversely, if the biofuels price increases above the strike price for e-kerosene, then e-

Support scheme	Pros	Cons
		kerosene producers will not benefit from this higher price.
Demand-side Contracts for Difference schemes	E-kerosene is expected to be blended with fossil kerosene for use by airlines. A demand-side CfD would allow airlines to purchase subsidised e-kerosene at stable prices.	With an EU mandate on RFNBO in aviation fuel, demand would be set by the mandate and a demand-side CfD could act as a secondary incentive. A demand-side CfD may subsidise unnecessarily and may not provide value for money for taxpayers funding the subsidy.
Carbon Contracts for Difference schemes	To produce e-kerosene, large quantities of CO_2 are needed in the process. This will need to be captured either by a fossil fuel combustion plant with CCUS or through direct air carbon capture (DACC). As power plants are already covered by the EU ETS, and must purchase allowances (EUAs), they will not earn EUAs from capturing CO_2. Thus, it is likely that DACC will be more suitable to a CCfD. A CCfD can provide a stable revenue of EUA sales, which can incentivise investments in DACC facilities.	As aviation will not receive free allocation of allowances after 2026 in the EU ETS, and all SAF will be zero-rated (allowances will not need to be purchased for either biofuel of RFNBO SAF), a CCfD will not be a suitable instrument for incentivising a switch from fossil fuels to renewable fuels when allowances are auctioned.
Fixed premium schemes	Fixed premium schemes provide a fixed top-up that can help bridge the revenue gap between what producers need to operate profitably and what consumers are willing to pay for e-kerosene. Fixed premium schemes limit the risk to the government, as it has some certainty on the cost of the scheme ahead of implementation. Setting a quantity cap can allow for full certainty on total cost of the scheme.	Fixed premium schemes do not guarantee a fixed revenue per unit of e-kerosene, as it also depends on the market price. Thus, an artificially low market price can hurt the producers of e-kerosene.

Maritime

Table 6-2. Pros and cons of public support schemes for Maritime

Support scheme	Pros	Cons
Supply-side Contracts for Difference schemes	Supply-side CfDs provide a stable revenue per unit of e-ammonia sold on the market that can reduce investor risk. A set quantity of e-ammonia procured can ensure the industry mobilises quickly enough and at the scale needed.	A supply-side CfD can create uncertainty on the costs to the CfD counterparty. A drop in the ammonia price will increase the cost to the CfD counterparty. Conversely, if the e-ammonia price increases above the strike price for e-ammonia, then e-ammonia producers will not benefit from this higher price.

Support scheme	Pros	Cons
Demand-side Contracts for Difference schemes	To use ammonia as a fuel, vessel operators are likely to incur additional operating costs and lose cargo volume due to extra safety/fuel storage systems onboard. To incentivise these investments, a demand-side CfD that covers the total cost of ownership (TCO) of running ships on ammonia can be implemented. Demand-side CfDs provide a stable price for which vessel operators can purchase e-ammonia, ensuring predictability in their costs.	A demand-side CfD may not mobilise the value chain for e-ammonia at the pace and scale needed.
Carbon Contracts for Difference schemes	If ETS allowances were allocated for free, ship owners could benefit by selling spare allowances when using e-ammonia as fuel. A CCfD can provide a stable carbon price and thus a long-term incentive for investing in emission reduction technology in this scenario.	As the maritime sector will be included in the EU ETS from 2024 with the auctioning of allowances, CCfD is not a suitable instrument to incentivise a switch from fossil fuels to e-ammonia. Auctioning means ship operators must purchase allowances, and thus do not benefit from earning allowances from emission reduction measures.
Fixed premium schemes	Fixed premium schemes limit the risk to the government, as it has certainty on the cost of the scheme as the fixed premia schemes are usually determined ahead of implementation.	Fixed premium schemes do not guarantee a fixed revenue per unit of e-ammonia, as it also depends on the market price. An artificially low market price can hurt the producers of e-ammonia.

6.2 FINDINGS FOR THE AVIATION SECTOR

Following identification of CfDs as a possible candidate to support the scale up of RFNBOs, a model was created and applied to the aviation sector. A summary of the approach applied and the key results on the potential for CfD in terms of size, scope and fuel penetration are presented below.

The analysis of the CfD scheme for the aviation sector considered four scenarios:

- **FF55:** a business-as-usual scenario, with alternative fuel mandates as agreed by the EU Parliament and Council and the EU ETS with the agreed phase-out of free allowances.
- **DMan:** a scenario with passenger transport demand capped at 2019 levels, delivering almost 100% carbon neutrality for the sector by 2050;
- **No DMan:** a scenario with increased uptake of RFNBO to deliver the same reductions in emissions found from DMan, also delivering almost 100% carbon neutrality by 2050;
- **FF55++:** a “Fit for 55 +” scenario, with the EU ETS extended to all EEA departing flights, giving significant reductions in emissions relative to FF55, but not delivering full carbon neutrality by 2050.

Under each scenario, two options for the CfD scheme implementation were considered:

iii. A “Basic scheme”, with the CfD used to reduce the costs to aircraft operators of the mandated uptake of RFNBO under the ReFuelEU Aviation Regulation, by effectively reducing the price of RFNBO to that of biofuel-based SAF;

iv. A scheme in which the CfD has the aim of increasing RFNBO uptake to the full SAF mandate (i.e. displacing all biofuel-based SAF) at least to the extent that can be supported by the available funding.

For the aviation sector, there is already a requirement for significant levels of SAF use in future years mandated under the ReFuelEU Aviation Regulation. Therefore, the primary focus of the CfD scheme being investigated is to increase the proportion of RFNBO consumed within the mandate by displacing the biofuel SAF content. To achieve this, the target for the application of the scheme is to reduce the price difference between RFNBO and biofuel SAF (giving an effective subsidy for RFNBO varying from €1,040 per tonne (35%) in 2025 to €370 (16%) in 2040), rather than between RFNBO and fossil kerosene (which would significantly limit the quantity of RFNBO that could be supported under the scheme as the price difference would be significantly greater than that to biofuel SAF). Thus, the existence of a CfD scheme could enhance the environmental benefits provided by the overall ReFuelEU Aviation mandate.

Under the basic scheme, the full mandated RFNBO uptake can be supported at 100% of the price difference between RFNBO and biofuel-based SAF only under the DMan and FF55++ scenarios, as the available funding falls short of that required under the FF55 and No DMan scenarios. Under DMan, this results in a total RFNBO uptake between 2025 and 2039 (across two CfD auction periods) of 27.1 million tonnes at a scheme cost of €19.9 billion, while under FF55++, 22.1 million tonnes of RFNBO are supported at a cost of €15.5 billion. Under the FF55 scenario, the funding available is less, leading to 18.0 million tonnes (80% of total RFNBO uptake) being supported at a scheme cost of €13.3 billion; the full RFNBO consumption can be supported during the first auction period (2025 to 2034); the shortfall occurs during the second period (2030 to 2039). To meet the emissions reductions of DMan, with the full passenger transport demand, No DMan requires a RFNBO uptake significantly greater than the mandate. This results in slightly greater than 20% of RFNBO used being supported by the scheme; however, the total RFNBO supported is still greater than under the other scenarios at 40.9 million tonnes at a scheme cost of €34.8 billion.

Under the scheme supporting the uptake of RFNBO up to the total SAF mandate, the analysis calculated an increased quantity of RFNBO that could be supported; however, the scheme was not able to support 100% of the total RFNBO consumed under any scenario. The results for the different scenarios were:

- **FF55:** 22.1 million tonnes (25% total RFNBO consumption) at a scheme cost of €18.1 billion;
- **DMan:** 36.1 million tonnes (61% total RFNBO consumption) at a scheme cost of €29.3 billion;
- **No DMan:** 40.9 million tonnes (21% total RFNBO consumption) at a scheme cost of €34.8 billion;
- **FF55++:** 58.6 million tonnes (67% total RFNBO consumption) at a scheme cost of €45.4 billion.

Under the FF55 scenario, the RFNBO content of the total fuel mix is increased from (the mandated) 1.2% in 2030 in the absence of the CfD scheme to 2.1%, with little effect seen thereafter. Under the FF55++ scenario, the increases in RFNBO in the fuel mix due to the CfD scheme occur through to 2040, with increases from 1.2% to 6.1% in 2030, from 5.0% to 12.0% in 2035 and from 10.0% to 24.3% in 2040. In each case, the increase in RFNBO use is accompanied by an equivalent reduction in biofuel SAF consumption.

A further option was also considered in which remaining funding (after support was provided for all mandated SAF to be RFNBO) could be used to support additional displacement of fossil kerosene (giving a total RFNBO uptake greater than the mandated SAF uptake of all kinds). To achieve this, the additional support would be provided on the basis of the price difference between RFNBO and fossil kerosene, rather than between RFNBO and biofuel SAF. The additional RFNBO uptake under this scheme was small (and only occurred during the first auction period), so the additional complexity of the scheme may result in it not being cost-effective.

Results have also been presented for schemes in which only 60% of the price difference (between RFNBO and biofuel SAF or between RFNBO and fossil kerosene) is covered by the CfD. These show a greater quantity of RFNBO can be supported, but the benefit to the airlines is less (RFNBO remains more expensive than biofuel SAF), so the extent to which it would promote an increased uptake of RFNBO beyond the mandate is not clear.

Under the basic scheme, the key benefit of the CfD scheme is that it enables airlines to meet the obligations for RFNBO use under the ReFuelEU Aviation mandate, while limiting their cost increases to those that would occur if the full mandated SAF could be met by biofuel alone. This would reduce the impact of the regulation on their ability to meet the demand for passenger travel (by limiting the ticket price increase). However, it would not lead to any increase in RFNBO in the fuel mix and, hence, would not deliver any additional environmental benefits. Under the scheme supporting RFNBO uptake up to the total SAF mandate, the environmental impact would be substantially greater, with a reduction in biofuel SAF use and a commensurate increase in RFNBO use, particularly under the FF55++ scenario.

Overall, based on the analysis performed, the option that is expected to have the greatest impact on RFNBO uptake is FF55++ (i.e., one in which the expected SAF mandate and changes to aviation fuel taxation are implemented and the EU ETS is extended to all flights departing EEA airports). The support scheme would be designed to support RFNBO uptake at the price difference between RFNBO and biofuel and for quantities of RFNBO up to the total SAF mandate (i.e., exceeding the RFNBO sub-mandate). This should support a total quantity of RFNBO 58.6 million tonnes across the two auction periods (of a total RFNBO uptake of 87.3 million tonnes) at a scheme cost of €45.4 billion (equivalent to €774.74 per tonne, or approximately €18 per GJ).

6.3 FINDINGS FOR THE MARITIME SECTOR

For the maritime sector results a bespoke Excel-based model was created to simulate a CfD scheme. The model calculates EU ETS revenue generation under 4 identified scenarios and then takes 25% of the generated revenue and makes it available to support RFNBO uptake in the sector it assumes that any revenue generated in a given year in all fully utilised in-year to support RFNBO uptake. For the modelled maritime sector scenarios, the following results were found:

The analysis of the CfD scheme for the maritime sector considered four scenarios:

- **FEUM:** a baseline scenario with an emission intensity reduction target of 80% by 2050 and RFNBO sub-quota of 2%.
- **FEUM + efficiency:** As FEUM scenario but incorporating additional energy efficiency measures as per the IMO 4th GHG Study by vessel type until 2023 and then interpolating up to 38.6% additional energy efficiency by 2050.
- **DE_DK:** a scenario with a required 100% emission intensity reduction by 2050 and RFNBO sub-quota of 2% in 2030 rising to 70% in 2050.
- **DE_DK + efficiency:** As DE_DK scenario but incorporating additional energy efficiency measures as per the IMO 4th GHG Study by vessel type until 2023 and then interpolating up to 38.6% additional energy efficiency by 2050.

Under each scenario the available ETS revenue to support RFNBO uptake was calculated (25% of total available) and allocated out to see how much could be supported during the auction periods (2025-2039). It was assumed that the ETS revenue would be used to 100% fund the price gap between fossil fuels and RFNBOs based upon their expected market costs over time.

- **FEUM:** €40.7 billion total revenue available across both auction periods
- **FEUM + efficiency:** €36.1 billion total revenue available across both auction periods
- **DE_DK**: €39.5 billion total revenue available across both auction periods
- **DE_DK + efficiency:** €35.1 billion total revenue available across both auction periods

The revenue available from the ETS was allocated in a number of different ways. Proportionally to the expected uptake of each RFNBO, split equally across RFNBOs and solely to support e-ammonia.

Proportional allocation

- Under the FEUM scenarios e-ammonia is the only RFNBO expected to be in the fuel mix during the auction period. Under the proposed CfD scheme prior to 2036 there is sufficient revenue generated within the EU ETS (at 25%) to fully support the expected uptake of e-ammonia. Furthermore, there is excess revenue available to support additional e-ammonia uptake beyond the expected levels. This additional revenue can support up to 5-9% of the total fuel consumption by the maritime sector during the period 2025-2036. After 2036 the expected uptake of e-ammonia exponentially increases and there is no longer sufficient support under the CfD scheme to fully subsidise this uptake. Through the CfD scheme across the auction period 5% (increasing to 9%) of the total fuel consumed can be fully supported. This exceeds the RFNBO targets set out in FuelEU Maritime and also aligns broadly consistent with the IMO indicative checkpoint targets of achieving 5% of fuel from zero or near-zero sources by 2030 and 10% by 2040.
- Under the DE_DK scenario e-ammonia, e-LNG and e-diesel are all RFNBOs with expected uptake under this scenario. E-ammonia can again be fully supported under the proposed CfD scheme in this scenario prior to 2036 and there is also some additional revenue generated to support e-ammonia uptake beyond its expected uptake. The amount of additional revenue is lower compared to the FEUM scenario as within the DE_DK scenario the natural expected uptake of e-ammonia is higher. That

being said the additional revenue generated is still able to support 3.6% rising to 9% of the total fuel consumed across the auction period.

With e-LNG and e-diesel there is a small amount of expected uptake early on in the auction period (2025-2030) throughout this period there is sufficient revenue generated under the ETS (at 25%) to fully support the uptake of e-LNG. There is also surplus revenue generate to support additional e-LNG uptake peaking at 1.5% of the total fuel consumption in 2025. After 2030 no further e-LNG uptake is expected under this scenario.

It is a similar case for e-diesel with a small initial uptake expected which can be fully supported under the CfD scheme. To a lesser extent additional e-diesel can be supported peaking at 0.4% of the total fuel consumption. Again post 2030 no further uptake of e-diesel is expected during the auction years.

Equal allocation

- Under the FEUM scenarios e-ammonia expected uptake can be fully supported under the proposed CfD scheme prior to 2032 and there is additional revenue during the years 2025-2032 to support up to 1.8% of the total fuel consumption as e-ammonia. Beyond this point the level of e-ammonia that can be supported remains ~2% whereas the expected uptake increases significantly beyond the levels of revenue generated.

  There is no expected uptake of other RFNBOs under this scenario during the auction period. However, under an equal allocation revenue dispersion mechanism there is revenue allocated to support these RFNBOs. A peak of 1.2% of the total fuel consumption can be supported as e-methanol, a 1.1% peak can be supported as e-LNG and a peak of 0.4% can be supported as e-diesel.
- Under the DE_DK scenarios expected e-ammonia uptake can only be support until 2030 with limited surplus revenue available to support further uptake.

  There is expected uptake of e-LNG and e-diesel during the auction period in this scenario and through equal allocation there is ample revenue available to fully support the uptake of these fuels. E-LNG can be supported up to a peak of 1.1% of the total fuel consumption and e-diesel supported up to a peak of 0.4%. E-methanol can additionally be supported up to a peak of 1.1% of total fuel consumption even though there is no expected uptake.

Funding 60% of price differential

Results have also been presented for schemes in which only 60% of the price difference (between RFNBO and fossil fuels is covered by the CfD – these are shown in Appendix 2. These show a greater overall quantity of RFNBO can be supported.

- Under the FEUM scenarios e-ammonia is the only RFNBO expected to be in the fuel mix during the auction period (Table A2-1). Full subsidisation of the price differential of e-ammonia can be achieved up to 2037 (1 year more than in the 100% price differential subsidisation case). There also additional revenue available to support additional e-ammonia uptake beyond the expected levels. This additional revenue can support up to 8-15% of the total fuel consumption by the maritime sector during the period 2025-2037. After 2037 the expected uptake of e-ammonia increases beyond the level of support available (Figure A2-11).
- Under the DE_DK scenario e-ammonia, e-LNG and e-diesel are all RFNBOs with expected uptake under this scenario (Table A2-2). E-ammonia can again be fully supported under the proposed CfD scheme in this scenario again prior to 2037 and there is also some additional revenue generated to support e-ammonia uptake beyond its expected uptake (Figure A2-12). The amount of additional revenue is lower compared to the FEUM scenario as within the DE_DK scenario the natural expected uptake of e-ammonia is higher. The additional revenue generated in this case is able to support 5% rising to 13% of the total fuel consumed across the auction period however in 2035 under this scheme a peak of 15% of total fuel consumption can be supported. This is due to the fact beyond 2035 there is a rapid increase in the expected RFNBO uptake therefore ETS revenue payments decrease beyond this point.

  With e-LNG and e-diesel there is a small amount of expected uptake early on in the auction period (2025-2030) throughout this period there is sufficient revenue generated under the ETS (at 25%) to fully support the uptake of e-LNG. There is also surplus revenue generate to support additional e-LNG uptake peaking at 2.5% of the total fuel consumption in 2025. After 2030 no further e-LNG uptake is expected under this scenario.

It is a similar case for e-diesel with a small initial uptake expected which can be fully support under the CfD scheme. To a lesser extent additional e-diesel can be supported peaking at 0.6% of the total fuel consumption. Again post 2030 no further uptake of e-diesel is expected during the auction years.

Overall, the best option for scheme design, and ETS revenue allocation, is dependent on the overall objectives of initiating the CfD scheme. If the aim is to solely stimulate as much RFNBO uptake as possible a lower subsidy rate (60% as opposed to 100%) is the preferred option.

When choosing between allocating the ETS revenue on a proportional, equal or only to e-ammonia basis the choice of “best” scheme design is subjective. An equal allocation basis would give industry support for production and use of a wider range of RNFBOs (e-ammonia, e-methanol and e-LNG) this could be a more technology agnostic approach to follow and from the results of the modelling work conducted could serve as a springboard for greater uptake of e-LNG and e-methanol than predicted under the modelled scenarios. Allocating on a proportional basis seeks to back whichever fuel (e-ammonia in this case) has the greatest long term promise as a future marine fuel. This approach is less agnostic but it would avoid spending public funds on fuels that may not stand the test of time. Allocating to only e-ammonia provides a clear sign to industry that e-ammonia will be the future fuel of the global shipping industry and give a clear signal and confidence to investors to transition to ammonia-powered vessels. Whilst providing greater certainty caution must be taken as some companies may have already invested, or are planning on investing, in alternative technologies and may feel aggrieved if public funds are also not available for the fuel technology they have selected.

6.4 FINAL CONCLUSIONS

This study has provided a useful top-level overview of the potential for a CfD scheme in aviation and maritime sectors, including potential size, scope, key risks, and the subsequent impacts which may occur.

It has demonstrated that a CfD may be a feasible option to support RFNBO scale up within the maritime and aviation sectors. Whilst not clear cut, the research conducted would suggest that the options:

- **For the aviation sector,** the scheme is based on a budget of 25% of revenues from the EU ETS and that it is used to support uptake of RFNBO up to the total SAF mandate levels in the ReFuelEU Aviation regulation. The greatest impact will be obtained if the EU ETS is also extended to all flights departing EEA airports (including extra-EEA flights).

  To produce e-kerosene, a supply-side CfD can be used (and already are used in some countries) to incentivise increased production of green electricity (solar and wind farms); a supply-side CfD can also be used to incentivise investments in electrolyser capacity and the production of green hydrogen. Whilst a CCfD would incentivise capture CO_2 from existing unabated power plants. The aviation mandate on SAF should sufficiently incentivise aviation operators to adopt e-kerosene without requiring a demand-side CfD. The aviation sector would then have to absorb the costs of purchasing e-kerosene on the market and may decide to pass on some or all of the cost increase to consumers.

- **For the maritime sector,** a CfD scheme may be feasible to accelerate the uptake of RFNBOs in the short-medium terms (2035 and earlier). In the modelling performed, the CfD scheme has shown that utilising 25% of the revenue generated from maritime elements of the EU ETS has the potential to support RFNBO use beyond what is expected from the baseline scenarios in the earlier years that the scheme is active. This could have a benefit beyond the life of the scheme as greater RFNBO utilisation will lead to greater levels of production and, through economies of scale, reduce the cost and increase the uptake even further.

  To produce e-ammonia and other RFNBOs, a similar process can be used to that of aviation. A supply-side CfD incentivise production of green electricity, a supply-side CfD can be used to incentivise investments in electrolyser capacity and the production of green hydrogen. Support for nitrogen production may be needed. A further supply-side CfD can be used to incentivise the production of e-ammonia from the inputs higher up the value chain. Finally, a demand-side CfD can incentivise the consumption of e-ammonia in the maritime sector. A TCO demand-side CfD can support vessel operators with the cost of retrofitting and adapting ships to run on ammonia.

Whether multiple CfDs along the fuels value chain are needed depends on the structure of the value chain and the coordination amongst stakeholders. If the sector is split into different companies operating at different points of the fuels value chain, a CfD at each stage may be required to incentivise investments at the scale and pace required. If a large vertically integrated company operates across the fuels value chain (producing green electricity, owns electrolysers and CCUS power plants), it would be beneficial to only place the CfD at the last stage of the fuel value chain in which it operates, to avoid any conflicts of interest of a vertically integrated company having multiple CfDs along the fuels value chain. If there is limited competition in CfD auctions or in the wholesale market, governments could restrict companies to only bid for CfDs at a single point in the fuels value chain.

Whilst possible, Ricardo suggests a demand-side only scheme (placed at the consumption of RFNBOs) would make it harder ensure the scheme is effective across the full fuels value chain, and each agent in the fuels value chain have the correct incentives to invest at the scale and pace needed.

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8. APPENDICES

8.1 APPENDIX 1: RISK REGISTER

OBJECTIVE AND SCOPE

The objective of the Risk Register is to provide a clear overview of key issues arising for aviation and maritime supply chains as a result of the implementation of a CfD. Risks identified, without mitigation may inhibit the successful uptake of RFNBOs and the implementation of an effective, suitable, and flexible scheme.

The initial goal was to:

1) Identify key risks and describe their impact without mitigation.
2) Align appropriate mitigation solutions with the recognised risks. Specifically, through application of the best known and available solutions (such as scheme design mechanisms and government policy) to reduce or fully mitigate their adverse impact.

By evaluating impacts of a CfD across both aviation and maritime supply chains we captured risks with varying degrees of directness. These have been categorised as 'direct risks' and 'indirect risks':

1) **Direct risks** have a clear and immediate impact on the success and viability of the scheme.
2) **Indirect risks** affect the scheme through reduced demand and/or supply of RFNBOs.

A1.1.1 Risk types

Eleven risk categories were identified across common, aviation and maritime themes. These 'risk types' are presented below in Table A1-1, alongside their average risk rating, a high-level description, and some exemplar risks. Whilst risks are separated into risk types, it should be noted that there can be interplay across several categories. For clarity, risks have been assigned to the risk type which best relates to the ultimate impact of the risk.

Table A1-1: Descriptions and examples for risk type categories

Risk type (count)	Average risk rating	High-level description	Risk examples
Competition (6)	**4.3**	Mostly risks relating to the effect that fuels outside the scheme's scope will have on the supply of EU RFNBOs.	• Competition with cheap RFNBO imports in aviation. • Competition with blend-in fuels in Maritime.
Contractual and Financial (3)	**4.3**	Uncertainties/design in contracts and financial relationships across supply chain impacting effectiveness of CfD scheme.	• Long-term nature of CfD contracts • Risk of companies defaulting on commitments
Cost (3)	**7.5**	Increased costs – both from higher upfront CAPEX investment and increased operational costs dampen incentives for uptake (reduced demand).	• High cost of retrofitting ships
Demand-side (3)	**4.7**	Weak demand signals birthed from the complex nature of industry and its alternative fuels development.	• Long life span and low replacement rates of current fleets • Demand specific to green corridors
Perception (2)	**4**	Views which perpetuate reduced support for and slow growth within the RFNBO industry.	• Negative views on safety and performance • Vested interest and lobbying for different technologies
Price (6)	**5.3**	Mostly relating to the high price of H2 but also surrounding EU ETS and willingness to pay.	• Fluctuating ETS price causing budgetary forecast issues

Risk type (count)	Average risk rating	High-level description	Risk examples
			● Low willingness to pay for zero-emission solutions
Regulatory and policy (7)	**5.6**	Aspects relating to potential scheme design but also immature regulatory environments.	● Scheme design - schemes only applying to fuel producers or missing mechanisms. ● Weak H2 regulatory environment ● Less ambitious RFNBO targets in Maritime
Scope (3)	**2.3**	Impacts of scheme outside of the EU and scope of support mechanism.	● Sales to non-EU operators ● Fuel only versus TCO
Supply-side (10)	**4.2**	Mostly supply-side constraints which slow RFNBO availability and scaling.	● Production capacity limits ● Technologies scaling asymmetrically. ● Logistical constraints on RFNBO production
Technological (4)	**4.25**	Uncertain path and potential success of RFNBOs.	● Impact of alternative technologies ● Technology path 'lock-in'

Table A2-1 shows that the average risk ratings are broadly similar for most risk types (eight out of 10 risk types with more than one risk are between four and 5.3). Only scope and cost deviate notably from this central cluster of scores. Scope risks are particularly low, suggesting adverse effects borne from the scheme's international interactions are not of high concern. Conversely, risks relating to cost are shown to be of high concern.

A1.1.2 **Defining impacts**

Risks fall broadly into three categories of impact type, which capture the section of the supply chain in which the risk impacts:

- **Demand-side impacts:** these are impacts which reduce the incentive for operators and vessel owners to uptake RFNBOs, or, which reduce the incentive to continually invest in zero emission technologies that use RFNBOs.
- **Supply-side impacts**: these impacts relate to risks which reduce the incentive for fuel producers to develop plants and expand production of RFNBOs.
- **General impacts:** impacts affecting the full supply chain.

A1.1.3 **Mitigation action**

Mitigation actions are split into their different 'mitigation type' which follows similar logic to the risk types where mitigations of similar themes and origins are grouped by their mitigation type in Table A1-2.

Table A1-2: Mitigation types and descriptions

Mitigation type (count)	Description of mitigation type
Policy and legislation (21)	The EU and government institutions have a range of tools and potential market interventions at their disposal – targets, mandates, adapting/new policy and regulation – which can reduce the risk rating
Scheme design (19)	The schemes effectiveness lies heavily in its design and implementation. Risk ratings are reduced by allowing for flexibility mechanisms which align the scheme with the market reality (e.g., price setting, price staggering, multiple rounds, subsidies, allowing specificity, etc.)

Mitigation type (count)	Description of mitigation type
Advocacy and research (5)	Knowledge and best practice sharing through commissioning support studies to increase scheme efficiencies, improve effectiveness and foster development and increase support
Technical (1)	Improving mapping software to account for new green fuel locations
No action required (1)	-

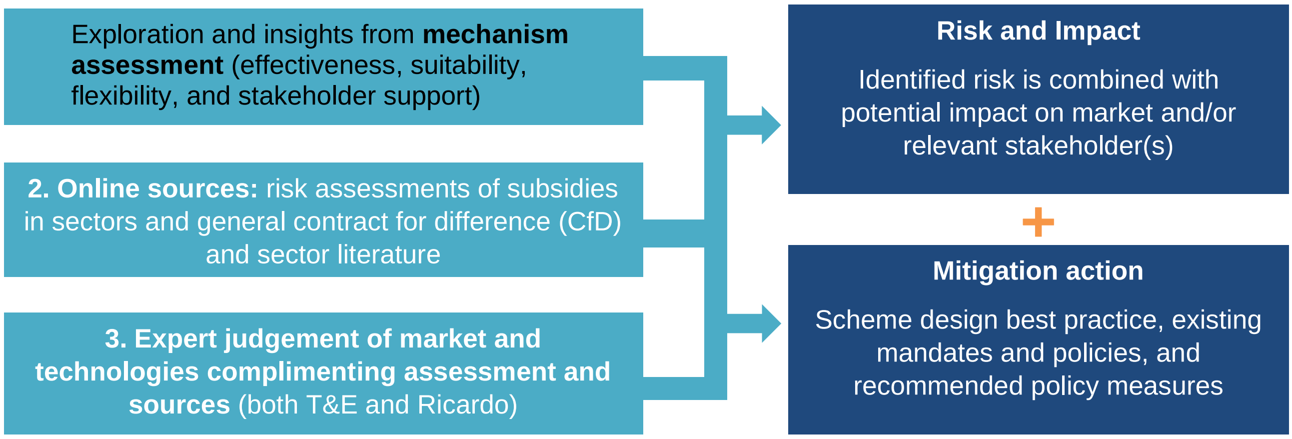
Clearly, the most suitable mitigations are those under the autonomy of the major public institutions. Scheme design and implementation may be supported by private stakeholders, but its design will be under the government's control. Similarly, the mitigation solutions relating to policy and legislation will mostly fall within the remit of the EU and Member State Governments. However, there are actions private sector stakeholders will be able to take to ensure a successful scheme is adopted (and so that the RFNBO market thrives in its development), these relate to advocacy and research. Private stakeholders across the supply chain will also play a key role in lobbying for useful policy, and in the appropriate design of any scheme. Public bodies with decision-making power therefore must involve the private sector in policy formation and scheme design. Interaction between the public and private sectors is also integral for their success.

A1.2 METHODOLOGY

A1.2.1 Risk, impact, and mitigation discovery

To identify risks and subsequent impacts of a CfD a desk-based study was conducted. Within the primary research multiple sources were consulted including white papers and academic journal articles. These sources – which are presented in Figure A1-1 below – were then used to pair the risks and implement a suitable mitigation action.

Figure A1-1: Overview of risk register methodology



Combining multiple key sources for risks over the project ensured those critical for the for the effective implementation of a CfD were identified, analysed and mitigated against:

1. Potential risks were paid attention to across the whole project but were unveiled largely in section 4, where the strengths and weaknesses of public support mechanisms were assessed with respect to their effectiveness, suitability, flexibility and stakeholder support. This process naturally revealed many of the inherent risks associated with planning, implementing and managing a CfD scheme (such as running a scheme that is 'fuel-only' or that does not account for the benefits of promoting technological neutrality).
2. Two studies with specific relevance to support schemes for RFNBOs were selected to contribute to the risk register. The first – "National and regional policy for green shipping corridors" by the Global Maritime Forum (GMF, 2023) – evaluates the risks and mitigation mechanism of demand- and supply-side subsidies, and was used to cross reference our understanding of (and add to) the critical risks relating to subsidies in these sector types. The second – "The Green Hydrogen Gap" (SASHA, 2023) – was used to cross reference and add risks relating to public incentives for RFNBO production.

3. At the inception of the project, T&E proposed nine risks to be included in the register which were either kept or adapted slightly. In addition, Ricardo's aviation and maritime experts thoroughly analysed potential risks separately to the risk discovery processes in 1 and 2, making suggestions for the inclusion of additional ones. Correspondingly, T&E reviewed the risk register, making further suggestions at the project's interim stage.

A1.2.2 **Framework for assessing risks**

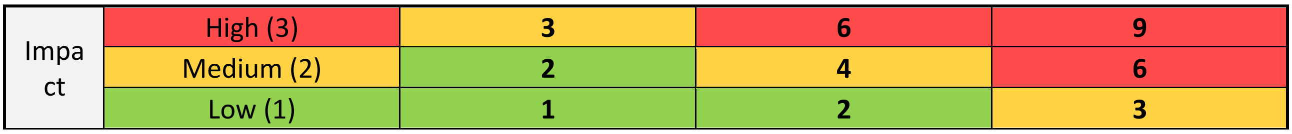
Ratings were provided according to the traffic light framework below in Table A1-3. For each risk, the **risk likelihood** was rated from low – medium – high based on the chance of that risk occurring. The **risk impact** was also assessed per risk, measuring the risk's effect on RFNBO uptake and on market development.

Table A1-3: Framework for assessing likelihood and impact of risks

Likelihood/ impact rating	Level	Explanation
🟢	Low likelihood/impact	**Risk** - low chance of this risk occurring in the near or long term. **Impact** - limited impact on the successful uptake of RFNBOs/development of zero-emission technologies and alternative fuels.
🟡	Medium likelihood/impact	**Risk** - reasonable chance of this risk occurring in the near or long term **Impact** - noticeable impact on the successful uptake of RFNBOs/development of zero-emission technologies. These risks will slow market development without hindering it completely.
🔴	High likelihood/impact	**Risk** - near certain or very high likelihood of this risk occurring in the near or long term. **Impact** - significant impact on the successful uptake of RFNBOs/development of zero-emission technologies. Without mitigation, these risks are likely to completely restrict market development.

The combined **risk likelihood** and **risk impact** gives an overall **risk rating** – a number detailing the total magnitude and severity of the risk where likelihood (1-3) is multiplied by impact (1-3) to arrive at the overall risk rating (1-9) – as shown in Figure A1-2 below.

Figure A1-2: Risk rating matrix



Impact	High (3)	3	6	9
	Medium (2)	2	4	6
	Low (1)	1	2	3

	Low (1)	Medium (2)	High (3)
	Likelihood		

The framework and matrix approach are a standard way of evaluating the total impact (severity and magnitude) of risks and allowed for the most critical risks to come to the foreground in our assessment.

Despite these strengths, this framework and matrix approach does not capture aspects relating to the risk's scope. For example, some risks are only relevant to RFNBOs which necessitate vessel or aircraft technological development (as opposed to 'drop-in' fuels which are ready-to-use – i.e., technological progression is not required for their use). Also, for the common sector of risks, the framework does not make a comment on which sector the risk would be more likely to occur in, or which sector it might have the biggest impact on.

A1.3 LIMITATIONS TO RISK REGISTER

A robust methodology was implemented to ensure relevant and most impactful risks were captured in the risk register process, however, there are some limitations to the register and its use:

- The framework and matrix approach does not capture aspects relating to the risk's scope, nor does it distinguish between the sectors it will impact more for the common risks.
- There will likely be additional and unforeseen risks not captured by the Risk Register as RFNBO production ramps up and the aviation and maritime markets develop further. Correspondingly, the Risk Register is unable to account for unforeseen risks related to the changing landscape of European policy and its effect on any proposed scheme.

A1.4 FULL RISK REGISTER

Below is the full Risk Register. Where ratings are included, 1 is low and 10 high.

ASSESSMENT OF RISK LOG										
Sector	**Risk Type**	**Risk**	**Likelihood rating**	**Demand-side Impact**	**Supply-side Impact**	**General impact**	**Impact rating**	**Mitigation Action**	**Mitigation type**	**Overall risk rating**
Common risks	Competition	Competition for green hydrogen and green hydrogen-based fuels is high across other sectors	1		Supply shortfall even with subsidies in place		1	• Strategies focussed on hydrogen demand must call for hydrogen to go only to those sectors, like shipping and aviation, that don't have alternative options for decarbonisation. • Policymakers need to adopt a cross-departmental approach to hydrogen policy, ensuring transport stakeholders are involved in decision-making on future uses of green hydrogen and that hydrogen strategies recognise its importance in	Policy and legislation	9

								decarbonising shipping and aviation.		
	Technological	Transport operators required to select a decarbonisation pathway (H2 technology 'lock-in')	2	Chosen pathway may not prove as most cost-effective or viable long-term solution compared with new or competing technologies			1	Government and industry much foster a technology-neutral environment whilst cost-effectiveness and long-term viability of solutions are established. This can be done through fair and incentives across technology options.	Policy and legislation	**6**
	Demand-side	Long life span and low replacement rate of current fleets	1	Gradual and long-term replacement of fleets leads to a slow and gradual rise in demand for RFNBOs where the introduction of fuel necessitates new engines (as for H2 burning ICE)	Provides a weak demand signal for RFNBO production		2	CAPEX subsidy schemes for new vessels which are zero-emission (replacing those close to operational lifetime) and strong emphasis on government targets and mandates for uptake	Policy and legislation	**6**

				but for drop-in RFNBOs, this risk would not have an impact						
	Demand-side	Fluctuating global demand from economic downturn or global crisis	2	Varying demand for fuel overall, impacting their economic viability and price stability but also for RFNBOs as a sub-group within fuels	Affecting investment decisions related to bringing RFNBO production online		2	Clear gov mandates with sufficiently high levels to guarantee a high level of demand. This would send the correct market signals and improve confidence through guarantees for the industry.	Policy and legislation	4

	Supply-side	Production capacity limit and infrastructure scalability issues	1		Undermines the incentives in place to uptake RFNBOs. Cost parity with traditional aviation and maritime fuels through subsidy is futile without sufficient supply		1	Complementary policies are important to address supply-chain issues to ensure there are producers willing to invest in RFNBO capacity. There are risks in terms of the time and resources required to build new solar and wind farm, electrolysers including suitable land and water source, electricity network to connect to electrolyser if not on site, CCUS installations for RFNBO types that require CO_2 etc. Coordination amongst the value chain will be important, and the government should make sure the price support schemes are aligned at the correct points in the value chain. For example, to produce green kerosene, a CfD might be needed	Scheme design	**9**

								for a new solar and wind farm, another CfD might be needed to stimulate investment in electrolyser capacity. A CCfD may be needed to incentivise CCUS for capturing CO_2 as an input into e-kerosene. Governments should play a leading role in facilitating that different companies (wind developers, electrolysers, CCUS) have the right incentives along the value chain. There is also a risk that large energy conglomerates will provide a vertically integrated supply chain, which could put them at a competitive edge to smaller companies bidding for CfDs at specific parts of the value chain. From a demand		

								respective (aviation and ship operators), the longer-term decisions required around engines and supporting infrastructure mean governments can play a role by providing long term emission targets for the sector. Long term planning and certainty can reduce the risk, together with sufficient complementary policies on the RFNBO supply chain to reassure aviation and maritime companies that competitively priced RFNBO will be available to meet their long-term demand.	🟩	🟥

	Supply-side	Access to funding (dependence on ETS revenue and other in-sector revenue-raising tools such as taxes)	2		The success of CfD programs relies on access to funding from schemes such as shipping-ETS or in-sector revenue raising (potentially from ticket sale tax or kerosene sale tax), which are politically uncertain sources of revenue. Variations in available funding for schemes could impact the funding available for CfD programs in the aviation and maritime sectors, potentially affecting their effectiveness. Despite this, EU ETS funds may also be used on other schemes or other programmes which also		3	Provide subsidies also from national budgets – not just Innovation Fund – to guarantee support	No action required	**2**

					incentivise RFMBO uptake (not just CfD)					
	Supply-side	Scheme funding competition from other sectors	3		Limit availability of RFNBOs as a result of missing incentive to scale up production		2	Earmarking part of the support budget for offtakes within shipping/aviation	Policy and legislation	2
	Supply-side	Missing fuelling infrastructure both domestically and at adjacent international connections	2	Operators reluctant to invest in zero-emissions technologies			2	Development of green shipping corridors and adjacent flight paths can provide investment certainty in alternative fuels for infrastructure developers and operators	Policy and legislation	4
	Supply-side	Logistical constraints on RFNBO production	1	Supply-side subsidies only available for selected locations creating an uneven distribution of			3	Design of support scheme to incentivise production in locations where existing support is unavailable. For example, in	Scheme design	3

				production capabilities. Also there is an issue with low volumes (due to low % mandate) required initially, suggesting that logistics might be inefficient in certain locations				ReFuelEU the flexibility mechanism allows for the most efficient distribution of supply in its initial years.		
	Prices	Increased H2 prices in other markets	1	Hydrogen price rises, causing unbudgeted subsidy increases to stay competitive			2	Reduce the producer’s preference for higher offtake price through subsidy design features. Subsidy level sufficiently high to prevent profit chasing. Dynamic scheme that could alter level of subsidy provided based on volume of RFNBO supplied. Include condition within offtake agreement that hydrogen must be supplied to certain sector(s) either fully or a given amount.	Scheme design	6

	Prices	Price inflation by producers	2			Unfair and uncompetitive pricing reduces the effectiveness of the subsidy scheme. Increased cost for the government and/or reduced demand incentive.	1	Reducing the producer's preference for higher offtake price through subsidy design features. Run an auction to push supplier to propose the lowest possible price.	Scheme design	6
	Prices	H2 market price volatility	1		Hard to set a consistent strike price potentially leading to under or overpayments by the government		2	Allowing for flexibility in scheme design. Multiple rounds and design alterations based on industry and technology.	Scheme design	6
	Prices	Higher production cost of H2 compared with traditional fuels means higher prices	1		Reduced incentive for new producers to enter the market if high production costs reduce the business case. This will reduce the available supply – however, this should be counterbalanced somewhat by the RFNBO mandates (at		2	Accurate price setting mechanism in scheme design – multiple rounds and flexibility over time to allow for scheme efficiency, and also allows for closer price parity with traditional fuels, encouraging market entry and competitiveness	Scheme design	6

					least for aviation)					
	Prices	Fluctuating ETS price	2	Difficulty in forecasting available budget for CfD support, leading to uncertainty in arranging long-term agreements			3	Ensure that there is headroom in budget when arranging CfDs; follow up with additional agreements when residual budget is determined.	Scheme design	**2**
	Regulatory and policy	Weak green H2 regulatory environment	1		Weak regulatory environment (UK and EU) for green hydrogen and zero-emission infrastructure creates a policy gap, and encourages the use of RFNBOs without explicitly and directly driving investment and developing technologies		1	• Implement stringent sectoral emission reduction targets for both shipping and aviation that are aligned with a Paris Agreement-compatible trajectory. • Adopt ambitious mandates for the use of green hydrogen and green hydrogen derived fuels to drive demand, and therefore supply	Policy and legislation	**9**
	Regulatory and policy	No price setting mechanism	2	Difficulty in setting a reference price in supply-side CfDs could lead to			2	Comprehensive impact assessment of pricing mechanism to be performed prior to	Advocacy and research	**4**

				inefficient and costly schemes from the government's perspective				price setting to ensure best value for money scheme implemented		
	Contractual and financial	Counterparty risk	2	Imposes financial risk if private sector companies fail to deliver on commitments, reducing the effectiveness of the mechanism.			2	Government to underwrite risk on offtake agreements	Scheme design	4
	Contractual and financial	Long-term nature of CfD contracts	1	CfD contracts typically involve long-term commitments. If technology advancements or regulatory changes make green fuels obsolete or less cost-effective, governments may be locked into costly agreements.			2	Align with lifetime cycle of assets and their potential future technology upgrades. If these upgrades involve radical changes in fuel technology, amend support to retrofitting and CAPEX support.	Scheme design	6
	Technological	Alternative technologies impacting RFNBOs	1		Reducing overall demand of RFNBOs, reducing long-term market potential		1	Cross sector studies identifying energy/fuel demands for all transport sectors and prioritising where RFNBOs are needed to	Advocacy and research	9

								ascertain demand levels and provide security for investment		
	Technological	Immature stage of technological development for zero-emission vessels/aircraft	1			Uncertainty surrounding investing in production and fuelling infrastructure leading to slow market development	2	investment in R&D plus clear government targets and mandates relating to zero-emission fuels and technologies	Policy and legislation	6
	Perception	Negative views on safety/performance/sustainability	2		Reduced support for schemes within the industry		3	Targeted advocacy to major industry stakeholders. Pilot demonstrations and workshops focusing on zero-emission readiness, safety and impact	Advocacy and research	2
	Perception	Vested interests and lobbying for specific technologies	1	Makes it difficult for governing bodies to foster a technology-neutral environment, one that encourages unilateral innovation across possible zero-emission solutions. In saying this			2	Schemes addressing zero-emission cost gap must be designed in a way that necessitates detailed specificity to encourage the right level and range of RFNBO production and uptake	Scheme design	6

				there must be a balance between incentivising technology neutrality which encourages fair competition across technologies that are truly zero-emission, with not encouraging neutrality in a way that supports technologies with pre-existing infrastructure (and historical subsidies) that are not necessarily future-proof, e.g. biofuels or e-LNG					🟩	🟥

	Competition	Competitiveness gap between fossil fuels and RFNBOs from the emergent nature of RFNBO technologies (high upfront costs of investment)	2		This gap may discourage private investment in zero-emission fuels and hinder their adoption, slowing down the decarbonization process in the maritime industry.		2	Binding targets including the updated IMO GHG targets confirmed in July 2023 should provide the external pressure needed to begin the shift to RFNBO however, this needs to be complemented with an economic measure to ensure compliance is upheld (still undecided at time of writing) Targets within the EU including the inclusion of maritime emissions in the EU ETS, FuelEU Maritime which imposes a mandate on RFNBO of 2% should natural uptake be less than 1% by 2031 and a gradual reduction in permissible emission intensity from energy used on-board ships.	Policy and legislation	4

	Competition	Auctions aiming to reduce marginal cost to the government (through encouraging cost reduction by bidders) could adversely impact smaller producers	2	Smaller producers lack the capital to compete based on cost reduction, this mechanism may exclude them from innovation process, causing negative effects on early-stage technology development			2	Smaller producer protection such as price staggering per MW produced. Additional subsidy/incentive for producers based upon volume of supply.	Scheme design	4
Aviation	Regulatory and policy	Support scheme may only apply to fuel producers	1	May not be passed through fully to fuel consumers (airlines), thus still giving high fuel costs to airlines. Would reduce the impact of the measure in improving the competitiveness of RFNBO relative to advanced biofuels.			2	Governments can offer separate conditional subsidies to airlines that undertake engine and infrastructure investments to support SAF. It is likely that the subsidy would need to cover the whole investment cost if there are no other private benefits of switching to SAF. Alternatively, governments can tax aviation airplanes that cannot burn SAF, and therefore create an	Scheme design	6

								economic incentive to switch to an engine that will not be taxed. Or they could mandate that all airlines need to have SAF-compliant engines and related infrastructure.		
	Supply-side	ReFuelEU Aviation poses the logistical constraints of supplying e-fuel in all Union airports.	3		Increased costs for fuel suppliers, compared to distributing greater percentages of RFNBO to smaller number of airports as part of a flexibility mechanism (for same total quantity of RFNBO). However, the SAF flexibility mechanism already provides a 10 year flexibility period to comply with the mandates in the most cost effective		3	Consider further supply chain flexibility mechanisms	Scheme design	**1**

					way, plus ReFuel EU also foresees exemptions for smaller airports/remote					
	Supply-side	Subsidy reinforcing market power to a handful of suppliers	2		The subsidy would be a positive economic shock for fuel producers already with established production, however, because there are no large-scale or established production facilities in the EU, this impact will be lower, and may even help mature the technologies. Additionally, there are a good number of plants already planned,		2	Complementary policies can be introduced to ensure there is available land, available financing, and risk mitigation for new entrants to enter the market. Introducing national CfD schemes can also mean different players can bid, and there could be requirements to have a footprint in the country, which would stimulate local jobs and growth. By stimulating support at different levels of the value chain can mean different specialised firms	Policy and legislation	4

					reinforcing competition.			can enter parts of the value chain, without requiring vertically integrated companies to deliver the full product from start to finish. In terms of CfD design, there could in theory be introduced a max cap on production capacity/volume per entrant, which would stimulate more competition, but at possibly higher strike prices.		
	Competition	A local mechanism introduced (e.g. EU level) would impact competitiveness of global market	3	Potential for concerns to be raised by non-European countries regarding the unbalanced competition. May not be a significant problem in reality, as the aim is to make RFNBO competitive with other alternative fuels (i.e. biofuels) for European			3	Ensure that experience is shared with other major aviation markets with the aim of encouraging them to follow suit.	Advocacy and research	**1**

				supply. This should not lead to a destabilisation of the global SAF market. Additionally, there is also the anti-tankering provision in ReFuelEU aviation, preventing adverse competition.						
	Competition	Competition with cheap RFNBO imports	3		Competition of RFNBOs produced in Europe with cheap biofuel imports would risk cancelling out the positive effect of the subsidy.		2		Policy and legislation	**2**
	Regulatory and policy	High level of regulation of fuels, and lengthy certification process, may delay availability of RFNBO to the point that the CfD is ineffective.	3		Acting to slow progress on establishing CfD mechanisms		2	Ensure that other schemes provide sufficient support to RFNBO producers, including through the testing/certification process, to have sufficient availability for the CfD scheme to be effective. The SAF clearing house is an EU in	Advocacy and research	**2**

								testing facility under development which will facilitate the development, evaluation, and qualification of jet fuel from sustainable sources.		
	Regulatory and policy	Failure of the regulatory instruments with operators preferring to pay penalties than to provide e-fuel at airports despite a mandate being in place	3	Reduced effectiveness of the measure as uptake of SAF is reduced and CfD is insufficient to overcome the problem			1	Increase penalties to increase incentives to provide (and take-up) SAF to ensure CfD is sufficient for competitive RFMBO	Policy and legislation	3
	Contractual and financial	Lack of full disclosure of purchase agreements between airlines and fuel providers	1		Makes it difficult to confirm the effectiveness of the measure. Benefits may be hidden behind confidentiality clauses.		3	Include requirement for disclosure of fuel purchase agreements when providing CfD subsidies.	Scheme design	3
	Technological	Differing applicability of fuel types (hydrogen likely only for short-medium haul, with new aircraft and engine technology, drop-in e-kerosene applicable to long-haul flights using current technology)	3		This is unlikely to be a problem. If total support leads to the replacement of a given quantity of kerosene by		3	None required	No action required	1

					RFNBO, benefits will be the same.					
	Scope	International nature of aviation (fuel sales within the EU will include sales to non-EU registered airlines as well as those not contributing to the EU ETS)	1	If the scheme applies only to fuel sold in the EU, the overall emissions reductions on flights departing EU airports would still be the same (for the same quantity of RFNBO sold), whether the RFNBO is purchased by EU or non-EU airlines). However, there could be significant difficulties faced by the scheme with it being used to subsidise fuel sales to airlines that do not contribute to the EU ETS (the revenue used to provide the funding for the CfD scheme). As well as	-	-	3	It is important to review the environmental benefits that the scheme is intended to deliver and to consider whether having emissions reductions being achieved by airlines that do not contribute to the funding of the scheme is detrimental to the promotion of its benefits. If having non-European airlines benefitting from the support provided to RFNBO producers is considered to be detrimental to the aims of the scheme, consideration could be given to restricting support only to RFNBO SAF provided to airlines for use on intra-EEA flights.	Policy and legislation	3

				political difficulties, this could also impact EU airlines' ability to promote their green credentials.						
Maritime	Demand-side	Tramp trade limited access to alternative fuels	2	Some ships do not follow fixed routes so may not always have access to green fuels and may miss out on incentives to decarbonise and fall behind required emission reduction targets. Could disproportionally support owners/operators travelling along fixed routes which are arguably easier to decarbonise via green	Demand side: Some ships do not follow fixed routes so may not always have access to green fuels and may miss out on incentives to decarbonise and fall behind required emission reduction targets. Could disproportionally support owners/operators travelling along fixed routes which are arguably easier to		2	A mandate to RFNBO as fuel will force these companies to rethink their fuel supply strategy. Also, ports (or countries) that provide RFNBO might be in an advantageous position to other ports (or countries). This could stimulate countries to support RFNBO uptake to deliver fuel to these vessels. A supply-side CfD scheme could ensure there is sufficient RFNBO production to	Policy and legislation + Scheme design	6

				shipping corridors or bilateral agreements.	decarbonise via green shipping corridors or bilateral agreements.			cater for tramp trade fuel needs.		
	Supply-side	Short term fuel availability and supply	1	Some technologies, such as Direct air capture, not fully mature or economically viable to address short term demand. At scale alternative fuel production might be unable to address shortages, leading to slower market development and an ineffective CfD scheme.	There are still few vessels operating on alternative fuels and few ports with appropriate bunkering solutions. Orders of alternative fuelled vessels are on the rise and will require bunkering infrastructure to operate. Average fleet owner owns 5 vessels they will be unable to compete with industry giants to pay a premium for green fuels.		1	Development of green shipping corridors can provide investment certainty in alternative fuels for both vessel and port owners breaking the chicken and egg scenario on a route basis. Broader action would be mandates and policy that creates a level-playing field and clarity for green fuels on an international level and not route specific	Policy and legislation	**9**

	Supply-side	Additional complexity of supply chains	2		Added logistical challenge for vessel owners as alternative fuel uptake increases ensuring that vessels operating on alternative fuels are able to bunker with the correct fuel along its voyage.		3	Vessel owners to implement additional parameter into planning tools to map alternative fuel bunkering facilities . Here, the "green corridors" would be helpful here to ensure that vessels find relative alternative fuel supply somewhere along their routes	Technical	2
	Prices	Low traditional fuel price means low willingness to pay for zero-emission solutions	1	Likely high subsidy or incentive needed to encourage RFNBO uptake and production. Subsidy/incentive needs to be maritime-specific to avoid competition from other sectors. If supply side incentive exists for hydrogen production it could theoretically be			2	Subsidy/incentive needs to align with existing and future policy scenarios. Supply side scheme would need assurances that fuel created was directed to maritime sector. It could be technically possible to restrict offtake agreements to some sectors/one sector if the support is supply-side	Scheme design	6

				used in any sector.						
	Market	Lead time for supply chains (fuel, bunkering, ships) to get set up	1			Slows the effectiveness of any scheme implemented although vessel technology will also take time to develop	3	Policy and regulation must take this into account when creating the policy framework	Policy and legislation	3
	Regulatory and policy	Compared with aviation, less ambitious targets for shipping decarbonisation and varying domestic policy	2		IMO targets are only indicative in 2030 and 2040 with some ambiguity on net zero "on or around 2050". EU has additional policy mechanisms such as the EU ETS which must be complied with. UK has general net zero by 2050 target and its own ETS scheme. Lacking hard targets and differing		1	Could adopt mandates for the use of RFNBOs to drive demand, and therefore supply. Current IMO strategy looks to impose a goal-based fuel standard which reduces the GHG intensity of fuel over time. FuelEU Maritime has a critical role here to play, which provides a mandate for e-fuels in 2034.	Policy and legislation	6

					domestic policy reduces industry-wide incentive for production.					
	Costs	Excess operational costs for shipowners related to RFNBOs	1	Reduced incentive to uptake as a result of higher fuel costs			2	Potentially using a total cost of ownership CfD which covers additional running costs of using alternative fuels (although not full retrofitting cost) Combining the OPEX support in the scheme (like that announced as part of the EU's Innovation Fund) with distinct but related capex support (which the Innovation Fund traditionally supports)	Scheme design	6
	Costs	Compatibility and cost of retrofitting ship engines	1	Initial upfront high investment cost to retrofit existing engines will act as a barrier to overall industry RFNBO demand. "Fuel			1	Demand-side CAPEX subsidies through technology readiness grants, utilising existing government schemes e.g. Innovation fund,	Policy and legislation	9

				only" CfD would not cover full CAPEX costs.				Enova Enterprise funding		
	Competition	Competition with blend-in fuels	2		Scheme needs to incentivise RFNBO uptake in addition to drop-in fuels or owners/operators will default to the cheaper and more available (in the short term) drop-in fuels. These result in some GHG emission at a minimal cost increase and no major modifications made to a vessel.		1	Policy measures specifying a mandated uptake of RFNBOs could be implemented as per aviation sector. Note included in FuelEU Maritime but only comes into effect if RFNBO uptake is 1% in 2031.	Policy and legislation	6
	Supply-side	Competing RFNBOs will fail to scale symmetrically	2	Different RFNBO options exist for the maritime sector. Ammonia, hydrogen e-methane, e-LNG and e-methanol. Question as to where the support extends to;	May unfairly support owners operators depending on which RFNBO they use as a fuel.		1	May need tailored support depending on fuel type used.	Scheme design	6

				only hydrogen production or full fuel production. May lead to greater hydrogen production but limited other fuel production.						
	Scope	Geographical scope	2	The EC announced funding for projects of added value to the EU; which could mean hydrogen produced abroad and used by EU companies/on routes to the EU	More competition internationally for RFNBO production so subsidy scheme needs to be attractive to encourage EU RFNBO production.		3	Scheme design should take into account international impact assessment on RFNBO production outside of the EU	Scheme design	2
	Scope	Scope of scheme (Fuel only vs TCO)	3	A fuel only scheme is likely only applicable to new build and existing dual fuel vessels which is a minority of the current market. It requires less financial support but relies on ship owners/operators			2	Governments should take a leading position by offering support, either as a TCO based demand-side CfD, or provide subsidies or tax breaks that will encourage vessel owners to invest in the necessary modifications and infrastructure to run on RFNBOs.	Policy and legislation	2

				building/converting vessels to use alternative fuels to be effective. A TCO scheme covers the cost of the entire vessel operation incl. building. This requires significantly more financial support but likely to see high uptake from owners/operators. May encourage more shipbuilding in the EU.				Alternatively, governments can implement regulation that requires new-built ships to be RFNBO-ready, with supporting infrastructure. Or governments could tax vessels that are not RFNBO-ready. This will create an economic incentive to invest in the required infrastructure to support vessels running on RFNBO.	🟧	🟩

8.2 APPENDIX 2: SCHEME SIZE AND SCOPING ADDITIONAL RESEARCH

8.2.1 CfD Subsidy Levels

Aviation 60% support scheme results

In addition to the results presented above, analyses have also been made of an option in which the support provided is limited to 60% of the price difference between RFNBO and biofuel-based SAF (or the price difference between RFNBO and fossil kerosene for cases where additional displacement can be funded). The results of these analyses are presented below. Figure A2-1 and Figure A2-2 show the funding available from the EU ETS (which is unchanged from the case with 100% support) and that required to support all the RFNBO under the relevant scenario and scheme. In comparison with the results for the 100% scheme (Figure 5-13 and Figure 5-14 in the main report body), the funding required is reduced, leading to a greater proportion of the total RFNBO being able to be supported. Under the basic scheme, sufficient funding is available to support all RFNBO under the DMan and FF55++ scenarios, while support for all RFNBO under DMan can be provided through to 2034 (and the difference between available funding and that required is very small thereafter to 2040). Under the scheme with all SAF being RFNBO (Figure A2-2), it is still not possible to support the full RFNBO consumption during the CfD scheme period (i.e. from 2025, but the full RFNBO consumption can be supported to 2031 under both DMan and FF55++ scenarios. As previously, it is not possible to support all the RFNBO under No DMan at any time during the auction periods.

Figure A2-1: Funding available from EU ETS revenues and required to support RFNBO uptake under the basic scheme with 60% support scheme

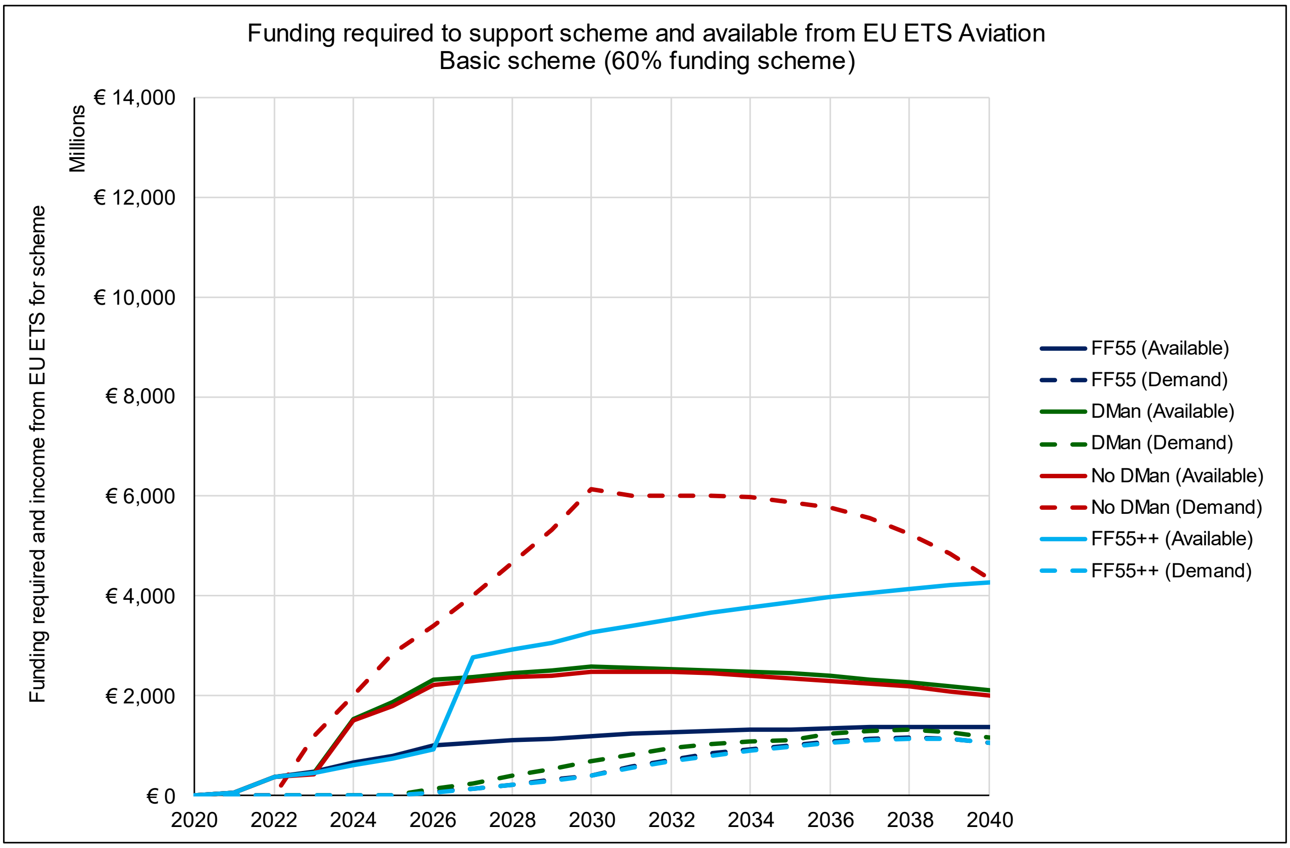
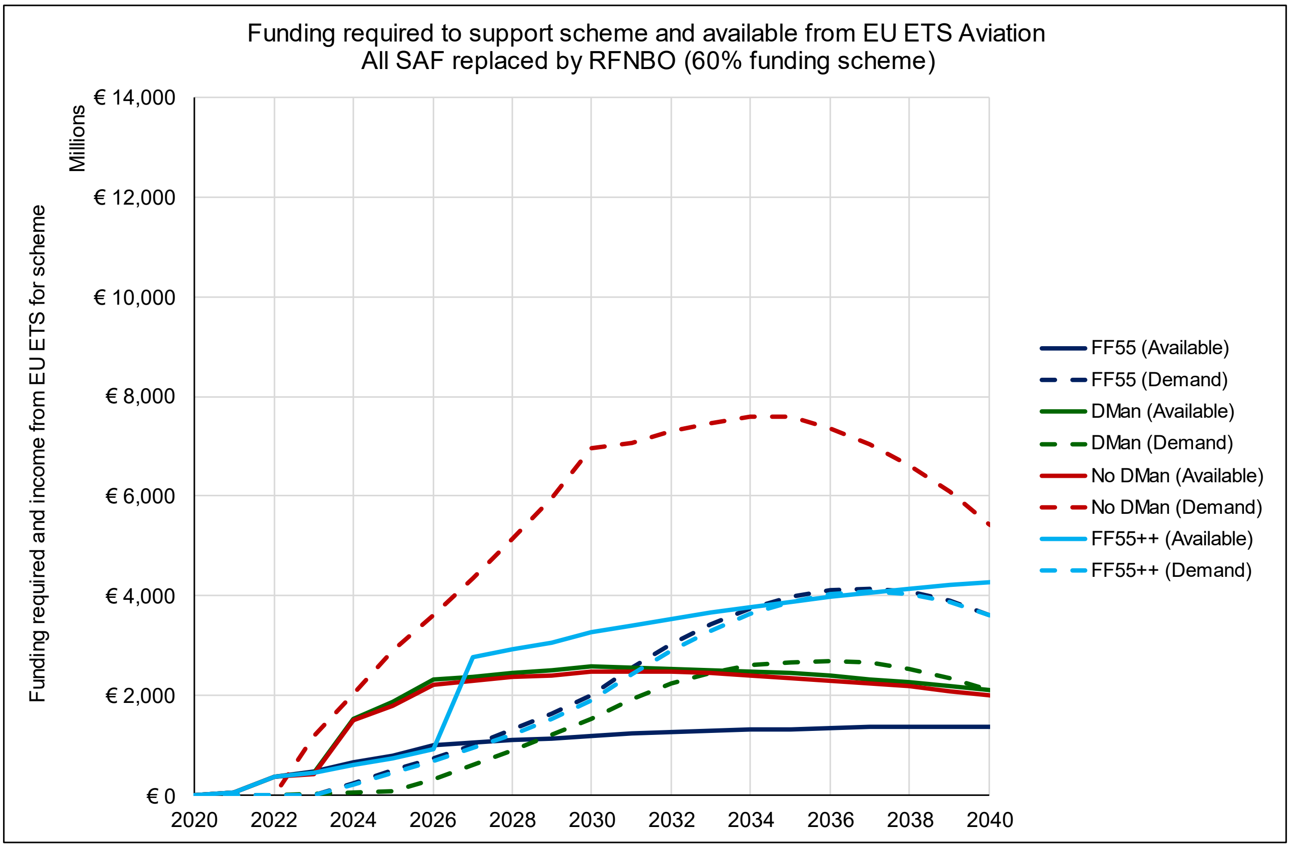


Figure A2-2: Funding available from EU ETS revenues and required to support RFNBO uptake if all SAF is RFNBO with 60% support scheme



Figures A2-3 to A2-5 show the quantities of RFNBO consumed and that which can be supported under the CfD scheme for each scenario, for the basic scheme, the scheme with all mandated SAF being RFNBO and that in which additional RFNBO (beyond the mandate) is also supported.

Under the basic scheme (Figure A2-3), all required RFNBO can be supported at 60%, except for a very small shortfall in FF55 between 2035 and 2038. Under the case with all SAF being RFNBO (Figure A2-4), as noted above, it is not possible to support the full quantity of RFNBO in any years under FF55 and from 2031 onwards for the DMan and FF55++ scenarios. In 2040, the percentages of total RFNBO that can be supported at 60% of the price difference are:

- 27% under FF55.
- 80% under DMan.
- 45% under No DMan.
- 94% under FF55++.

The results in Figure A2-5 show that additional quantities of RFNBO can be supported (displacing fossil kerosene) between 2025 and 2031 for the DMan and FF55++ scenarios (with the dashed lines being above the solid lines during this period); however, the additional quantity is small compared to the total uptake in later years..

Figure A2-3: Quantity of RFNBO required for basic scheme (mandated RFNBO only) and that which can be supported under the scheme with 60% support scheme

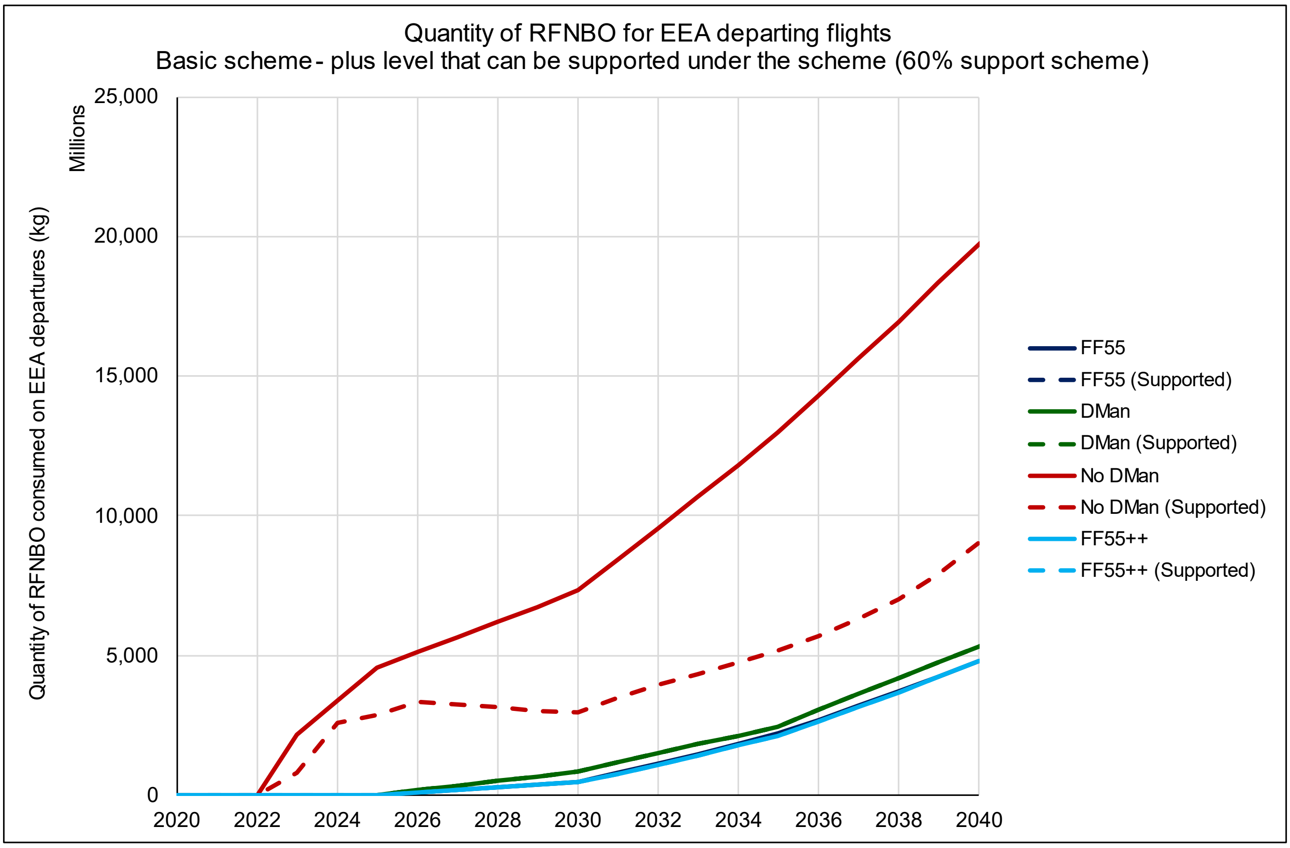


Figure A2-4: Quantity of RFNBO required if all SAF is RFNBO and that which can be supported under the scheme with 60% support scheme

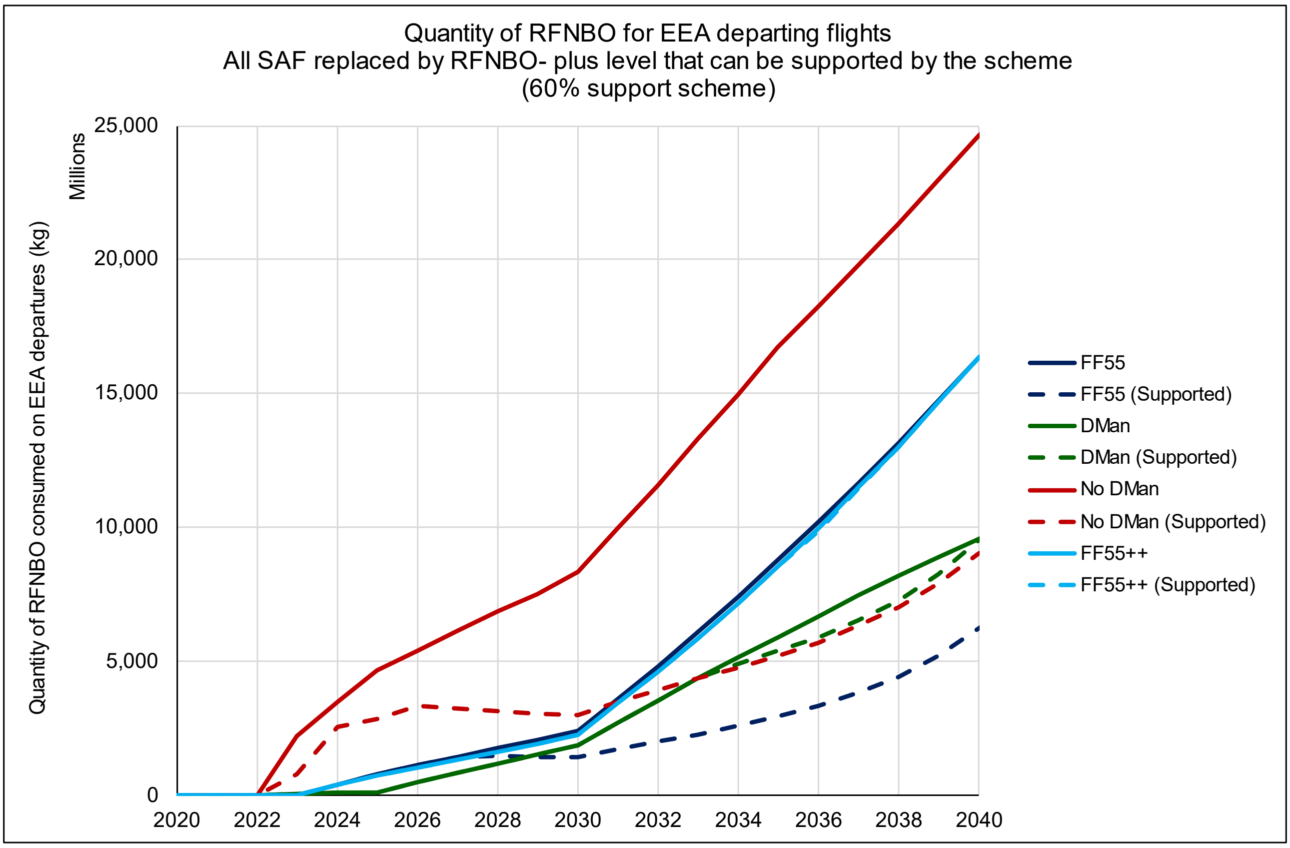
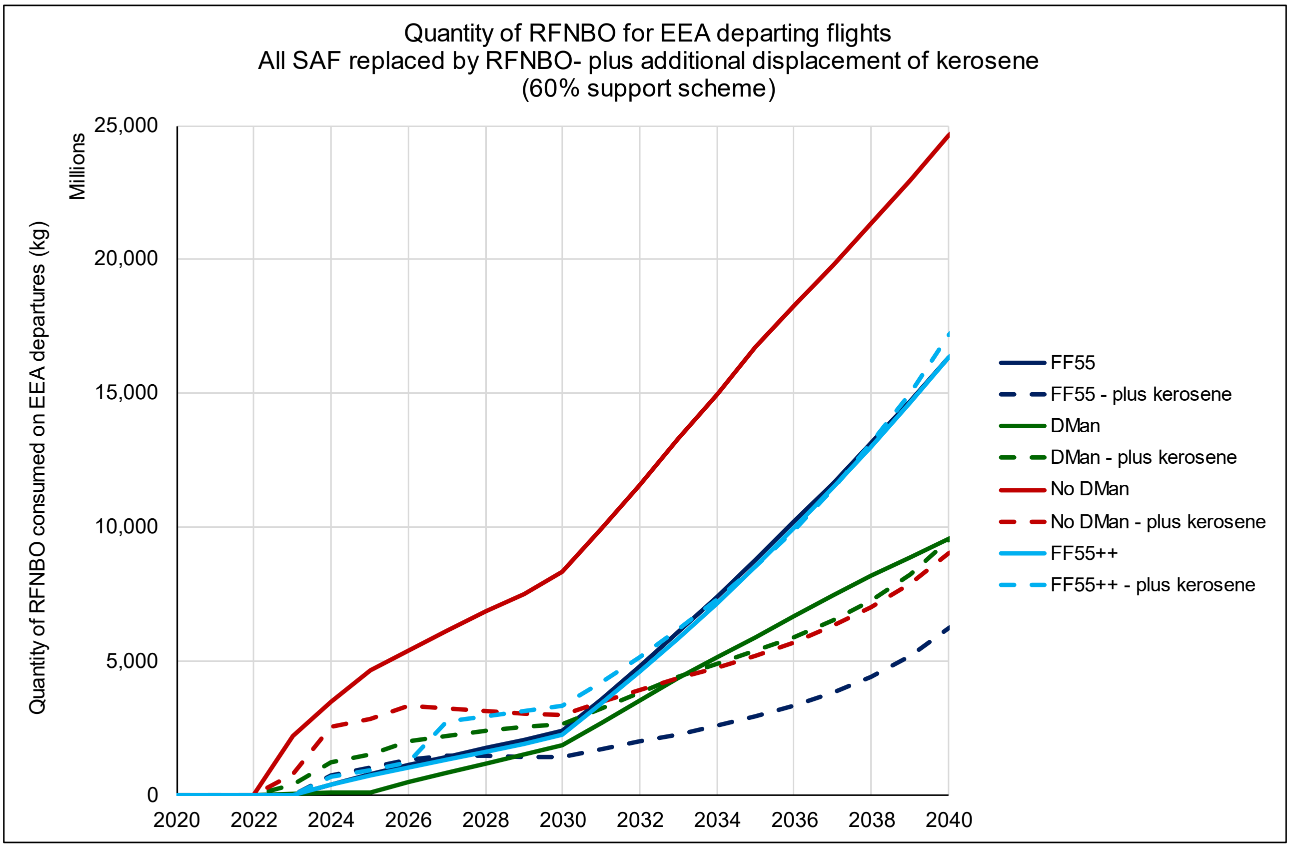


Figure A2-5: Quantity of RFNBO required if all SAF is RFNBO and that which can be supported under the scheme, including additional displacement of kerosene under 60% support scheme



Maritime 60% support scheme results

The methodology for the maritime model does not vary for the 60% subsidy level. The amount of revenue available under the EU ETS does not change it is only the subsidy intervention level that changes. Graphs have not been replicated from the main body of text to show this. The results of funding allocation at a 60% subsidy level can be found in Section 8.2.2.

8.2.2 Level of RFNBO supported

Aviation 60% support scheme results

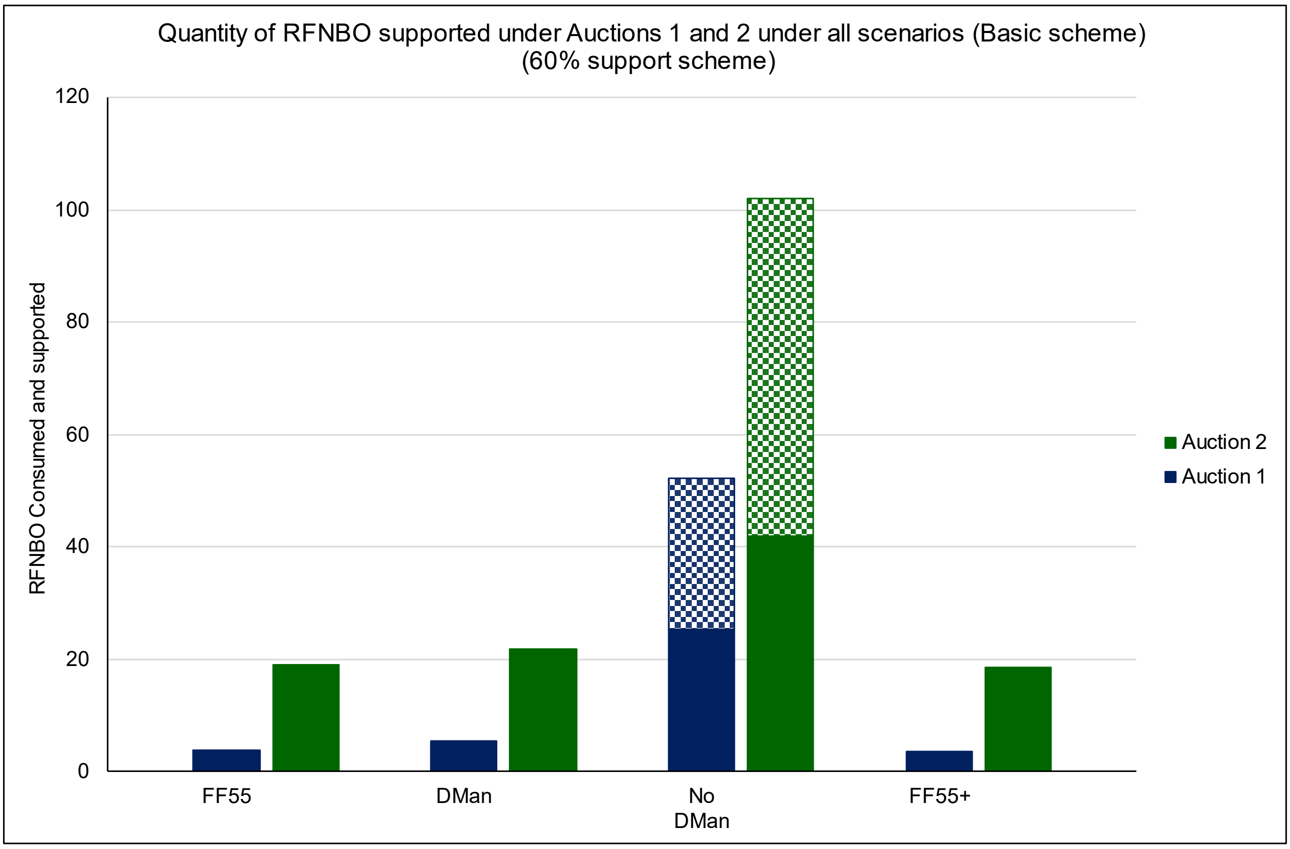
The results shown in Section 8.2.1 produce the quantities of RFNBO that can be supported under the two auction periods shown in Figure A2-6 and Figure A2-7, with the associated costs shown in Figure A2-8 and Figure A2-9. Under the basic scheme, the No DMan scenario continues to provide the greatest quantities of RFNBO that can be supported, with 25.2 and 42.9 million tonnes under auctions 1 and 2, compared to 15.1 and 25.7 when support is provided at 100% of the price difference. Under the case in which all mandated SAF is RFNBO, the scenario that delivers the greatest quantity of supported RFNBO is FF55++, with 18.2 and 69.0 million tonnes under auctions 1 and 2 (compared to 14.8 and 43.8 million tonnes if the CfD scheme covers 100% of the price difference). When the available funding allows the support of additional RFNBO (displacing fossil kerosene), under the DMan and FF55++ scenarios, the quantity of RFNBO that can be supported through auction 1 rises to 20.1 million tonnes for DMan and 23.9 million tonnes for FF55++ (compared to 13.1 and 16.0 million tonnes for the same Scenarios when 100% of the price difference is covered).

For the basic scheme, 100% of the mandated RFNBO could be supported at 100% of the price difference for the full period of the two auctions (2025 to 2040) under the FF55++ scenario and for the period of the first auction (to 2035) under the DMan scenario. Therefore, for those combinations of scenarios and auction period, reducing the support to 60% of the price difference reduces the costs to the same percentage but does not increase the quantity of RFNBO supported. For FF55, 100% of the RFNBO consumed could be supported at 100% of the price difference for some of the period of auction 1; therefore, for this combination, reducing the support to 60% of the price difference gives both an increase in RFNBO supported and a reduction in costs. For FF55 during auction 2 and No DMan during both auctions, the quantity of RFNBO that could be supported at 100% of the price difference was limited by the available funding, so reducing the support to 60% of the price difference increases the quantity of RFNBO supported without reducing the costs of the scheme.

For the scheme with all SAF being RFNBO (Figure A2-7), the ability to support all RFNBO at 100% of the price difference was only available for the DMan and FF55++ scenarios for part of auction 1. For these combinations, therefore, reducing the support to 60% of the price difference gives both an increase in RFNBO supported and a reduction in costs. For all other combinations of scenario and auction, the RFNBO that could be supported was limited by the funding available, so reducing the support to 60% of the price difference results in an increased quantity of RFNBO supported with no reduction in costs.

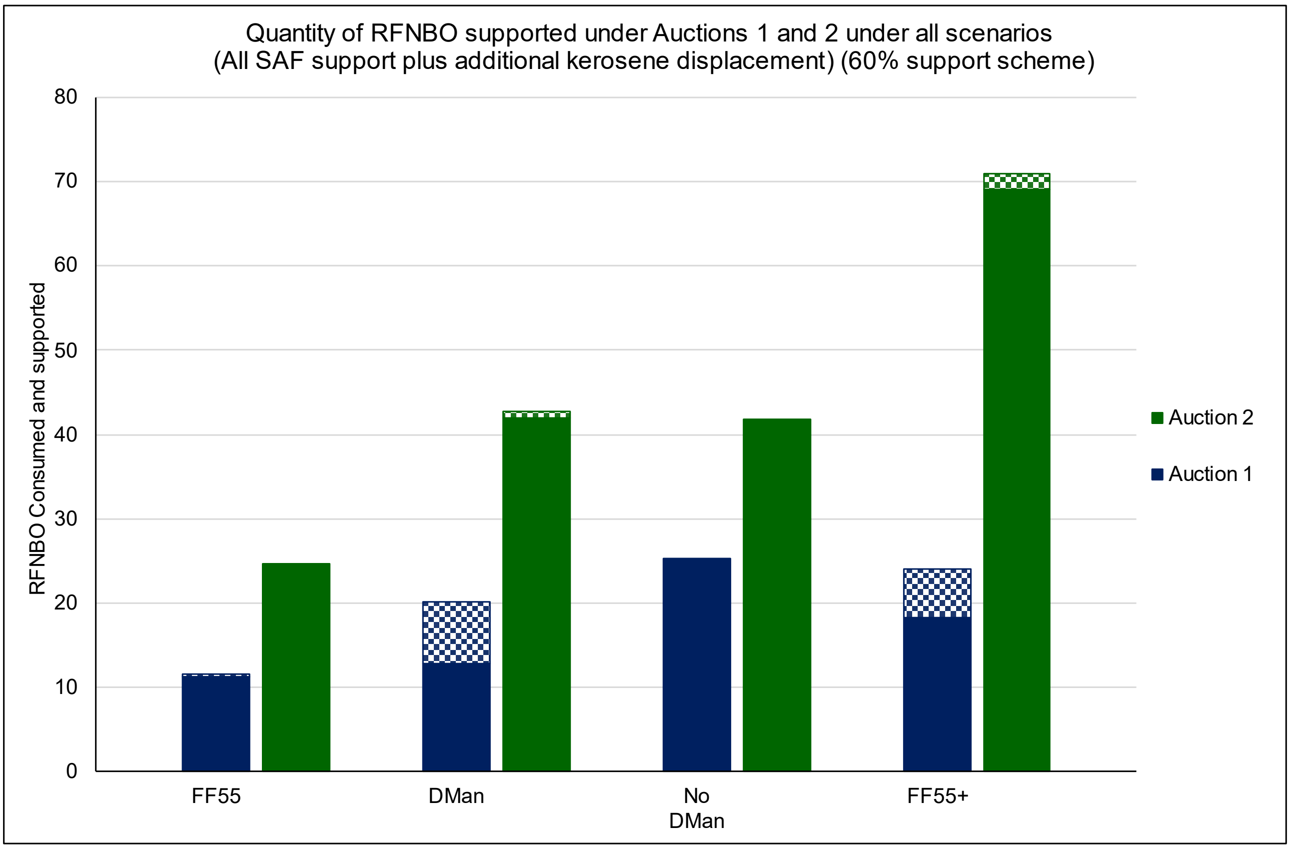
For the case in which any remaining funding is used to support additional RFNBO uptake, displacing fossil kerosene (also shown in Figure A2-9), the total quantity of RFNBO supported is limited by the available funding, so the costs are the same whether the support is provided at 100% or 60% of the price difference.

Figure A2-6: Quantity of RFNBO that can be supported under the two auction periods under the Basic scheme with 60% support scheme



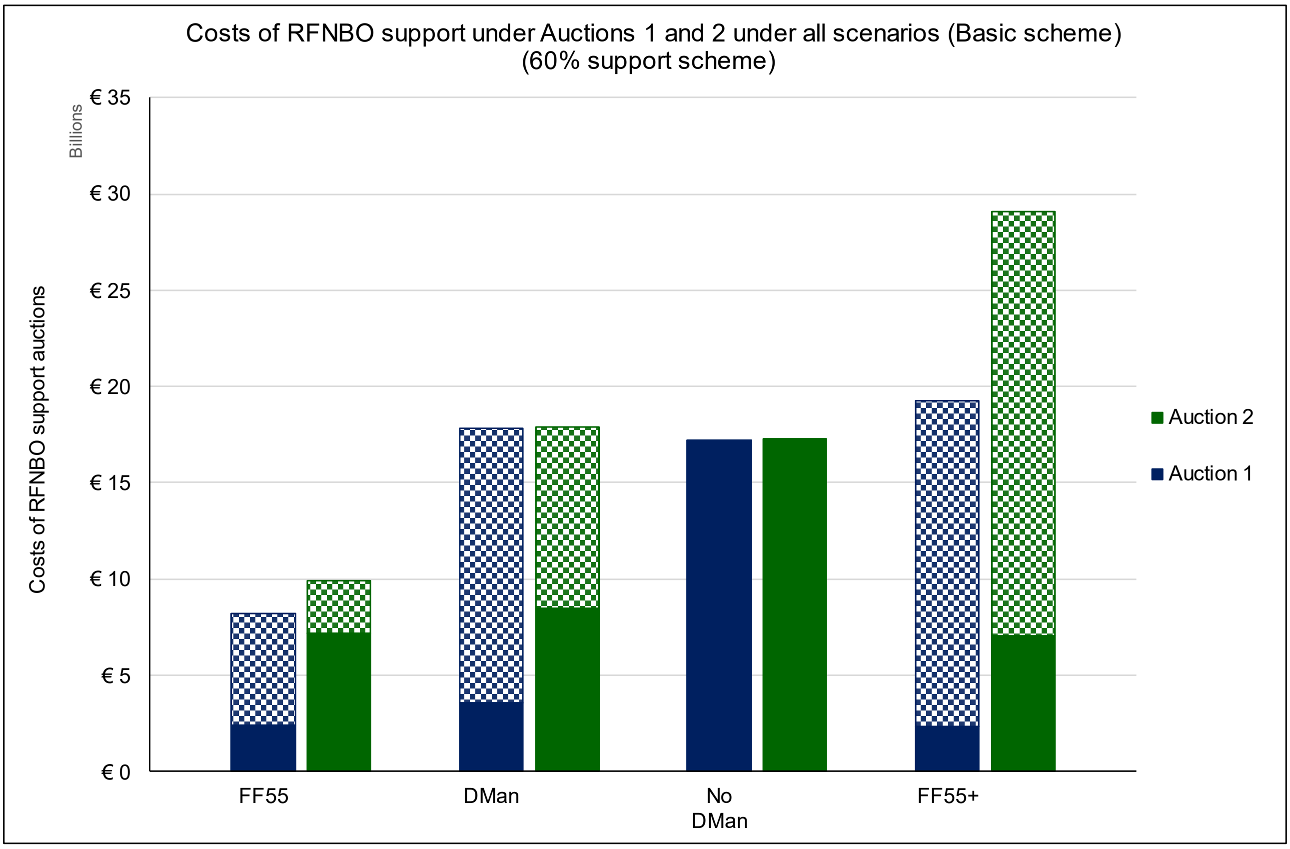
Solid areas show the quantities of RFNBO supported under the auctions; the hatched areas show the additional RFNBO consumed, but not supported under the scheme.

Figure A2-7: Quantity of RFNBO that can be supported under the two auction periods if all SAF is RFNBO, with additional displacement of kerosene, with 60% support scheme, including case with additional displacement of fossil kerosene



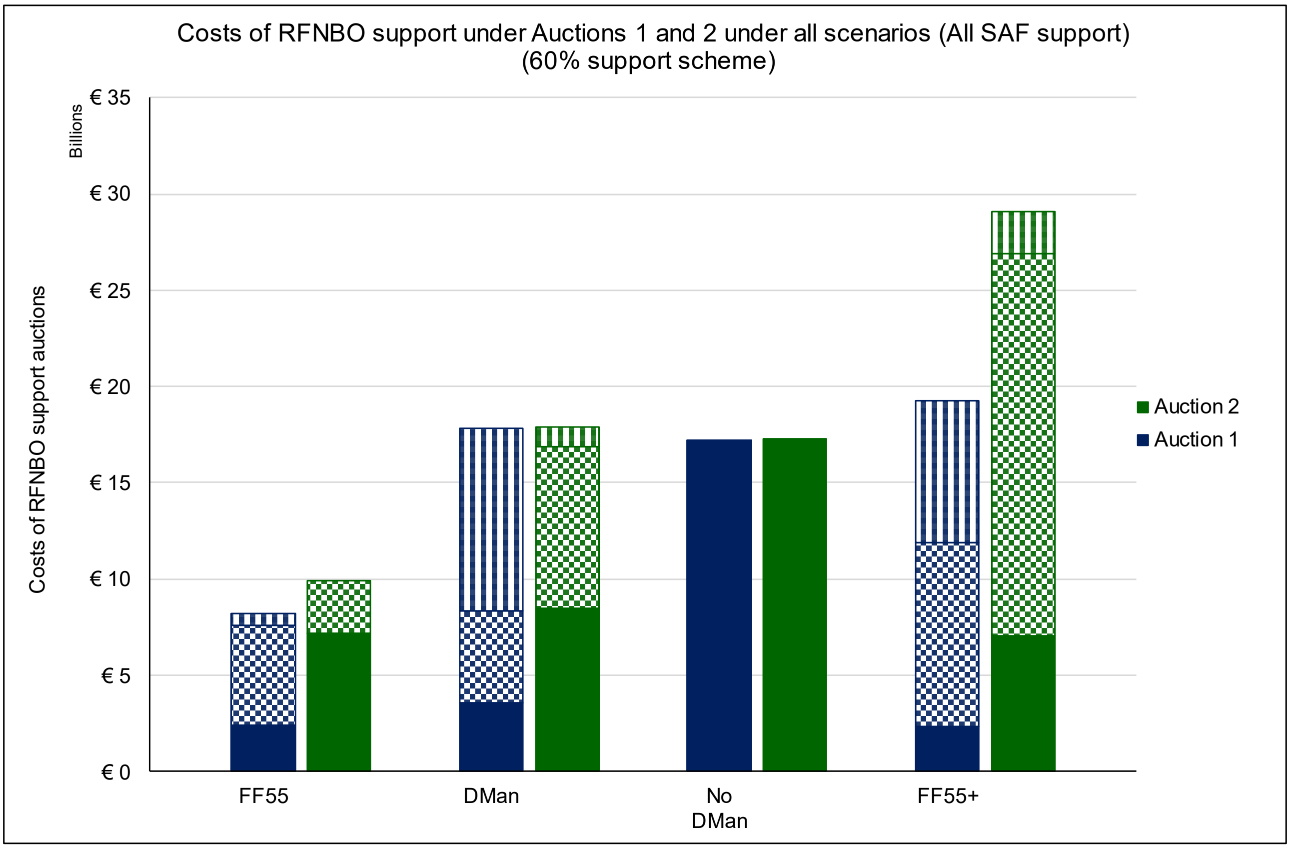
Solid areas show the quantities of RFNBO within the relevant SAF mandate supported under the auctions; the hatched areas show the additional RFNBO supported, displacing fossil kerosene consumption beyond the mandate.

Figure A2-8: Costs of RFNBO support scheme for two auction periods under the Basic scheme with 60% support scheme



Solid areas show the costs of supporting RFNBO under the two auctions. The hatched areas show the available funding that exceeds that required for the auctions.

Figure A2-9: Costs of RFNBO support scheme for two auction periods if all SAF is RFNBO with 60% support scheme, including case with additional displacement of fossil kerosene

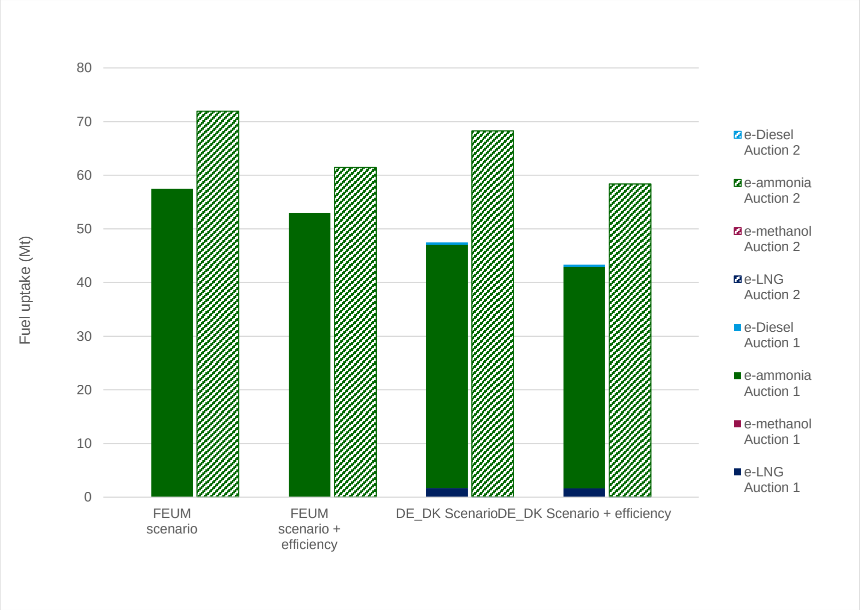


Solid areas show the costs of supporting mandated quantities of RFNBO; hatched areas show the costs of supporting the displacement of biofuel SAF by RFNBO; dotted areas show the costs of additional displacement of fossil kerosene by RFNBO.

Maritime 60% support scheme results

Figure 2-10 shows the amount of RFNBO that could be supported if only 60% of the cost gap between fossil fuel and RFNBOs was subsidised through the CfD scheme. Once again, 2 auction rounds were considered running from 2025-2034 and 2030-2039 each lasting 10 years. The fuel uptake scenarios remain the same as per the 100% subsidy level. With only a 60% subsidy it is expected that more fuel can be supported within each scenario. However, a limitation of the modelling approach means that with the extra level of fuel supported, one would expect that more fuel is produced hence the cost of the fuel decreases due to economies of scale. As there is no feedback loop within the model the additional expected cost decreases are not shown in Figure A2-10.

Figure A2-10: Level of RFNBO supported under a 60% subsidy scheme (proportional allocation of ETS revenue)



In the FEUM scenarios uptake of e-ammonia is considered as there is no expected uptake of other RFNBOs during the auction periods. For the DE_DK scenarios there is some expected uptake of e-LNG and e-methanol. Detail of how much of each fuel types that can be supported is outlined in Table A2-2.

Table A2-1: RFNBO supported for FEUM and FEUM + efficiency scenarios (proportional ETS allocation)

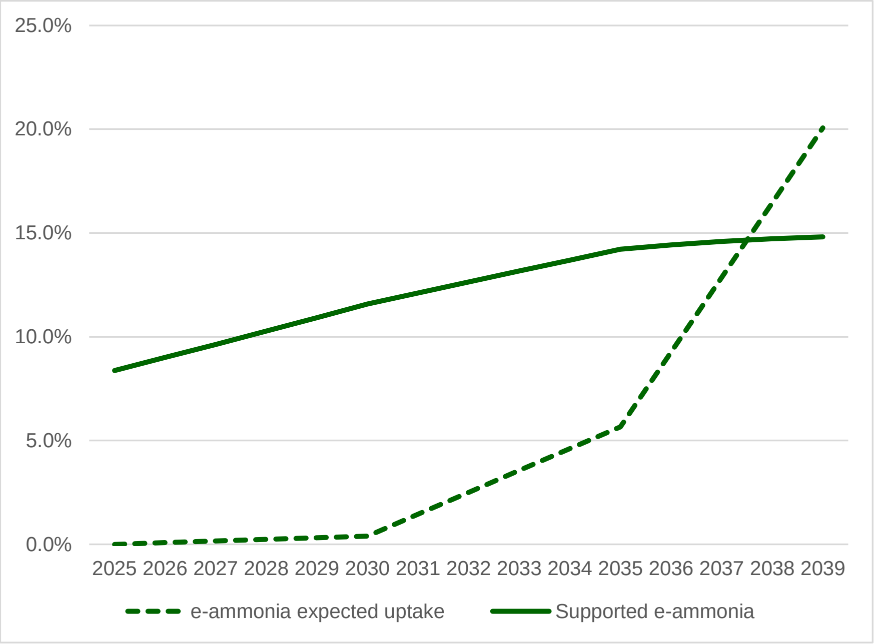
	FEUM		**FEUM + efficiency**	
Fuel supported (tonnes)	Auction 1	Auction 2	Auction 1	Auction 2
e-ammonia	57.5 million	71.9 million	52.9 million	61.5 million

Table A2-2: RFNBO supported for DE_DK and DE_DK + efficiency scenarios (proportional ETS allocation)

	DE_DK		**DE_DK + efficiency**	
Fuel supported (tonnes)	Auction 1	Auction 2	Auction 1	Auction 2
e-ammonia	45.3 million	68.2 million	41.3 million	58.4 million
e-LNG	1.72 million	0.02 million	1.65 million	0.02 million
e-diesel	0.45 million	0	0.43 million	0
Total	47.5 million	68.2 million	43.3 million	58.4 million

Exploring proportional allocation of ETS revenue at a 60% subsidy rate Figure A2-11 shows over time the level of RFNBOs that are expected to be utilised in the FEUM scenario (dashed lines) alongside the level of RFNBOs that could be supported under the proposed CfD scheme (solid lines). The y-axis in this case is the percentage of RFNBOs in the total fuel mix. It can be seen that prior to 2037 sufficient ETS revenue (at 25%) is available to support more RFNBOs (only e-ammonia in this scenario) than is expected to be utilised. Note this is an extra year of fully subsidisation compared to the 100% funding of the price differential. Compared to the scenario where 100% of the price differential was subsidised more e-ammonia can be supported account for a peak of 15% of the total fuel consumption. This exceeds both the FuelEU Maritime and IMO targets significantly. For the final 2 auction years 2038-2039 there is no longer sufficient ETS revenue to fully support all the expected uptake of e-ammonia however it is able to support 75% of the expected uptake.

Figure A2-11: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under FEUM scenario (proportional ETS funding allocation 60% subsidy)



In the DE_DK scenario, proportionally allocating out the ETS revenue shows a similar trend in that prior to 2037 there is sufficient ETS revenue being generated in a given year to subsidise all the expected e-ammonia uptake and there is additional revenue that can supported further volumes of e-ammonia beyond the expected uptake up to a peak of 15% of the total fuel volume in 2035.

In the DE_DK scenario there is a small, expected uptake of other RFNBOs, Figure A2-13 focuses on the uptake of e-LNG and e-diesel only. From this figure it is clear that sufficient revenue is available to fully support the uptake of both fuels throughout the auction period and prior to 2031 there is sufficient revenue to support beyond the expected level of these fuels.

Figure A2-12: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario (proportional ETS funding allocation 60% subsidy)

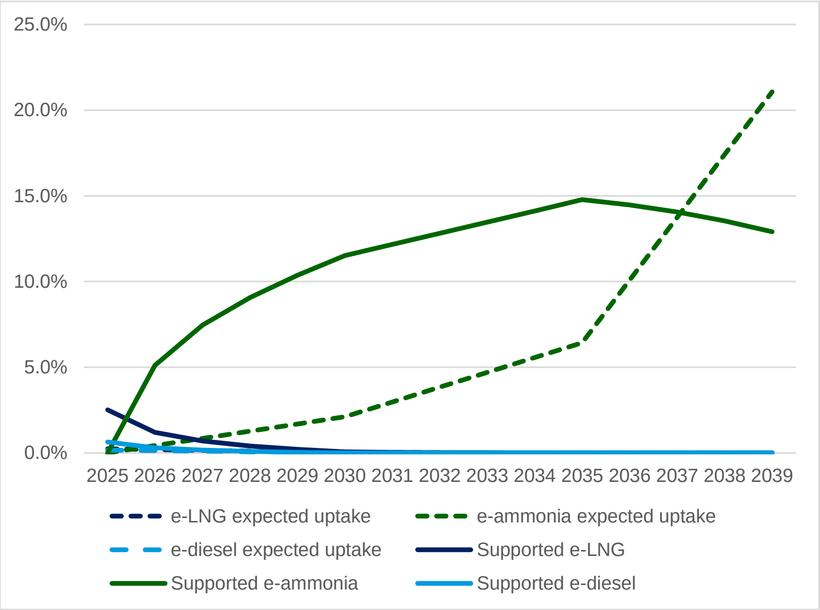
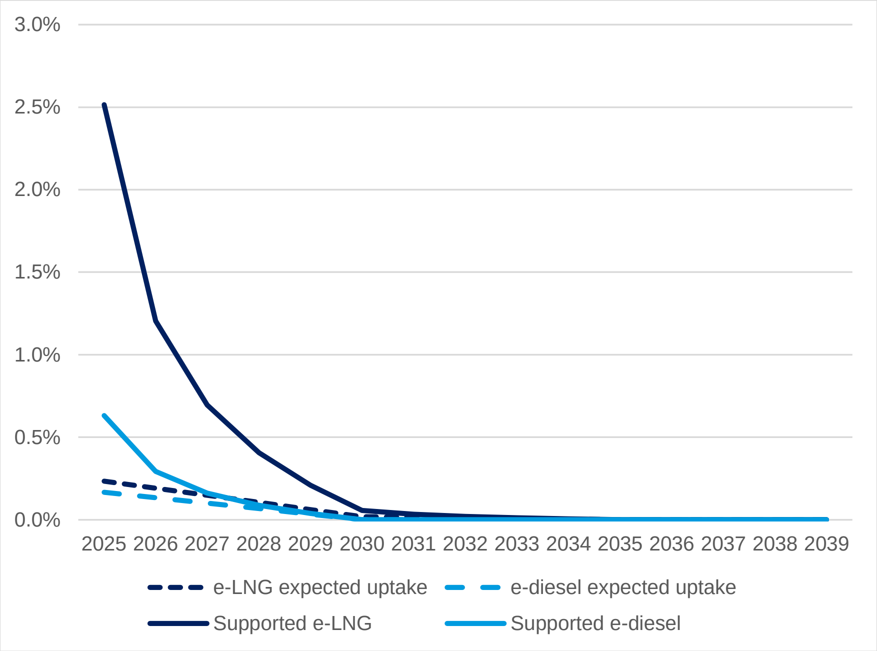


Figure A2-13: Volume of RFNBO supported under CfD scheme vs expected uptake of RFNBOs under DE_DK scenario excl. e-ammonia (proportional ETS funding allocation 60% subsidy)



8.2.3 Aviation sector analysis methodology

Overview

For the analysis of the impacts of the measures on the aviation sector, the overall results, including passenger demand and fuel consumption, were obtained using the AERO-MS tool, under licence from EASA.

The version of AERO-MS used was based on a base year of 2016, with projections for future years of 2025 and 2035. These projections were based on forecasts developed during the CAEP/11 cycle (2017 to 2019) and, therefore, did not include the impacts of the COVID-19 pandemic, and the subsequent recovery of the aviation sector. The impacts of the pandemic were, therefore, added via post-processing, with factors based on more recent forecasts from EUROCONTROL.

The different scenarios, including the different uptake of SAF and different related cost impacts (such as fuel prices, fuel taxes and EU ETS) were input to the AERO-MS policy calculations as a form of fuel tax. This allowed AERO-MS to calculate the impacts of the changes in costs on transport demand and fuel consumption, together with secondary impacts such as the rate of technology development (feeding through to fuel efficiency values. The results from the AERO-MS calculations were then exported as, for example, fuel consumption by flight stage in each of the analysis years. These results were then interpolated between the analysis years, COVID-19 factors applied and the quantities of different fuel types (including fossil kerosene, biofuel-based SAF and RFNBO-based SAF) calculated based of the prescribed share under the scenario definition.

Demand profiles

The baseline demand (expressed as revenue passenger kilometres, or RPK) was defined for the “no policy” case by the pre-existing base year definition for 2016 and the forecasts for 2025 and 2035. These forecasts implemented long-term forecasts developed by ICAO during the CAEP/11 cycle and specified expected growth in the aviation sector by each world region. These showed demand growth on intra-EU flights at 2.40% per annum from 2016 to 2025 and at 3.00% per annum from 2025 to 2035, together with 3.31% per annum and 4.10% per annum in the same periods for extra-EU flights.

The AERO-MS calculations include various responses to air transport cost inputs, such as fuel price changes or taxation, including:

- A demand side response whereby policy-induced cost increases are passed on to higher ticket prices, which results in a reduction in passenger and cargo demand.
- A supply side response whereby airlines shift towards the use of more fuel-efficient aircraft.

The default assumption in AERO-MS is that all policy-induced cost increases are passed on to passengers through higher ticket prices. The impact on demand which follows from these higher ticket prices is related to the price elasticities of demand in the model. The price elasticities of demand values in the AERO-MS are based on an IATA study (Intervistas, 2007). The elasticities used for intra-EEA flights by different carrier types are shown in Table A2-3.

Table A2-3: Average price elasticities used for intra-EEA flights

Airline type	Price elasticity
Traditional scheduled carriers	-0.84
Low-cost carriers	-1.06
Cargo demand	-0.64

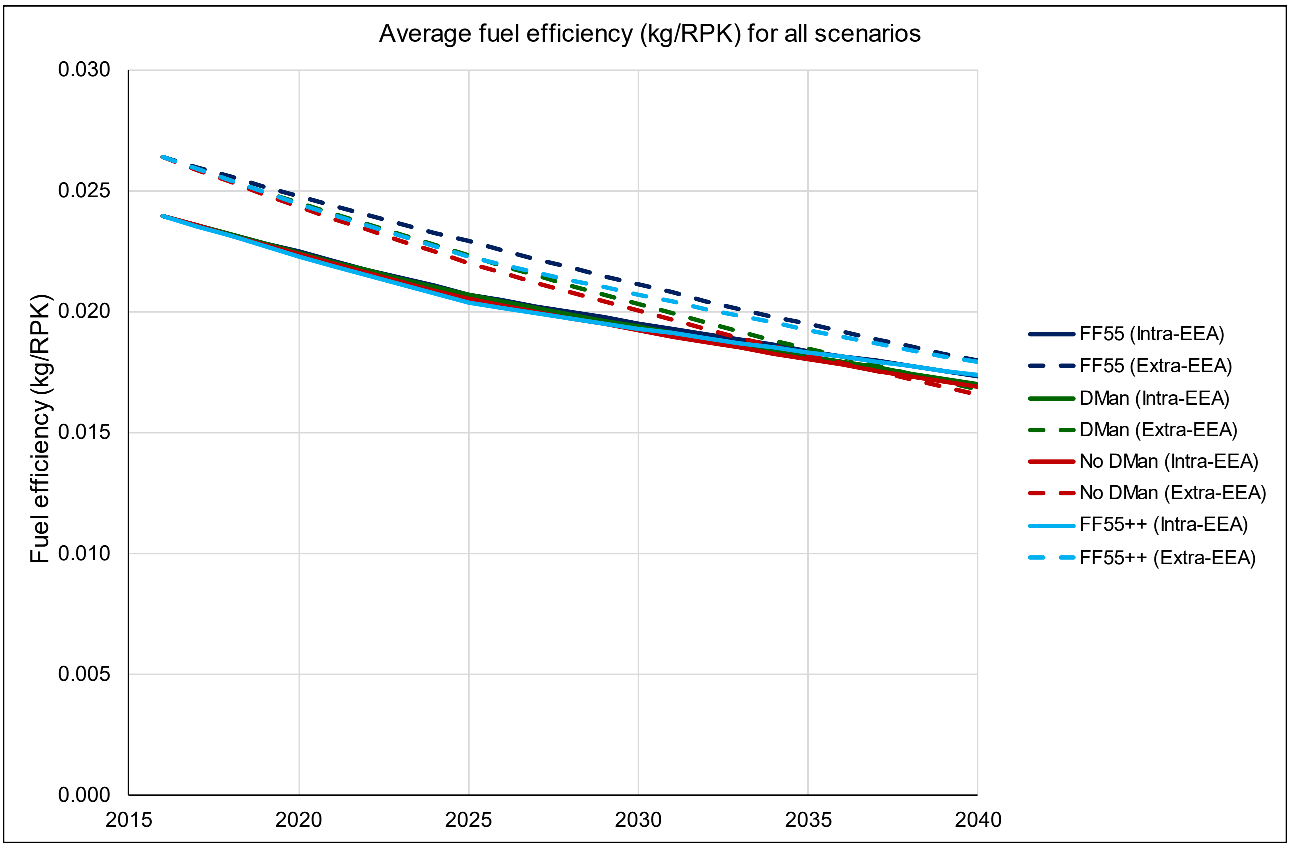
Fuel consumption profiles

The fuel consumption results were calculated by AERO-MS for the three analysis years, as described above. The results were extracted by each flight stage, with each flight stage being assigned to a route category, such as intra-EEA, extra-EEA, Rest of the World International, etc. Fuel consumption values for the other years were then derived using the same interpolation and factoring for COVID-19 impacts as described for demand.

Significantly, when implementing the effects of policies such as fuel taxes in the AERO-MS inputs, the extraction of fuel consumption at a flight stage level (from the baseline, no policy, calculation), allowed the impacts of the fuel tax to be defined at the same flight stage level, including whether flights to airports on EEA islands would be exempt from the tax, for example. The total “tax” (including other fiscal impacts such as the EU ETS) was then calculated for each flight stage and input to AERO-MS for the calculation of the impacts on demand and fuel consumption.

Using the calculated fuel consumption and RPK values, the average fuel efficiency (expressed as kg per RPK) is shown for intra-EEA and extra-EEA flights in Figure A2-14.

Figure A2-14: Average fuel efficiency derived from fuel and demand calculations for each scenario

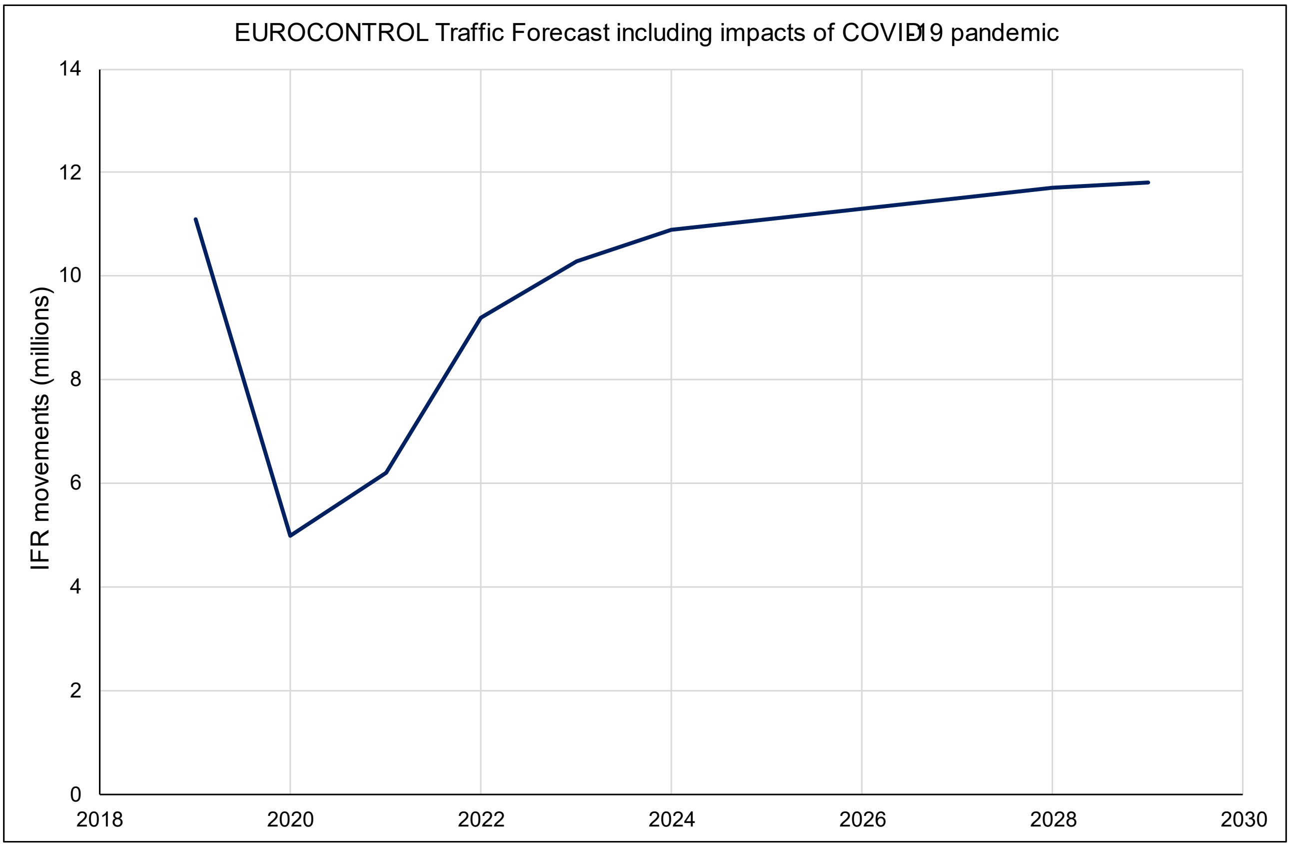


The fuel efficiency on intra-EEA flights is expected to be insensitive to the scenario and shows a gradual improvement over time. The effects of the scenarios are slightly more evident in the extra-EEA flights, with a slightly higher rate of improvement than on intra-EEA flights, which is consistent with the longer flights (with higher fuel consumption) driving a faster technology uptake.

Impacts of COVID-19

As noted above, the forecasts incorporated in the AERO-MS did not include the impacts of the COVID-19 pandemic, as they were from before 2019. To model the impacts oof the pandemic, therefore, traffic forecasts were obtained from EUROCONTROL (EUROCONTROL, 2023) and used to modify the outputs from AERO-MS as a post processing step. The forecasts gave the numbers of instrument flight rules (IFR) movements in European airspace, with historic data from 2019 to 2022, and forecasts to 2029, as shown in Figure A2-15.

Figure A2-15: IFR movements from EUROCONTROL forecasts



To apply these forecasts, the values for each year were divided by that for 2019 and the resulting factors were applied to the AERO-MS outputs (after those outputs had been interpolated to all years from 2019 to 2035). The calculated factor for 2029 was 0.802, i.e., the demand in 2029 was approximately 80% of what it would have been if the COVID-19pandemic had not occurred. The demand forecast calculations for years after 2029 used the same factor of 0.802 applied to the interpolated outputs from AERO-MS, using the assumption that the annual demand growth rate will have returned to the previous forecast by then.

The same factors were applied to demand and fuel consumption, effectively assuming that aircraft fuel efficiencies would not have been significantly affected by the effects of the pandemic.

Scenario definition and modelling

To model the different aviation scenarios, the different measures that cause an effective increase in fuel prices, including EU ETS, fuel tax and uptake of different forms of SAF, were combined and converted to an effective fuel tax for each of the AERO-MS analysis years (2025 and 2035). As some of the measures affected different flight routes differently (e.g., the EU ETS applies to intra-EEA flights, or intra-EEA and extra-EEA departures combined, depending on the scenario), the effective fuel tax was defined, and input to AERO-MS, at a flight stage level.

The inputs related to the different SAF uptakes were derived by using the prescribed percentages of conventional kerosene, biofuel SAF, RFNBO SAF and hydrogen, together with the assumed prices for each fuel type in the relevant year, to give an average fuel price associated with that mixture of fuel types. The "default" fuel price in AERO-MS was subtracted from this average fuel price to give the effective increase in fuel price associated with the mix of fuels as a "policy". As mentioned above, this effective increase in fuel price was combined with the other measures as an effective fuel tax for consistency with those other measures and for ease of input at the required level of detail.

To define the inputs for the No DMan scenario, the results of the DMan scenario calculations were used to calculate the total WTW emissions on European flights (all departures from European airports, including the EU, EEA, UK and Switzerland), taking the demand caps into account. The required percentages of RFNBO SAF to achieve the same emissions in the absence of the caps were then derived using the Excel "Solver" function (adjusting the percentage of RFNBO SAF applied to the fuel consumption calculated without the demand caps until the calculated WTW emissions matched). These percentages were then used to define the inputs to AERO-MS. The AERO-MS then accounted for the impacts (on demand and fuel consumption) of the additional costs of these increased percentages of RFNBO; the WTW emissions associated with these updated AERO-MS calculations were compared to those from DMan to check that the changes were small (as shown in Figure 5-9).

The outputs from these AERO-MS calculations gave the overall impacts of the costs associated with the different scenarios on transport demand, fuel efficiency development and hence fuel consumption, when considered against the "baseline" scenario (which, as mentioned earlier, did not include the impacts of the COVID-19 pandemic). The results from the calculations were exported to an Excel spreadsheet to allow the application of the COVID-19 factors and the derivation of more details of the quantities of different fuel types (using the same percentages of the different fuel types described above, now applied to the AERO-MS calculated total fuel consumption after adjustment for COVID-19 impacts).

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