



Enhancing the economic viability of e-fuels for aviation and shipping decarbonisation through market-based policy interventions

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Abstract

This paper examines how market-based policy interventions can enhance the economic viability of e-fuels for aviation and shipping, two hard-to-decarbonise sectors. A novel optimisation-based market penetration assessment model is developed and applied to three case studies, one based on a global shipping scenario with e-Ammonia and e-Methanol, and two based on national scenarios: UK aviation with advanced SAF and e-SAF. The optimisation model quantifies the effectiveness of Contracts-for-Difference (CfD), Carbon Contracts-for-Difference (CCfD), and optimised policy mixes in reducing e-fuel costs. Findings reveal that a combined policy approach can close the price gap between e-fuels and conventional fossil fuels. For instance, a carbon tax of \$33.6–\$162.8 per tonne CO₂, paired with subsidies of \$32.3–\$79.15 per MWh, could lower e-Ammonia costs by 24%, and e-Methanol by 29% in shipping. In the UK aviation sector, CfD schemes designed to stabilise advanced SAF prices have the potential to reduce government support costs by up to 30%, making advanced SAF more competitive. Moreover, implementing CCfDs linked to emissions reductions for e-SAF could achieve cost parity by 2040 when combined with carbon pricing projected at \$150 per tonne CO₂. This research supports a more informed and data-driven policy design, ensuring that economic barriers to synthetic fuel adoption are addressed through a balanced, market-driven approach.

keywords Market-based mechanisms · E-fuels · Aviation and shipping decarbonisation · Economic viability · Contracts for difference · Market penetration optimisation

Background

Decarbonising the aviation and maritime sectors is essential for meeting global climate goals due to their substantial greenhouse gas (GHG) emissions. Aviation contributes approximately 3% of global GHG emissions, and sustainable aviation fuels (SAF) could deliver two-thirds of required emissions reductions for the industry. Similarly, international shipping, responsible for around 90% of global goods transport, contributes nearly 3% of global CO₂ emissions (Feingold and Willige, 2024). Sustainable fuels, particularly

Power-to-Liquid (PtL)/e-fuels such as e-Ammonia and e-Methanol, are promising solutions for reducing emissions in these hard-to-abate sectors. PtL fuels can provide up to 100% GHG reduction depending on the carbon feedstock, whether sourced through direct air capture (DAC) or industrial point sources (IPS) (Rojas-Michaga et al. 2023). Research on their lifecycle analysis also evidences the GHG reduction potential (Micheli et al. 2022). However, high production costs, often 5–7 times those of conventional fuels like jet fuel and heavy fuel oil (HFO), are barriers to the wide-scale adoption of these low-carbon alternatives (Dell'Aversano et al. 2024). Several studies have identified green hydrogen as the cost driver, accounting for between 66 and 83% of total operational cost (Ozkan et al. 2024).

Market-based policy interventions, particularly carbon taxes, subsidies, emissions trading schemes, Contracts-for-Difference (CfD) and Carbon Contracts-for-Difference (CCfD), have emerged as effective strategies to enhance economic feasibility for synthetic fuels. CfDs stabilise revenues by setting a guaranteed strike price, minimising exposure to

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market volatility. CCfDs further link the strike price to emissions reductions, incentivising the adoption of fuels with lower-carbon intensity (Tran et al. 2024). CCfDs are based on the ‘emissions reduction’ potential of a technology; a value that is well established in feasibility studies and demonstration plants. The emissions trading scheme (ETS) price can be incorporated as a market reference in CCfDs (Richstein and Neuhoff, 2022). CfDs have proven successful in the renewable energy sector, especially offshore wind, and offer relevant models for SAF and maritime e-fuels (Rigby, 2021). In particular, the SAF industry has consistently emphasised the need for revenue confidence mechanisms akin to CfD (Calderbank and Malins, 2021). Most countries are also setting targets for SAF. For example, in the UK, the DfT is implementing a SAF Mandate in 2025, setting targets for SAF to reach 22% of aviation fuel by 2040, with 3.5% dedicated to e-fuel production (DfT, 2024). Plans for CfD and CCfD schemes are also in development, with consultations underway for implementing a revenue certainty mechanism by 2026 (DfT, 2024). Studies indicate that combining policy mechanisms such as carbon taxes, subsidies, and emissions trading schemes (ETS) could be more effective for reducing the cost disparity between e-fuels and fossil fuels (Metzger, 2021). This policy mix approach is projected to drive the transition to low-carbon fuel alternatives in aviation and shipping (Criqui et al. 2019).

Even though market-based policies improve the economic viability of e-fuels’ production by reducing investment risks and creating revenue certainty, there is a lack of quantitative evidence on how this is possible, especially for alternative fuels for shipping and aviation decarbonisation. In this work, specific market-based policy interventions and optimised policy mixes are applied to address the high production costs of synthetic fuels in hard-to-abate sectors like shipping and aviation. Most existing studies focus on technical feasibility or environmental benefits, neglecting the economic viability under various policy scenarios tailored to sector-specific challenges in a country and globally. While this study focuses on overcoming the economic constraints of e-fuel adoption through market-based policy interventions, it is important to acknowledge that economic instruments are only required to generate demand-pull for these alternative fuels. Non-economic parameters, including infrastructure limitations, technology readiness, regulatory uncertainty, and public acceptance, also influence the scalability and impact of these fuels. Although these aspects are beyond the quantitative scope of this paper, they remain important. Furthermore, technological innovation incentives, public–private partnerships, and regulatory alignment are also required to support scaling the production of alternative fuels for aviation and shipping. This paper contributes by clarifying the economic preconditions necessary for policy-driven market formation, which should be

complemented by broader system-level enablers in future research and practice.

Literature review

Recent literature has explored various strategies to achieve shipping and aviation decarbonisation, with a particular focus on alternative fuels and technological innovations. Shi et al. (2023) provide a comprehensive overview of shipping emissions and their environmental, social, and economic impacts, emphasising the need for policy interventions and technological advancements. In a review by Wang and Wright (2021), the authors assess the potential of alternative fuels in the maritime sector. They discuss various options, including hydrogen, ammonia, and biofuels, evaluating their feasibility and environmental benefits. The Royal Society’s policy briefing (2019) delves into sustainable synthetic carbon-based fuels for transport. It outlines the production processes of electrofuels (e-fuels) and synthetic biofuels, discussing their potential to replace fossil fuels in sectors like shipping. Furthermore, Krantz et al. (2023) evaluate the environmental impact of eight alternative fuels in maritime applications, using lifecycle analysis to identify the most sustainable option considering factors like marginal emissions and large-scale fuel transitions. While alternative fuels present promising pathways, their adoption is hindered by economic, infrastructural, and technological challenges. In the maritime sector, e-Ammonia and e-Methanol are particularly attractive due to their scalability and compatibility with existing infrastructure. IRENA (2021) projects a future demand of 3.5 EJ for e-Ammonia and 0.85 EJ for e-Methanol by 2050 to meet climate targets.

Despite their environmental advantages, these fuels face economic challenges that hinder their widespread adoption. Current production costs for synthetic fuels are higher than conventional options, due to the energy-intensive nature of PtL processes and high capital expenditure on infrastructure (Ozkan et al. 2024). The levelised cost of fuel (LCOF) for synthetic fuels remains up to 5–7 times that of conventional jet fuel or heavy fuel oil (HFO) (Dell’Aversano et al. 2024). The use of market-based policies, particularly CCfDs and subsidies, can encourage investment and offset costs. The success of CfDs in the renewables sector, particularly offshore wind, has informed their application in low-carbon fuel markets. Studies by Rigby (2021) highlight the potential of CfDs to reduce costs and foster market stability, particularly in nascent industries like SAF. Tran et al. 2024 also analysed the structure of the CfD, whether a one-way or two-way payment model affects the policy’s cost-effectiveness. Tran et al. 2024 discovered that a one-way CfD, which secures minimum price guarantees for producers without requiring repayments if market prices

rise, offers revenue predictability but at a higher cost to the government. In contrast, a two-way CfD entails payments from the producer to the counterparty if market prices exceed the strike price, aligning costs with real-time market conditions and enabling potential cost recovery for the government. Therefore, two-way Contracts-for-Difference (CfDs) are generally more effective than one-way CfDs in terms of cost-efficiency and market stability. In the aviation sector, e-fuels and advanced SAF (second-generation, lower-carbon fuels) are crucial for reducing emissions without altering aircraft or airport infrastructure, as SAF is compatible with existing engines and can achieve emissions savings of over 70% compared to traditional jet fuel (Micheli et al. 2022). For the maritime sector, e-Ammonia and e-Methanol have been identified as potential zero-emission fuels, with high compatibility for international shipping due to their scalability and reduced emissions profile (IRENA 2021). However, as with SAF, the economic feasibility of these fuels remains a key concern due to high production costs relative to conventional HFO (Feingold and Willige, 2024).

Market-based mechanisms, such as carbon pricing and emissions trading schemes, are essential for driving decarbonisation, but they are most effective when combined with complementary policies that address non-price barriers, including technology support and infrastructure investment (Criqui et al. 2019). Standalone market-based policies have shown limited effectiveness in supporting high-cost technologies in the early stages of development (Meckling, 2021). Combined policy approaches, such as those that integrate CfDs with CCfDs or subsidies, taxes, emissions trading schemes, appear more promising but are still underexplored in the context of synthetic fuels. Studies suggest that combining carbon taxes, subsidies, and emission trading schemes (ETS) could create a policy mix that fosters the competitive pricing of low-carbon fuels (Metzger, 2021), yet the impact on the economic viability of alternative fuels is yet to be quantified. In addition to financial constraints, international coordination issues, and the nascent state of fuel production infrastructure continue to hinder the transition to low-carbon fuels; however, the focus of this paper is on how market-based policy interventions can reduce the financial/economic constraints. As the SAF and PtL markets mature, more complex, flexible policy designs will likely be necessary to ensure that economic feasibility keeps pace with technological advances.

The analysis in this paper offers a unique approach to decarbonising aviation and maritime sectors by specifically addressing the economic feasibility of alternative fuels through tailored market-based policy interventions. Unlike most existing literature that primarily emphasises the technological feasibility (Mallouppas and Yfantis, 2021) or environmental advantages of alternative fuels (Balcombe et al. 2019), this work applies a novel market penetration

optimisation model (quantitative policy modelling) to explore pathways for achieving cost parity with fossil fuels. Traditional analyses of low-carbon fuels tend to focus on technical assessments such as for the combustion technologies (Wang et al. 2022), and scenario analysis for shipping decarbonisation pathways (Harahap et al. 2023), leaving gaps in understanding how targeted economic policies can enable the market adoption of synthetic fuels in sectors where direct electrification is challenging.

Recent research highlights the importance of market-based interventions, particularly in sectors where production costs for alternatives remain high. Studies such as Acemoglu et al. (2012) indicate that without a robust policy framework, the market penetration of low-carbon technologies is often slow and economically uncompetitive. Jaffe et al. (2005) also argue that achieving environmental goals through technological innovation requires addressing two market failures: environmental externalities and underinvestment in innovation, highlighting the need for a combined approach of environmental pricing mechanisms and targeted technology policies. While policy tools like carbon taxes and emissions trading schemes (ETS) are frequently discussed for their emissions reduction potential (Criqui et al. 2019), their impact on synthetic fuel cost structures has been less explored. This work addresses this gap by quantifying the effect of combining carbon taxes, subsidies, and CfDs to lower the price premium of e-fuels over fossil fuels. Additionally, while the role of CfDs in renewable energy, especially for wind energy, is well-documented (Richstein and Neuhoﬀ, 2022; Calderbank and Malins, 2021), its application to synthetic fuels is relatively novel. This body of work further develops CfD building on work done in Tran et al. 2024, examining how these policies influence government and industry cost-sharing in high-cost decarbonisation pathways. The application of these models to the maritime industry, using a global perspective, builds on prior studies by incorporating optimised policy mixes, which are shown to lower production costs and enhance competitiveness for e-Ammonia, e-Methanol, and green hydrogen (IRENA, 2021; Solakivi et al. 2022). Solakivi et al. (2022) highlight that while e-Ammonia has strong technical potential as a maritime fuel, policy support through carbon pricing and subsidies is essential to overcoming economic barriers and achieving widespread adoption. This work advances current literature by addressing the economic challenges of e-fuels and presenting empirically validated models that can inform both national and international policy frameworks aimed at decarbonising aviation and shipping industries. This approach suggests that a combination of economic incentives, revenue certainty mechanisms, and cost-sharing policies could drive the adoption of e-fuels, providing a roadmap for achieving climate targets in sectors where other low-carbon solutions may not be feasible.

Methodology

This study develops a set of market penetration optimisation models to evaluate the cost-effectiveness of various policy instruments (carbon tax, subsidy, ETS, CfD, and CCfD) in supporting the uptake of alternative fuels for shipping and aviation decarbonisation. The model structure varies by application sector: (1) Shipping (global, non-mandated): Minimises mitigation cost across multiple fuels and policy tools, (2) Advanced SAF (UK, mandated): Minimises total government expenditure while ensuring mandate compliance via CfDs, (3) e-SAF/PtL (UK, mandated): Minimises net government expenditure accounting for CfD, CCfD, and kerosene tax. The model is structured to determine the optimal policy interventions necessary to achieve cost parity with fossil fuels by simulating temporal price changes, cost reductions from subsidies, and revenue stability mechanisms like CfD and CCfD. The equations governing how market-based policy interventions improve the economic viability of e-fuels for shipping and aviation are provided below.

Market penetration assessment for e-fuels in global shipping

This study formulates a temporal linear market penetration optimisation model to quantify the cost-effective market penetration of low-carbon synthetic fuels e-Ammonia and e-Methanol in global shipping from 2023 to 2050, under various market-based policy scenarios. The model's primary aim is to determine the optimal combination of policies that achieve cost parity with Heavy Fuel Oil (HFO) while minimising the total mitigation cost borne by both government and industry.

Sets and Indices:

$i \in F$: fuel types $\{e - \text{NH}_3, e - \text{MeOH}\}$

$j \in Y$: years from 2023 to 2050

$k \in K$: market share levels $\{20\%, 40\%, 60\%, 80\%, 100\%\}$

Parameters

Symbol	Description	Unit
$FC_{avg,i,j}$	Average fuel cost of fuel i in year j	\$/MWh
$FC_{HFO,j,k}$	Fuel cost of HFO in year j for market share k	\$/MWh
$FD_{i,j,k}$	Fuel demand of fuel i in year j with market share k	EJ
CI_{HFO}	Carbon intensity of HFO	MtCO ₂ /EJ
$CE_{i,j}$	Carbon emissions associated with fuel i in year j	Tonnes/year
$FAPO_j$	Free allowance phase-out in ETS for year j	fraction

Decision Variables

Symbol	Description	Unit
$R_{i,j,k}^{sub}$	Incentive/subsidy rate	\$/MWh
$R_{i,j,k}^{tax}$	Carbon tax rate	\$/tCO ₂
$R_{i,j,k}^{ETS}$	ETS price	\$/tCO ₂
$R_{i,j,k}^{CCfD}$	CCfD strike price	\$/tCO ₂

Modelling equations

$$\text{Fuel cost of low-carbon fuel : } FC_{i,j,k} = FD_{i,j,k} \times FC_{avg,i,j} \quad (1)$$

$$\text{Total government subsidy (incentive): } P_{i,j,k}^{sub} = FD_{i,j,k} \times R_{i,j,k}^{sub} \quad (2)$$

$$\text{Carbon Tax Paid by Industry : } CE_{i,j} = FD_{i,j,k} \times CI_{HFO} \quad (3)$$

$$P_{i,j,k}^{tax} = CE_{i,j} \times R_{i,j,k}^{tax} \quad (4)$$

$$\text{ETS payment : } P_{i,j,k}^{ETS} = (1 - FAPO_j) \times CE_{i,j} \times R_{i,j,k}^{ETS} \quad (5)$$

$$\text{Carbon Contracts for Difference (CCfD)} \\ : P_{i,j,k}^{CCfD} = (R_{i,j,k}^{CCfD} - R_{i,j,k}^{ETS}) \times CE_{i,j} \quad (6)$$

The model constraints are provided below to ensure policy-driven costs are equal to or lower than fossil-based fuel; policy design constraints are also presented below:

$$\text{With subsidy : } FC_{i,j,k} - P_{i,j,k}^{sub} \leq FC_{HFO,j,k} \quad (7)$$

$$\text{With carbon tax : } FC_{i,j,k} \leq FC_{HFO,j,k} + P_{i,j,k}^{tax} \quad (8)$$

$$\text{With ETS : } FC_{i,j,k} \leq FC_{HFO,j,k} + P_{i,j,k}^{ETS} \quad (9)$$

$$\text{With CCfD : } FC_{i,j,k} - P_{i,j,k}^{CCfD} \leq FC_{HFO,j,k} \quad (10)$$

$$\text{With policy mix : } FC_{i,j,k} - P_{i,j,k}^{sub} - P_{i,j,k}^{CCfD} \leq FC_{HFO,j,k} + P_{i,j,k}^{tax} + P_{i,j,k}^{ETS} \quad (11)$$

$$\text{Non-negativity : } R_{i,j,k}^{sub}, R_{i,j,k}^{CCfD}, R_{i,j,k}^{tax}, R_{i,j,k}^{ETS} \geq 0 \quad (12)$$

The objective function is to minimise the total mitigation cost:

$$\text{Min} \sum_{i,j,k} [P_{i,j,k}^{sub} + P_{i,j,k}^{CCfD} + P_{i,j,k}^{tax} + P_{i,j,k}^{ETS}] \quad (13)$$

this is the same as : $\text{Min} \sum_{i,j,k} [FC_{HFO,j,k} - FC_{i,j,k}] \quad (14)$

CE are carbon emissions from producing the fuel, and FAPO represents free allowances under the ETS. Phasing out of free allowances by 2034 is integrated to reflect the timelines of phase-out around the world. The model is constructed in Microsoft Excel and solved using LINDO's What's Best! software. It includes 1260 variables, 2525 equations, and 2762 constraints. The model assumptions and data for the global shipping case are provided in Appendix A.

Market penetration assessment for advanced SAF in UK aviation

The second aspect of the methodology focuses on Advanced SAF, which covers production technologies like Alcohol to jet (AtJ), Gasification, and Fischer Tropsch (Gas + FT), which are mostly ready but not deployed at scale. The UK's Jet Zero Strategy aims for SAF to make up 50% of aviation fuel by 2050, backed by a mandate from 2025 to boost SAF demand. However, SAF production in the UK faces the uncertainty of future revenues, attributed to their first-of-a-kind (FOAK) technologies and high production costs (at least 2–5 times kerosene). Contract-for-Difference (CfD) is modeled as an intervention to offer price stability to SAF producers by guaranteeing a strike price that ensures profitability despite market price fluctuations. However, the financial implications of CfD schemes on Advanced SAF have not been assessed, both in terms of estimating government expenditure and supply effectiveness. The adaptation of the market penetration model for evaluating CfD for Advanced SAF consists of four components: (1) Fuel price and CfD cost modeling, (2) net cost and revenue from existing policy analysis, (3) mandate compliance and shortfall modeling, (4) scenario construction and pathway allocation. The first part of the methodology is the set of equations for Fuel Price and CfD Cost Modeling.

The below table summarises all the symbols used in the provided methodology, including their descriptions and units:

Kerosene and SAF Price Projection : $P_t^{\text{ker}} = P_{2025}^{\text{ker}} \cdot (1 + r_{\text{ker}})^{t-2025} \quad (15)$

Symbol	Description	Units
P_t^{ker}	Projected kerosene price in year t	£/tonne
P_{2025}^{ker}	Kerosene price in 2025	£/tonne
r_{ker}	Annual growth rate in kerosene price	Dimensionless (%)
$\beta_{\text{low},t}$	Lower bound multiplier for SAF price relative to kerosene	Dimensionless

Symbol	Description	Units
$\beta_{\text{high},t}$	Upper bound multiplier for SAF price relative to kerosene	Dimensionless
$P_{\text{low},t}^{\text{SAF}}$	Lower bound SAF price in year t	£/tonne
$P_{\text{high},t}^{\text{SAF}}$	Upper bound SAF price in year t	£/tonne
Payment_t	Government CfD payment in year t	£
S_t	Strike price in year t	£/tonne
P_t^{ref}	Reference market price of SAF in year t	£/tonne
Q_t	Total SAF volume contracted under CfDs in year t	tonnes/year
Q_i	SAF volume required in year i	tonnes/year
s	Standard SAF plant size	tonnes/year
V	SAF volume per CfD contract	tonnes/year
$\text{Cost}_{\text{total}}$	Total cost of the CfD policy over time	£
Net Cost_t	Net cost of the CfD policy in year t after ETS and APD revenues	£
ETS Revenue_t	Revenue from emissions trading (ETS) in year t	£
APD Revenue_t	Revenue from Air Passenger Duty in year t	£
E_t	Aviation emissions in year t	MtCO ₂
P_t^{ETS}	Carbon price in ETS in year t	£/tonne CO ₂
APD_{2025}	Air Passenger Duty revenue in 2025	£
g_{APD}	Growth rate of APD revenue (linked to passenger growth)	%
Shortfall_t	SAF supply shortfall against the mandate in year t	tonnes/year
M_t	SAF mandate volume in year t	tonnes/year
S_t	SAF supply from the market (outside CfDs) in year t	tonnes/year
Q_t	SAF volume contracted under CfDs active in year t	tonnes/year

SAF price bounds:

$$P_{\text{low},t}^{\text{SAF}} = \beta_{\text{low},t} \times P_t^{\text{ker}} \quad (16)$$

$$P_{\text{high},t}^{\text{SAF}} = \beta_{\text{high},t} \times P_t^{\text{ker}} \quad (17)$$

where P_t^{ker} is 808 £/tonne (US EIA 2023), r_{ker} is used to predict the future price of kerosene and is approximately 1.2% (US EIA 2023), $\beta_{\text{low},t}$, $\beta_{\text{high},t}$ range from 2.0 to 5.0 in 2025 to 1.2–2.8 in 2040.

The second part is equations for the CfD payment structure provided below:

$$\text{Payment}_t = \begin{cases} (S_t - P_t^{\text{ref}}) \times Q_t, & \text{if } S_t > P_t^{\text{ref}} \\ (P_t^{\text{ref}} - S_t) \times Q_t, & \text{if } S_t < P_t^{\text{ref}} \end{cases} \quad (18)$$

$$Q_t = \sum_{i=1}^t \frac{Q_i}{s} \times V \quad (19)$$

where S_t is the strike price (£/tonne), P_t^{ref} is the reference price, and Q_t is the total SAF volume contracted under CfDs, Q_i is the SAF volume required in year i (from mandate or scenario), s is the standard size of a SAF plant (about 80,000 tonnes/year), and V is the SAF volume per CfD contract (tonnes/year).

Below are equations for net cost and revenue assessment:

$$\text{The total cost of CfD policy is : } \text{Cost}_{\text{total}} = \sum_{i=1}^t \text{Payment}_i \quad (20)$$

Part of the analysis also checks if the cost can be covered by Aviation ETS revenues and Air passenger duty (APD) revenues:

$$\text{Net Cost}_t = \text{Payment}_t - (\text{ETS Revenue}_t + \text{APD Revenue}_t) \quad (21)$$

ETS revenue and APD revenue were calculated using:

$$\text{ETS Revenue}_t = E_t \times P_t^{\text{ETS}} \quad (22)$$

$$\text{APD Revenue}_t = \text{APD}_{2025} \times (1 + g_{\text{APD}})^{t-2025} \quad (23)$$

where E_t are emissions (MtCO₂), P_t^{ETS} is the ETS carbon price, and g_{APD} is assumed to be 2.5% based on passenger growth (refer to table in Appendix B).

The final part of the methodology checks if the CfD scheme is sufficient to ramp up production of Advanced SAF to comply with the UK mandate. Here the total SAF volume contracted under CfDs active in year t is the same as the policy-induced demand.

The shortfall can be calculated before and after implementing the CfD scheme for Advanced SAF using Eq. (24).

$$\text{Shortfall}_t = \max(0, M_t - (S_t + Q_t)) \quad (24)$$

where M_t is the SAF mandate volume in year t , S_t is the projected SAF supply from the market (i.e. outside of CfDs) in year t . Q_t is the total SAF volume contracted under CfDs active in year t . This equation checks whether the combination of market supply and CfD-backed supply is sufficient to meet the mandate. If not, the remaining gap is considered a shortfall.

Data was collected through a literature review and insights from expert interviews (also provided in Appendix B). Using this data, the market penetration model was

formulated to predict 2025–2054 government expenses for supporting Advanced SAF. The strike price is assumed to equal SAF minimum selling prices, meaning the prices achieved a net present value of zero and met the minimum attractive rate of return. SAF minimum selling price data was drawn from Tran et al. (2024) – Appendix B.

Market penetration assessment for e-SAF/ PtL in UK aviation

In the final adaptation of the market penetration model, the focus is on PtL or e-fuels for UK aviation; here, both CCfD and CfD mechanisms are designed to optimise economic viability (ex-ante design). The market penetration model calculates the cost of supporting Power-to-Liquid (PtL) fuels for sustainable aviation fuel (SAF) mandates. This combined model supports producers through both fixed-price (CfD) and carbon performance-based incentives (CCfD), creating a stable revenue while also encouraging emissions reduction. The below equations quantify the cost and economic tools needed to support PtL fuels as viable decarbonisation solutions.

The objective function is to minimise the total net government expenditure over the policy

$$\text{horizon : } \min \sum_{t \in T} [CfD_t + CCfD_t - KT_t] \quad (25)$$

Where CfD_t is the cost of the CfD scheme in year t , $CCfD_t$ is the cost of the CCfD scheme in year t , KT_t is the revenue from kerosene taxation in year t , and T is the set of years.

Decision variables are provided in the table below:

Symbol	Description	Units
SP_t^{fuel}	Strike price of PtL fuel in year t	£/tonne
$SP_t^{\text{CO}_2}$	Strike price of CO ₂ reduction in year t	£/tonne CO ₂
Q_t	Quantity of PtL required by SAF mandate in year t	tonnes

Parameters for the optimisation model are provided below:

Symbol	Description	Units
RP_t^{fuel}	Reference market price of kerosene in year t	£/tonne
$RP_t^{\text{CO}_2}$	CO ₂ reference price (e.g. ETS) in year t	£/tonne CO ₂
ER	Emissions reduction per tonne PtL	tonne CO ₂ / tonne PtL
J_t	Total jet fuel demand in year t	tonnes
α_t	PtL share mandated in total jet fuel in year t	% (as decimal)
QK_t	Share of kerosene in fuel mix in year t	%

Symbol	Description	Units
L_t	Kerosene tax level in year t	£/tonne
CD	Contract duration (fixed, 15 years)	years
$LCOF$	Levelised cost of fuel	£/tonne

Model constraints are provided below:

$$CfD_t = \begin{cases} (SP_t^{fuel} - RP_t^{fuel}) \times Q_t, & \text{if } t \in [t_0, t_0 + CD] \\ 0, & \text{Otherwise} \end{cases} \quad (26)$$

$$CCfD_t = \begin{cases} (SP_t^{CO2} - RP_t^{CO2}) \times ER \times Q_t, & \text{if } t \in [t_0, t_0 + CD] \\ 0, & \text{Otherwise} \end{cases} \quad (27)$$

$$KT_t = QK_t \times J_t \times L_t \quad (28)$$

$$\text{Mandated PtL Volume } Q_t = \alpha_t \times J_t \quad (29)$$

Strike price feasibility (for producer cost recovery):

$$SP_t^{fuel} \geq LCOF_f \forall t \in T \quad (30)$$

$$Payment_t^{CfD} = (SP_t^{fuel} - RP_t^{fuel}) \times Q_t \quad (31)$$

$$Payment_t^{CCfD} = (SP_t^{CO2} - RP_t^{CO2}) \times ER \times Q_t \quad (32)$$

If the value is positive then it's a government payment; if negative, it's payment from industry to government. The assumptions and data source to implement the market penetration assessment for e-SAF/PtL are provided in Appendix C.

The novel methodologies developed in this study are rooted in innovative market penetration optimisation models tailored for e-fuels in both shipping and aviation sectors. The models evaluate how economic tools can close cost gaps between e-fuels and fossil fuels using dynamic policy mechanisms such as carbon taxes, subsidies, Contracts-for-Difference (CfD), and Carbon Contracts-for-Difference (CCfD). The shipping model captures the complexities of policy interventions, including phased reductions in free allowances under emissions trading systems (ETS). For aviation, the models simulate CfD and CCfD designs to optimise strike prices, minimising government expenditure while securing cost recovery for producers. The methodology is applied to three case studies below.

Case study 1 optimal design of market-based policy for e-fuels for global shipping decarbonisation

This case study examines the application of market-based policy interventions to improve the economic viability of e-fuels in global shipping, focusing on e-Ammonia and

e-Methanol as primary candidates for decarbonising this sector (Fig. 1). The quantities of the fuel, i.e. demand, are provided in Figs. 1 and 2. Given the high costs of e-fuels, the study investigates a combination of market-based policy interventions: carbon taxes, subsidies, and emissions trading schemes (ETS) to close the cost gap and encourage adoption. The shaded orange region in Fig. 2 is the spread of e-ammonia (Fig. 2a) and e-methanol (Fig. 2b) available in literature today.

The demand for e-ammonia and e-methanol required to achieve net-zero in the global shipping sector is 3.5 EJ and 0.70 EJ, respectively (Fig. 1). Without policy support, e-ammonia becomes competitive from 2039 under low price assumptions for HFO, which will rarely happen; competition is not reached at high price assumptions for both fuels. E-methanol becomes competitive in 2030 still under low price scenarios. Hence, the need for market-based policy interventions. The methodology (Eqs. 1–14) was applied to determine the optimal mix of policies to trigger a demand-pull today. The value of a carbon tax to disincentivise the use of HFO and promote the uptake of the alternative fuels depends on the market share/ market adoption of the alternative fuels (Fig. 2a, b shows the market demand of each fuel required for global shipping decarbonisation). From Fig. 3a, b, at 100% market share, a tax of 400 \$/t on HFO is required today, reducing to 100 \$/t in 2050 to support the uptake of e-ammonia, and the value of the carbon tax reduces to 79.3 \$/t and 17.1 \$/t in 2050 at 20% market share. The means based on today's carbon tax values around the world, only less than 20% market share can be achieved for e-ammonia and e-methanol (Fig. 3a, b). In the presence of other policies like subsidies and emissions trading schemes (ETS), the tax required reduces to a value society can afford: 103 \$/t at 100% market share (Fig. 4). This shows combining policies is more practical. The same is observed for e-methanol in Fig. 5.

Demand for e-methanol does not start until the 2030s (Figs. 1 and 2). Under the ETS, the carbon price rate is also sensitive to market share, and if driven by ETS alone, the values are very high even at low market shares for both fuels (Fig. 6). Blending market-based interventions means the ETS price is lower. Large values are required if the adoption is solely driven by the ETS carbon price, with a value of 800 \$/t for e-ammonia and 700 \$/t for e-methanol (Fig. 6a, b). This reduces to a maximum of 160 \$/t when a carbon tax is also issued for e-ammonia, and 45 \$/t for e-methanol at 20% market share (Fig. 7 a, b). The policies also determine how much market share can be achieved; this is referred to as the policy-induced demand-pull for the alternative fuels (Fig. 8 a, b). These findings from a bottom-up analysis support the use of mixed interventions. Figure 9 shows that when only subsidies are used to improve the economic viability, a value

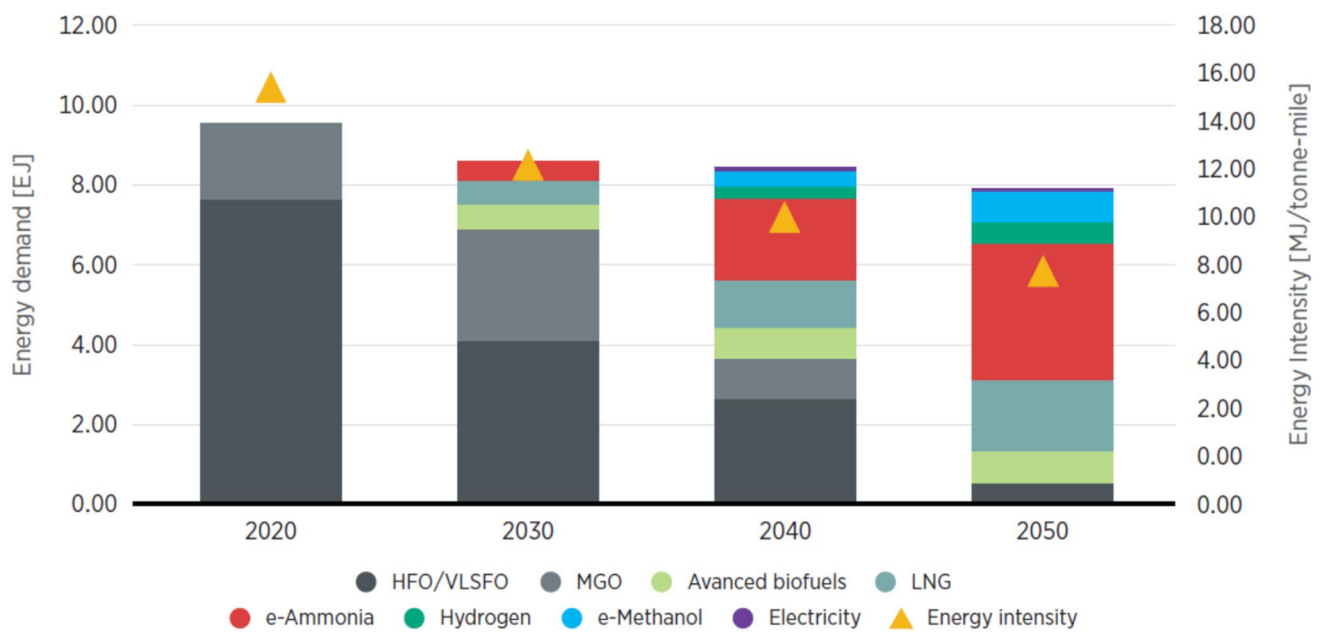


Fig. 1 Global decarbonisation pathway for the shipping sector, IRENA (2021). This figure outlines the projected reductions in emissions required to achieve net-zero goals in the shipping industry using alternative fuels such as e-Ammonia and e-Methanol

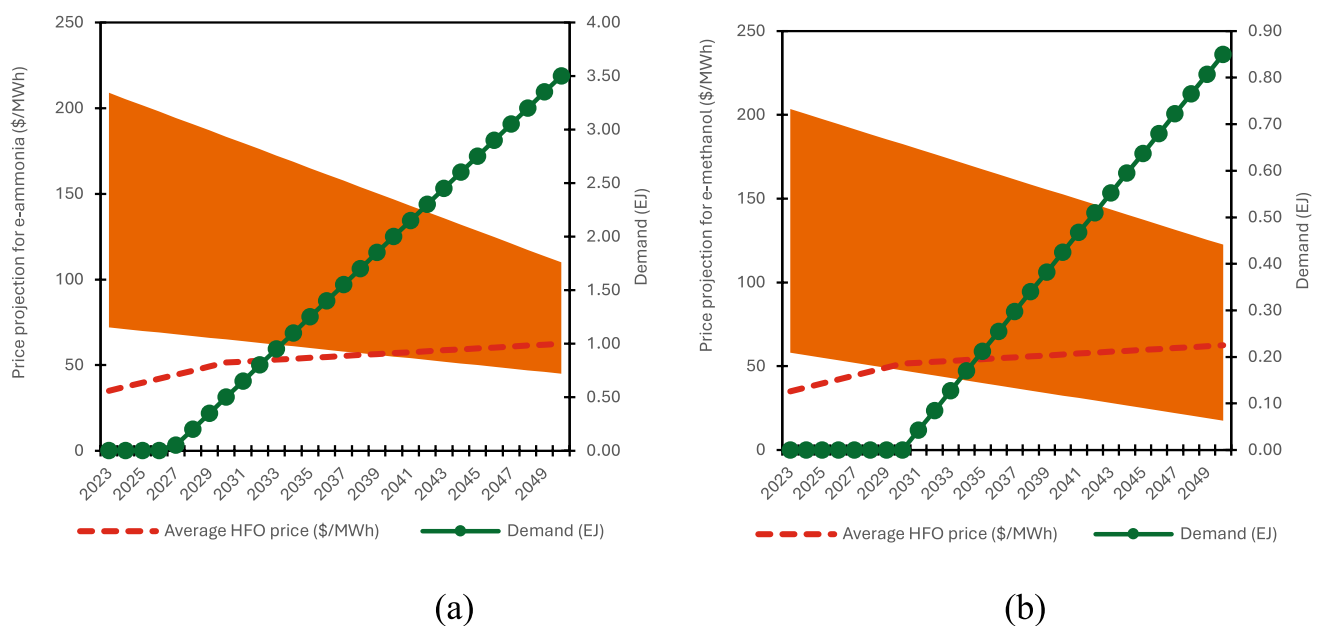


Fig. 2 Fuel Price projection and demand for **a** e-Ammonia, and **b** e-Methanol for global shipping decarbonisation. This figure displays the relationship between the projected prices of e-fuels and their anticipated demand under various policy support scenarios

as high as 115.9 \$/MWh is required, reducing to 68.3 \$/MWh with a tax and ETS scheme (Fig. 9a). The same trend is observed for e-methanol in Fig. 10, with 127.45 \$/MWh for only subsidy, reducing to 72.9 \$/MWh if combined with tax and ETS. Interestingly, this model desires to subsidise e-methanol more compared to e-ammonia (Fig. 10a, b);

results for the optimal policy mix for e-ammonia are shown in Fig. 11. Today, a tax of 102.8 \$/t and a subsidy of 62.85 \$/MWh are required to generate sufficient demand-pull for e-ammonia by reducing the price. The optimal mix of policies for e-methanol is also provided in Fig. 12. The optimal mix of policies provided in Figs. 11 and 12 was determined

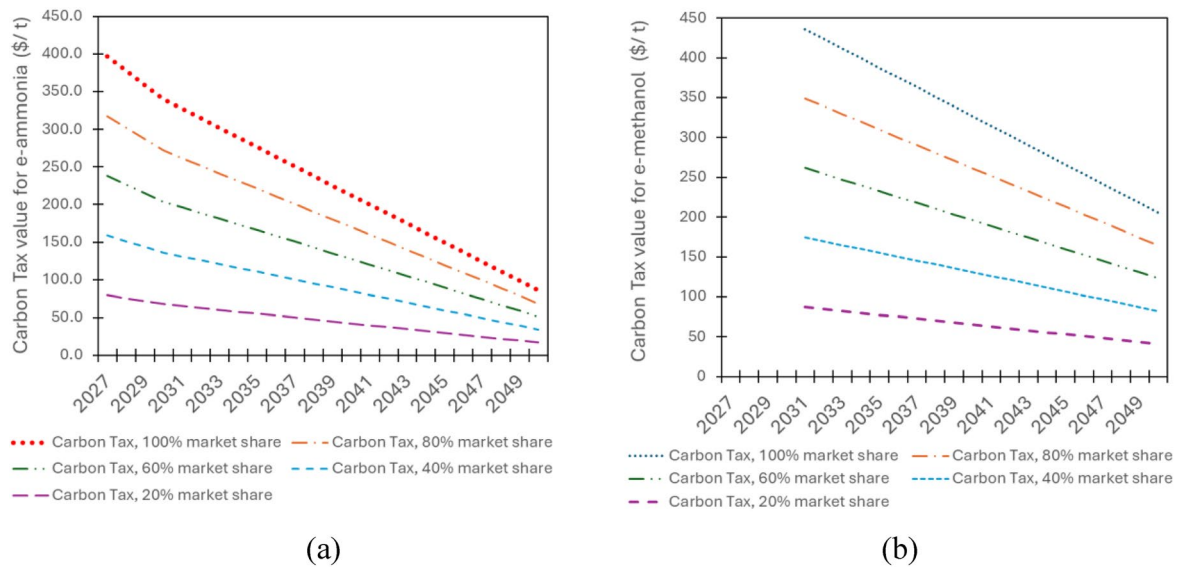


Fig. 3 Optimal carbon tax values for **a** e-Ammonia and **b** e-Methanol adoption under different market uptake scenarios. These figures illustrate how carbon tax levels influence the quantity of e-fuels that's economically viable to produce

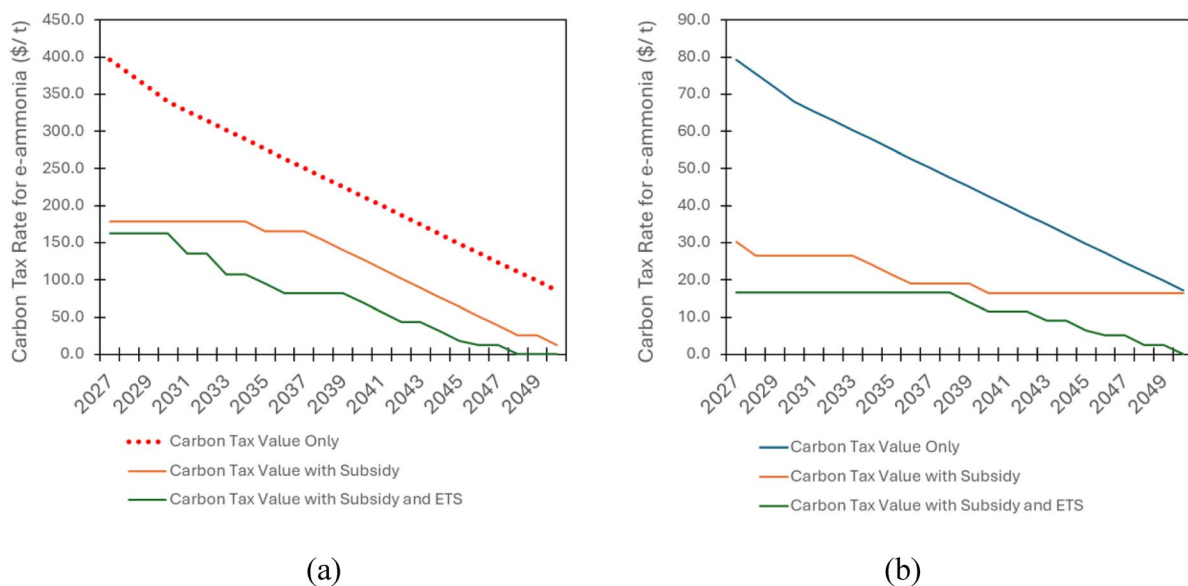


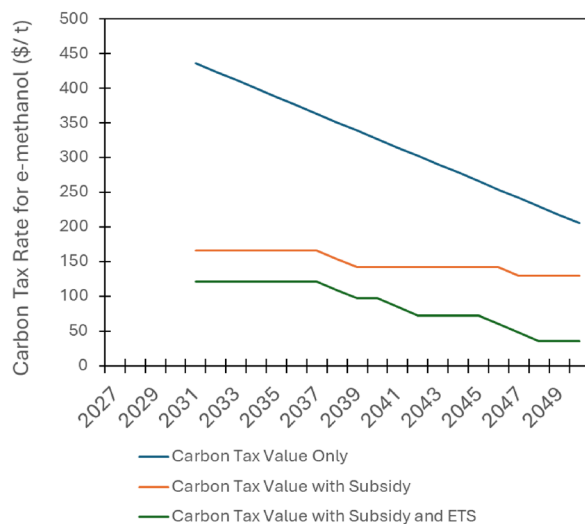
Fig. 4 Reduction in carbon tax value due to subsidy and ETS for e-Ammonia, for **a** 100% market share to meet the ambition in Fig. 2, and **b** only 20% of the fuel demand in Fig. 2 is met). The figure com-

pares the level of carbon taxes needed for market competitiveness with and without complementary policies

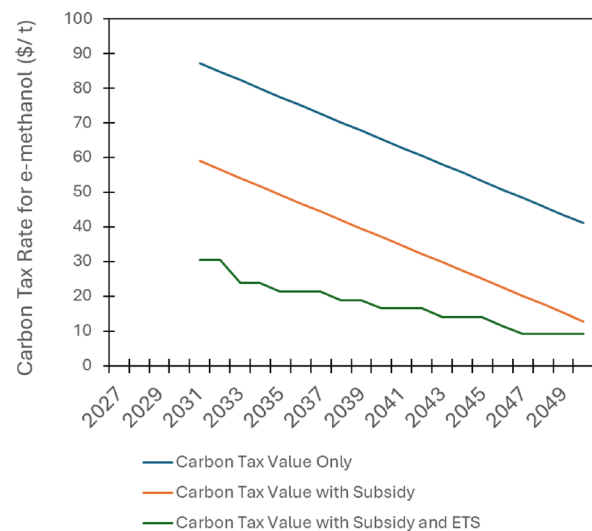
for an economically viable adoption of these fuels to meet the demand shown in Figs. 1 and 2.

An ETS, coupled with the gradual phasing out of free allowances over time, would drive the maritime sector towards adopting e-fuels by making fossil-based fuels progressively more expensive. The model assumes that ETS allowances decrease over time, reaching zero by 2034, which aligns with the European Union's phase-out plan and

adds market pressure to transition to e-fuels (ICAP, 2023). This study shows that applying both a carbon tax and subsidy results in a more equitable cost structure, with governments shouldering the cost of subsidies while shipping companies pay a tax on carbon emissions, thereby achieving a shared responsibility model. The combined approach aligns with findings from Criqui et al. (2019), who noted that layered policy mechanisms increase the effectiveness



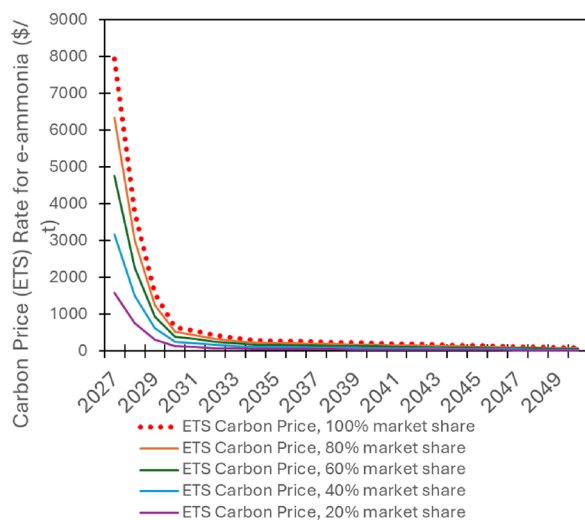
(a)



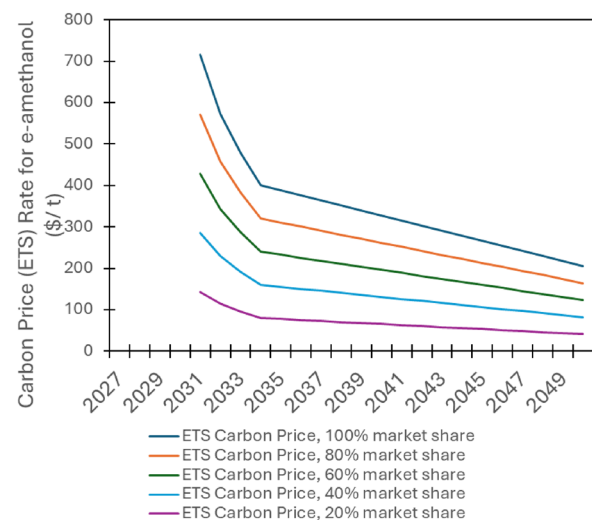
(b)

Fig. 5 Reduction in carbon tax value due to subsidy and ETS for e-methanol uptake as an alternative fuel, for **a** 100% market share to meet the ambition in Fig. 2, and when only 20% of the fuel demand in

Fig. 2. The figure compares the level of carbon taxes needed for market competitiveness with and without complementary policies



(a)



(b)

Fig. 6 Optimal ETS carbon price values required to accelerate the uptake of **a** e-Ammonia and **b** e-Methanol under different market uptake scenarios. These figures illustrate how carbon tax levels influ-

ence the quantity of e-fuels that's economically viable to produce. Note that the carbon tax will be on the conventional fuel; HFO

of decarbonisation strategies by addressing multiple facets of market economics. The results in this study align with previous research on market-based policies for decarbonisation. For instance, studies by Metzger (2021) and Feingold and Willige (2024) emphasise that carbon pricing, such as a carbon tax, drives a shift towards low-carbon alternatives in industries with high emissions like shipping. Metzger

(2021) found that a carbon tax alone raised production costs without offering incentives to switch to low-carbon alternatives; the findings in this work support this, showing that the addition of subsidies is necessary to directly support synthetic fuel adoption. Furthermore, these results echo those of Solakivi et al. (2022), who demonstrate that a combination of carbon pricing and subsidies effectively reduces

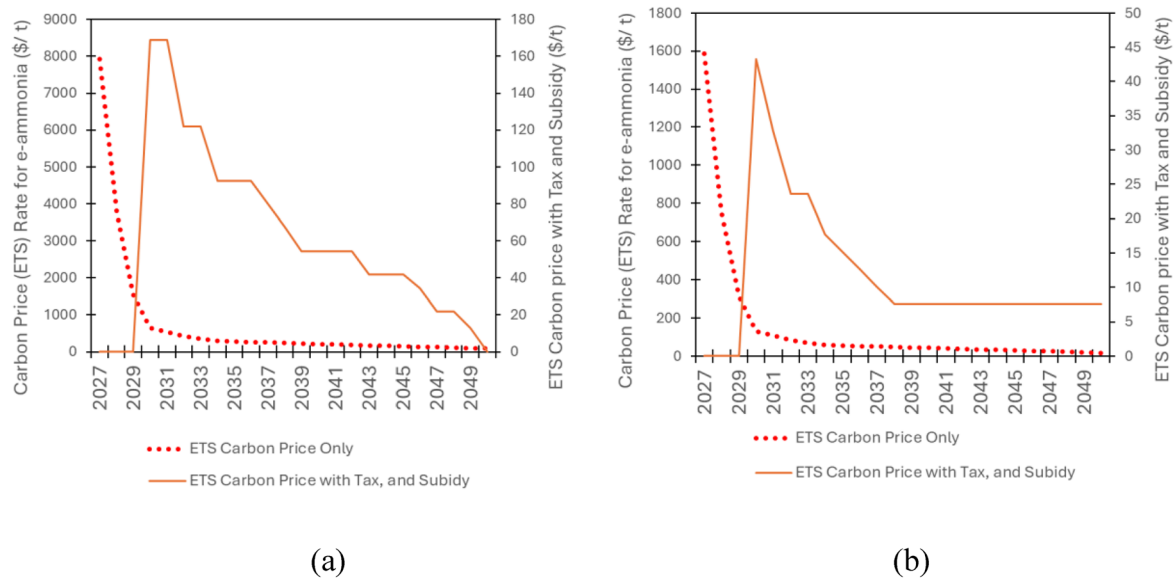


Fig. 7 Reduction in ETS carbon price value due to subsidy and carbon tax for e-Ammonia, for **a** 100% market share to meet the ambition in Fig. 2, and **b** when only 20% of the fuel demand in Fig. 2 is met

met. The figure shows the reduced ETS carbon pricing required to achieve economic viability when supported by carbon taxes and subsidies

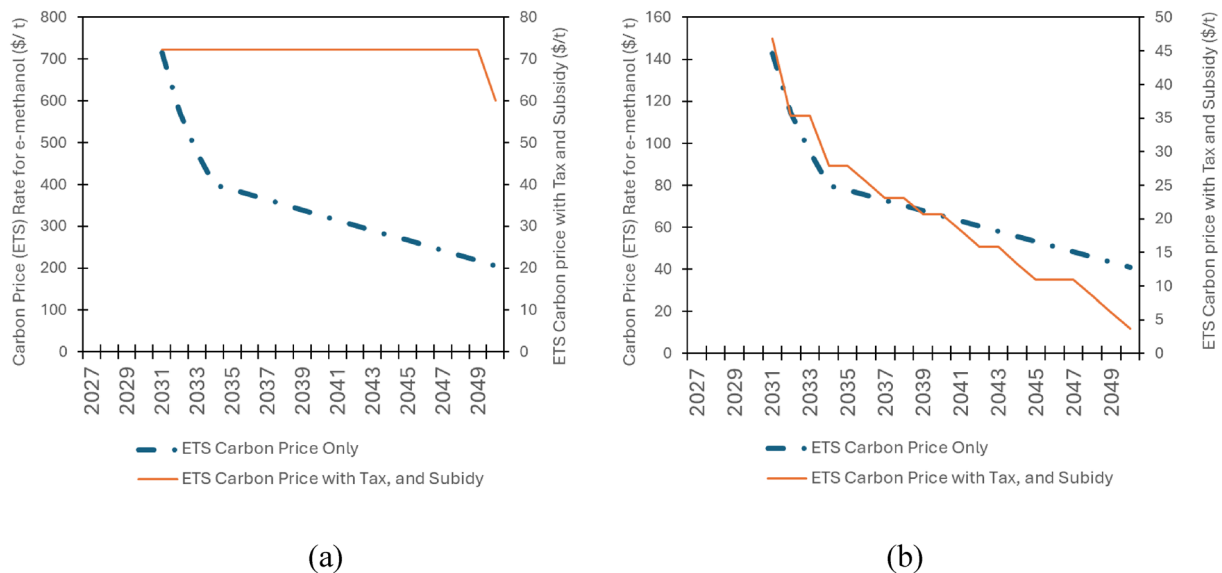


Fig. 8 Reduction in ETS carbon price value due to subsidy and carbon tax for e-methanol, for **a** 100% market share to meet the ambition in Fig. 2, and only 20% of the fuel demand in Fig. 2 is met. The figure

shows the reduced ETS carbon pricing required to achieve economic viability when supported by carbon taxes and subsidies

the price disparity between synthetic and fossil-based fuels. The current study validates this approach by showing that a subsidy, set between \$32.3 and \$79.15 per MWh, would cover the cost gap sufficiently to make e-fuels an attractive choice over HFO. This finding is also supported by IRENA (2021), which projected that e-fuels would remain economically uncompetitive without substantial policy intervention.

The carbon tax rate is designed to increase gradually, ensuring that it remains impactful as the costs of e-fuel production decline due to technological advancements. This dynamic policy adjustment is consistent with Meckling (2021), who argues that static policy models often fall short in adapting to market and technological changes.

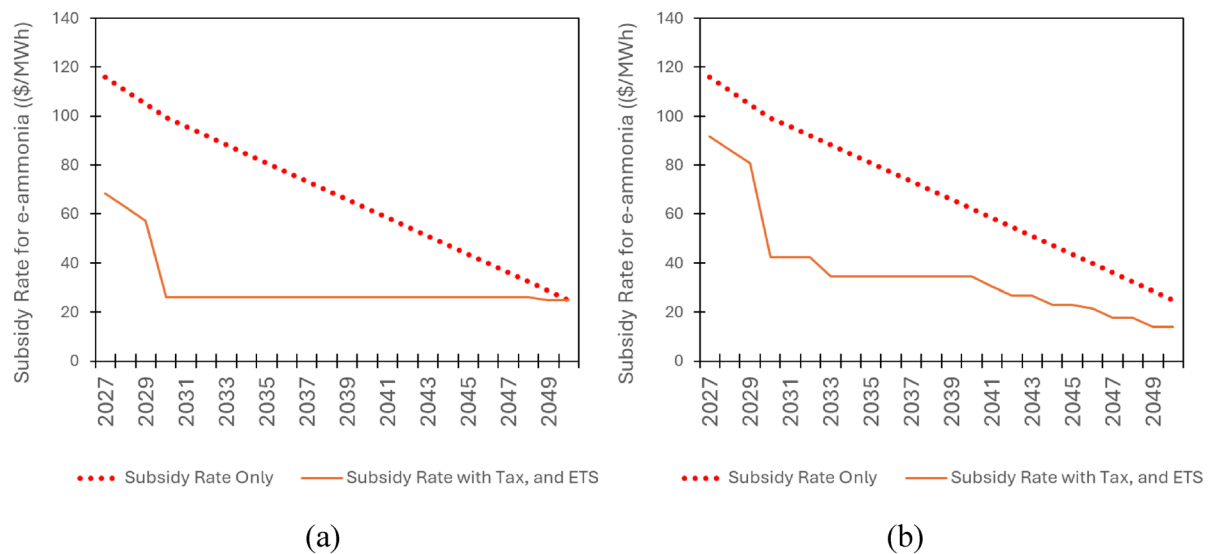


Fig. 9 Reduction in subsidy value due to ETS and carbon tax for e-Ammonia, for **a** 100% market share to meet the ambition in Fig. 2, and **b** only 20% of the fuel demand in Fig. 2 is met. The figure illus-

trates how subsidies alone and in combination with carbon taxes and ETS influence fuel costs

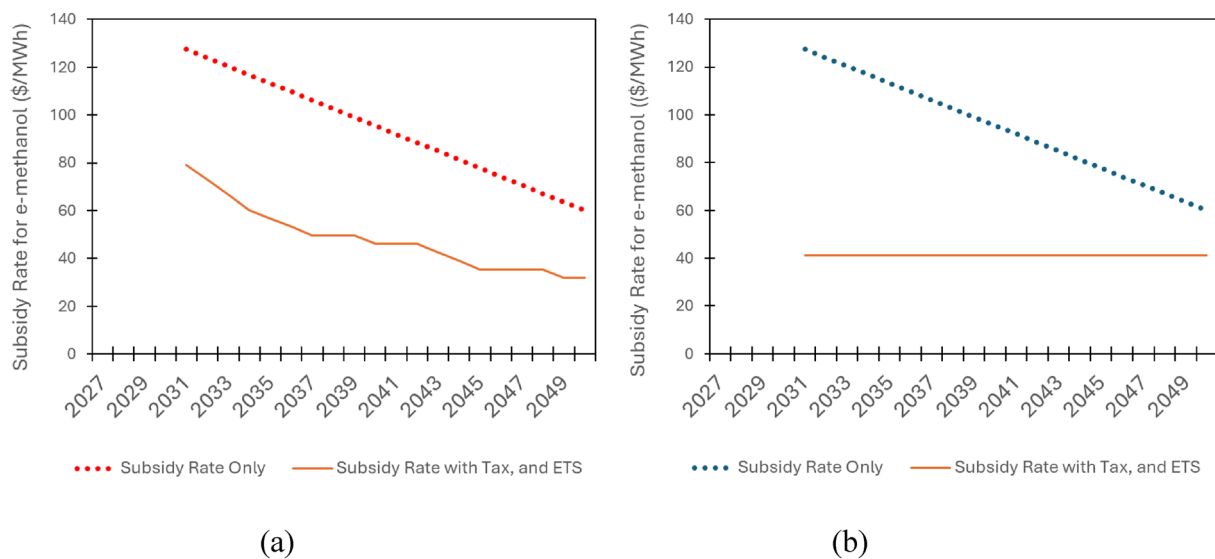


Fig. 10 Reduction in subsidy value due to ETS and carbon tax for e-methanol, for **a** 100% market share to meet the ambition in Fig. 2, and when only 20% of the fuel demand in Fig. 2 is met. The figure

highlights the subsidy values required to make these fuels competitive at different market penetration levels

Case study 2: optimal design of CfD schemes for advanced SAF – A UK case study

This case study evaluates the effectiveness of Contracts-for-Difference (CfD) schemes in funding the production of advanced Sustainable Aviation Fuels (SAF) for the UK aviation sector. The focus is on designing a CfD scheme that balances financial viability for SAF producers while

ensuring cost-efficiency from a policy standpoint given the cost difference between advanced SAF and kerosene (Fig. 13a). The orange shaded region in Fig. 13a shows the cost spread for e-kerosene in the UK today, using data mined from literature. Key factors analysed include determining an appropriate strike price, setting an exit point for the scheme, identifying funding sources, and exploring links to the UK's Aviation Emissions Trading Scheme (ETS) and Air Passenger Duty (APD). This

Fig. 11 Optimal policy mix for e-Ammonia adoption (100% based on the global decarbonisation pathways for shipping by IRENA in Fig. 1). Displays the combination of market-based mechanisms (taxes, subsidies, and ETS) required to make e-Ammonia economically viable

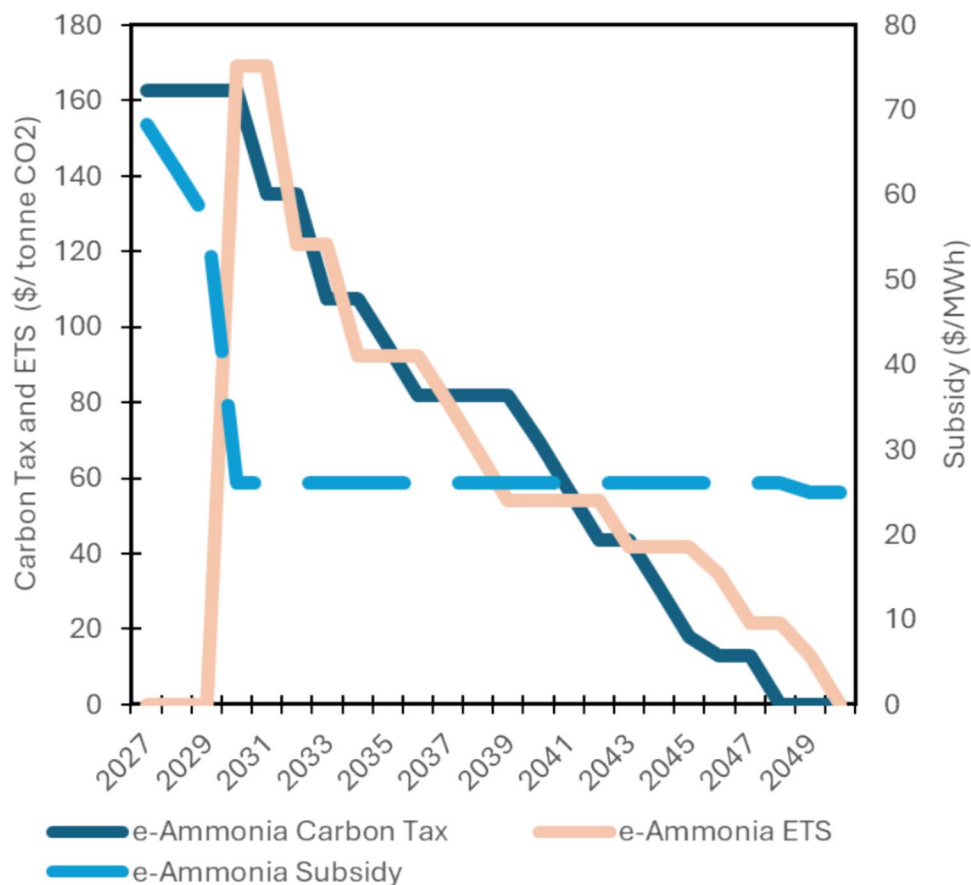
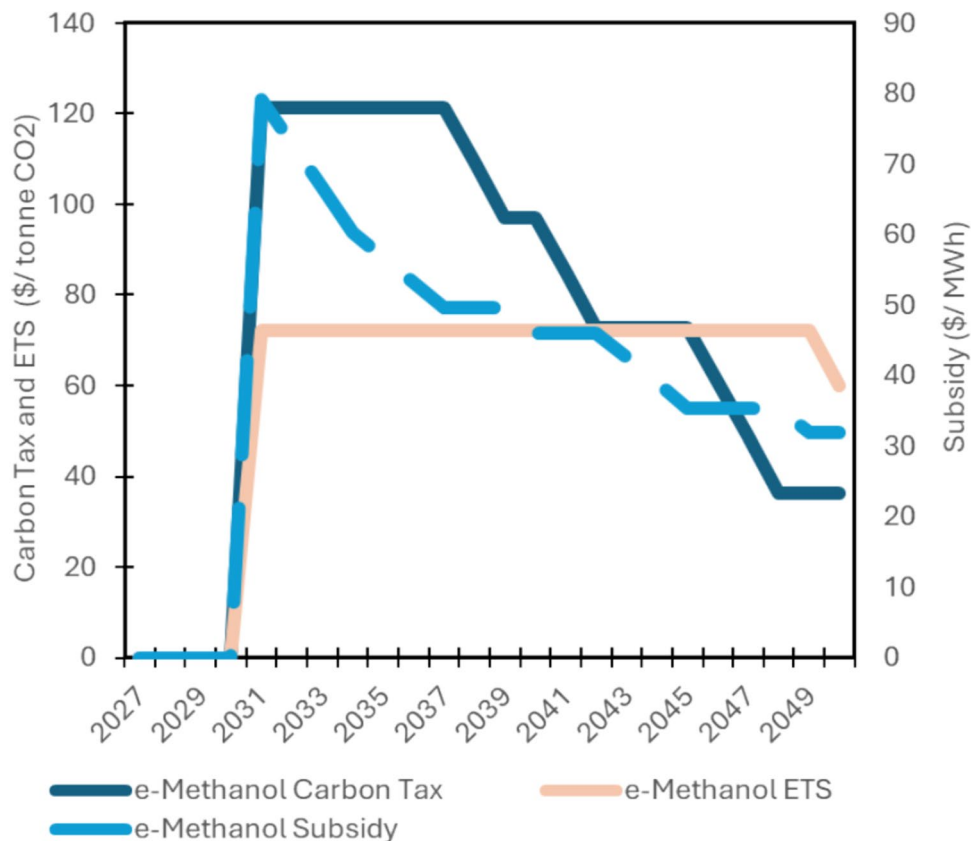


Fig. 12 Optimal policy mix for e-Methanol adoption (100% based on the global decarbonisation pathways for shipping by IRENA in Fig. 1). Shows the most cost-effective blend of policies for achieving price competitiveness for e-Methanol



analysis suggests that a strike price of \$800–\$1,000 per tonne of SAF is necessary to provide adequate financial incentives, attract investment, and cover production costs. This price level aligns with the break-even cost for advanced SAF production, which includes expenses related to feedstocks, technology, and operational factors. The spread of payment is shown in Fig. 13b. Another feature of the CfD scheme is the exit point, which defines the timeline for phasing out government support as SAF production becomes self-sustaining. This model forecasts that by 2040, SAF costs will be close to parity with conventional jet fuel prices, a timeline before 2040 if a tax is imposed on kerosene (Fig. 13c). This anticipated exit point ensures that government intervention is temporary, with subsidies diminishing as market conditions for SAF improve and production costs fall. This phased exit aligns with the UK's broader decarbonisation goals and similar findings from previous studies by Metzger (2021) and Criqui et al. (2019), who advocate for temporary interventions that taper off as green technologies achieve market competitiveness. Funding the CfD scheme is another

essential component for successful SAF deployment in the UK. The Aviation ETS and APD can be primary sources of funding. This analysis in this paper suggests that ETS revenues alone could cover approximately 70% of the necessary CfD support (Fig. 13d).

The APD is a tax on departing passengers, which generates revenue that can be earmarked for SAF subsidies, thus linking air travel with environmental goals. By dedicating a portion of APD revenues to the CfD scheme, the UK can fund approximately 30% of the SAF subsidy costs (Fig. 13d). This approach is consistent with the “polluter pays” principle, linking passenger travel with the environmental costs of aviation. Findings show that APD revenues, growing at an annual rate of 2–3%, would provide a stable and sustainable funding stream, reducing reliance on general taxation and aligning with public expectations that aviation-generated revenues support sustainable initiatives. The impact of the designed CfD scheme on meeting the UK mandate for advanced SAF is provided in Fig. 14. Figure 14 compares fuel supply scenarios under low feedstock (a–c) and policy-induced

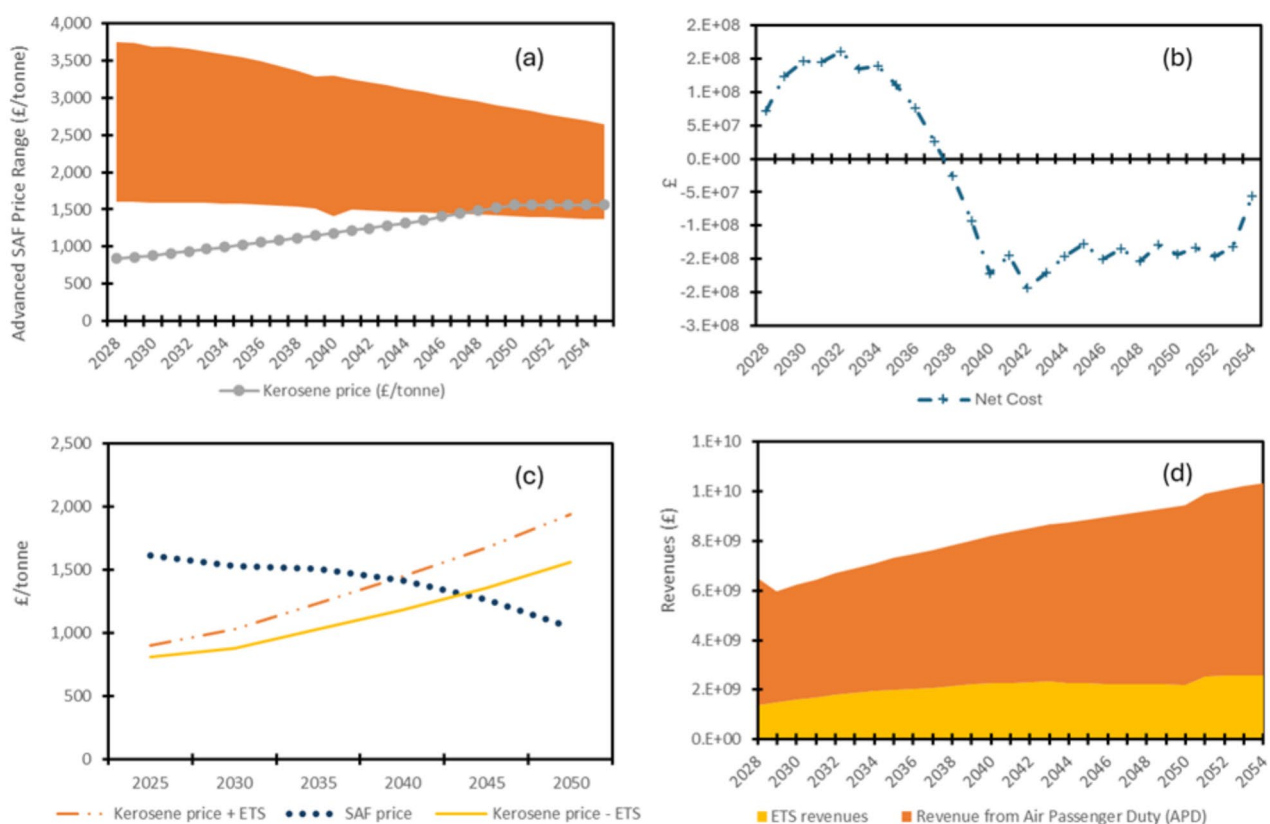


Fig. 13 Design of CfD schemes for advanced SAF in UK aviation. **a** difference between Advanced SAF and kerosene price, **b** CF flows, +ve for payment to industry, and -ve for payment to government), **c** exit point for CFD scheme with and without carbon price on

kerosene, **d** revenues from ETS and APD to support the cash drain in **b**. These sub-figures present the strike price ranges, payment spreads, and funding mechanisms required for SAF under CfD schemes

demand (d–f) across three options. Shortfalls dominate low feedstock scenarios, particularly in Option 3, while policy-induced demand increases Advanced SAF contributions significantly, meeting mandates by 2040.

Case study 3: optimal design of CCfD and CfD schemes for e-fuel economic viability in UK aviation

In this case study, the impact of Carbon Contracts-for-Difference (CCfD) and traditional Contracts-for-Difference (CfD) policies on the economic viability of e-fuels for aviation in the UK is examined for power-to-liquid (PtL)/e-fuels. As the UK aims to achieve its decarbonisation targets under the Jet Zero Strategy (Fig. 15a), policies that provide stable revenue streams, reduce investment risks, and incentivise the production and consumption of e-fuels are critical. There is a need for targeted financial interventions to bridge the substantial cost gap between e-fuels and fossil-based jet fuel (Fig. 15b for PtL made with CO₂ from DAC, and Fig. 15c for PtL made from CO₂ from point sources). The shaded region in Fig. 15b and c shows the price range of e-kerosene when CO₂ is sourced from DAC and industrial point sources (IPS), respectively.

At the heart of the CCfD and CfD policies is the concept of providing a guaranteed strike price, which stabilises revenue for producers by ensuring a minimum price for e-fuels regardless of market fluctuations (Figs. 16 and 18).

Figures 16 and 17 illustrate the financial and price dynamics of Contracts-for-Difference (CfD) applied to e-fuels derived from Direct Air Capture (DAC-PtL) and Industrial Point Source (IPS-PtL) technologies, respectively. For DAC-PtL (Fig. 16), the reference price begins at approximately £1000/tonne in 2026, rising steadily to just under £2000/tonne by 2054. Meanwhile, the central strike price declines from £4000/tonne in 2026 to £2000/tonne by 2038, while high and low strike prices follow similar declining trends. Notably, the reference price does not exceed the central strike price throughout the period but does surpass the low strike price around 2037, showing gradual progress towards cost competitiveness. In contrast, IPS-PtL (Fig. 17) demonstrates a more favourable cost trajectory. The reference price starts lower at £800/tonne in 2026 and increases to over £2000/tonne by 2054. The central strike price declines sharply from £2800/tonne to below £1000/tonne by 2040, and the reference price overtakes the central strike price from 2041. These results suggest that IPS-PtL could achieve market viability earlier than DAC-PtL, under the CfD mechanism. From the right panel of Fig. 16, DAC-PtL requires government payments peaking around £2500 million/year by 2039, which then decrease as industry payments (exceeding £2000 million/year post-2043) dominate. IPS-PtL (Fig. 16 right panel) shows lower government outlay, with a maximum around £2000 million/year by 2039, and a faster shift to industry contributions, highlighting its lower fiscal burden.

Figures 18 and 19 detail the performance of Carbon Contracts-for-Difference (CCfD), which link strike prices

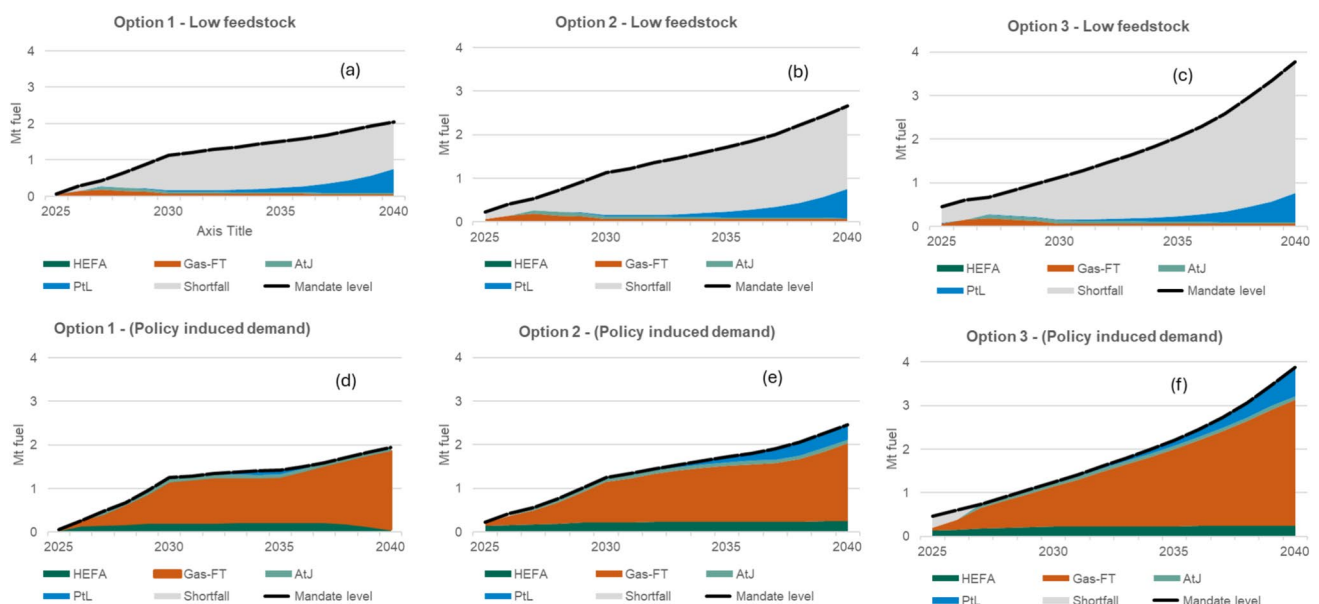


Fig. 14 Modelled fuel mix for SAF mandate trajectory options. Projects the SAF market penetration under different mandate scenarios and feedstock availability

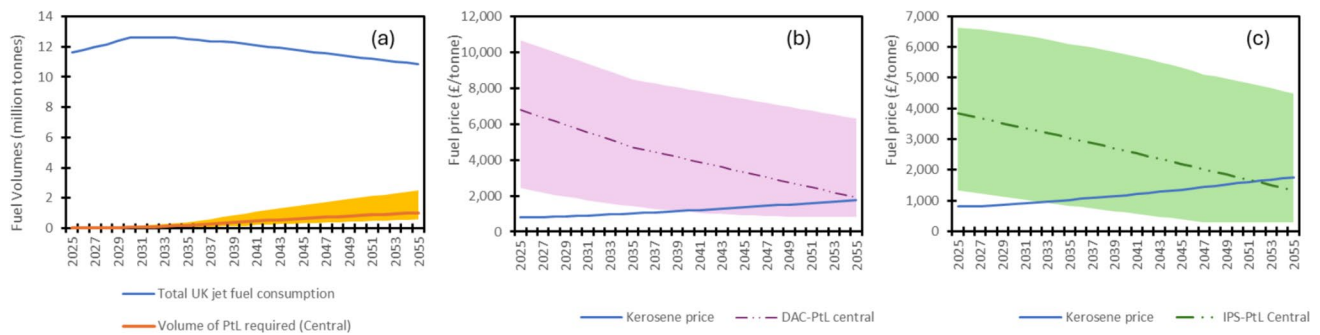


Fig. 15 a volume of PtL required for net-zero in the UK aviation sector, Cost gap analysis for PtL fuels made from b DAC and c IPS CO₂ sources. The figures highlight the cost difference between DAC-derived and IPS-derived e-fuels and their implications for policy design

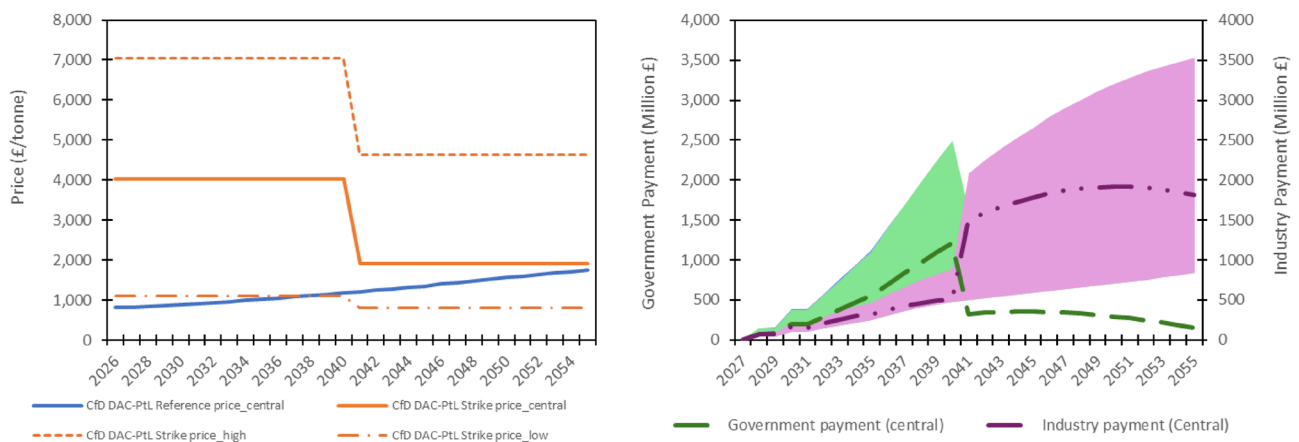


Fig. 16 Structure of the optimal CfD schemes for stabilising SAF (made with CO₂ from DAC) prices. Depicts the payment flows and strike price mechanisms under CfD policies

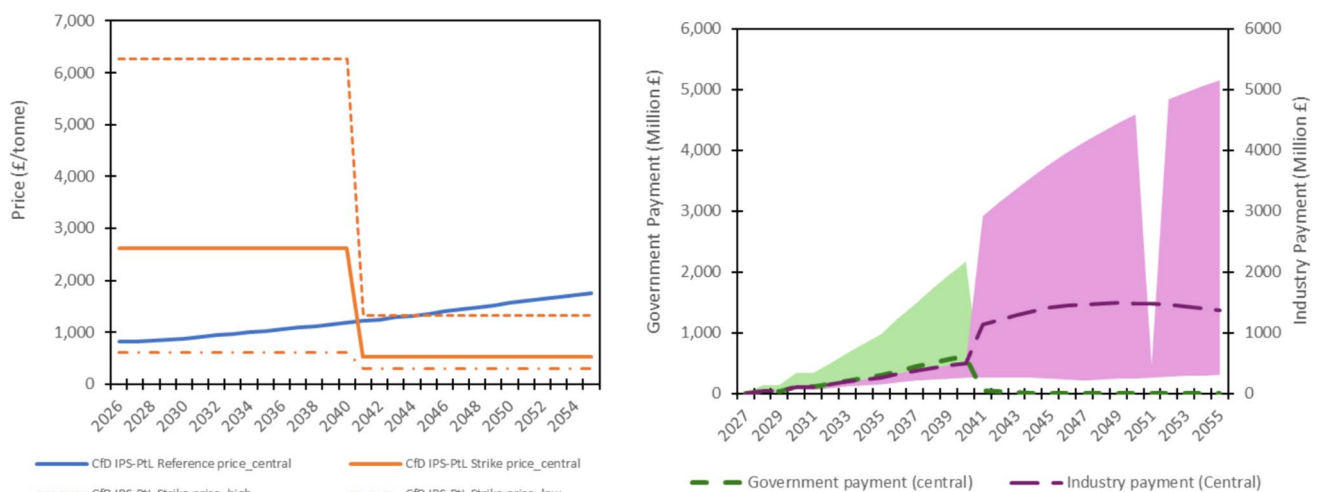


Fig. 17 Structure of the optimal CfD schemes for stabilising SAF (made with CO₂ from point source) prices. Depicts the payment flows and strike price mechanisms under CfD policies

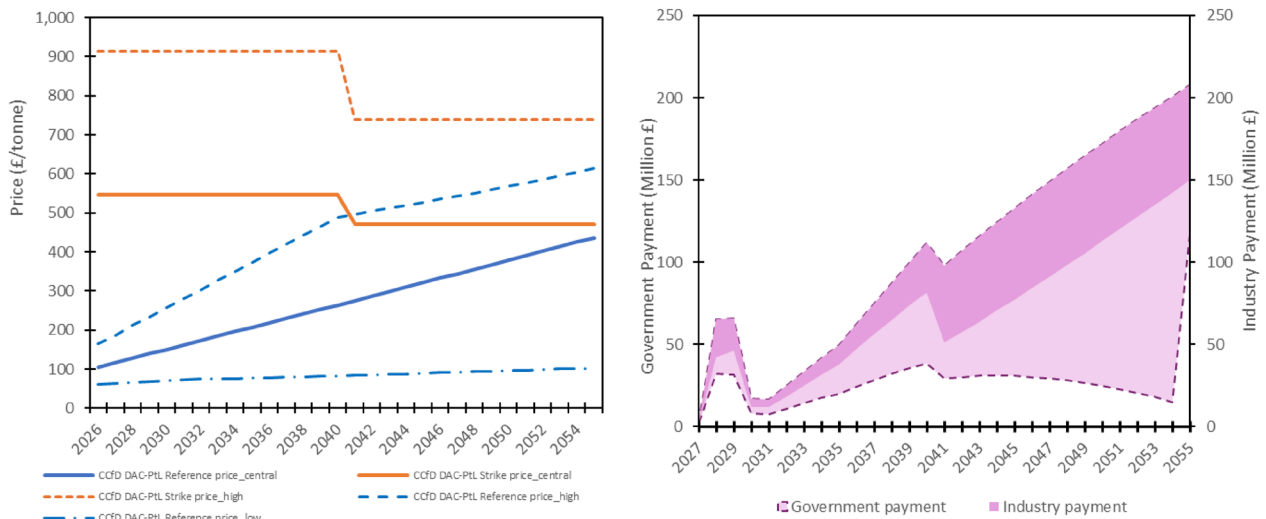


Fig. 18 Design of CCfD schemes for DAC-based e-fuels. Demonstrates how CCfD policies link strike prices to carbon reductions, providing additional incentives

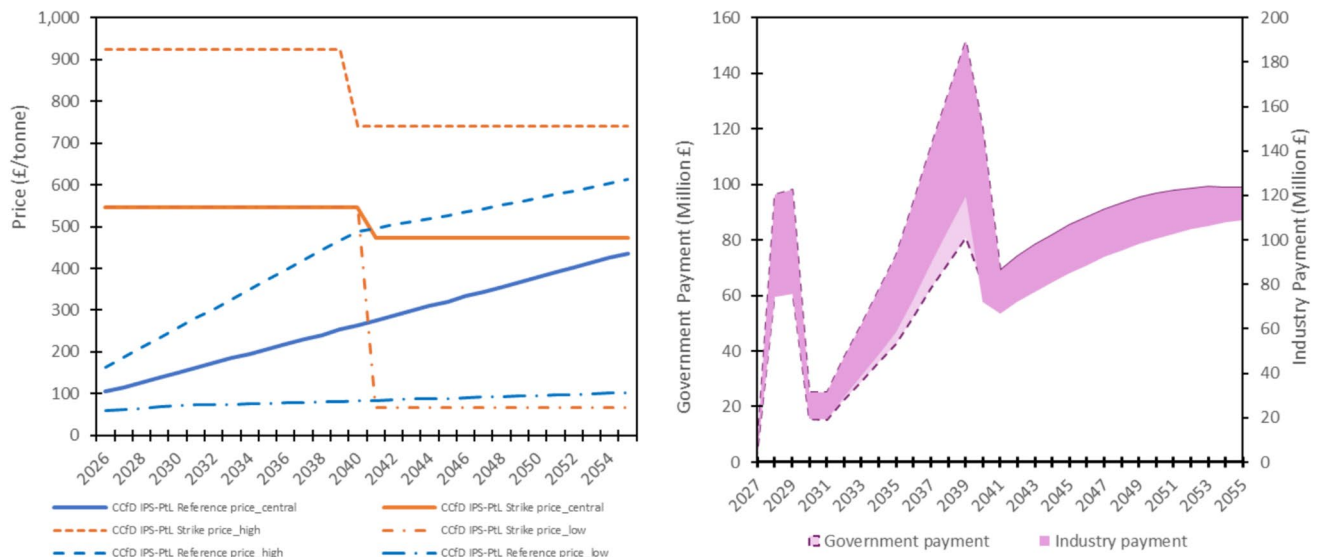


Fig. 19 Design of CCfD schemes for IPS-based e-fuels. Demonstrates how CCfD policies link strike prices to carbon reductions, providing additional incentives

to carbon reduction. Under CCfD, the central strike price remains constant at £550/tonne from 2026 to 2040, then decreases slightly. For DAC-PtL (Fig. 18), the central reference price rises from £100/tonne in 2026 to approximately £450/tonne by 2054, never exceeding the central strike price. As a result, government payments dominate, peaking at £100 million/year by 2039, before falling steadily. Industry payments rise but remain below £200 million/year by 2054. In IPS-PtL (Fig. 19), the reference price starts at £100/tonne and increases to £450/tonne by 2054, approaching but not exceeding the strike price. Government payments also peak at £100 million/year by 2039, with industry payments

growing consistently thereafter, but remaining under £150 million/year. Compared to DAC-PtL, IPS-PtL again shows a lower fiscal burden, with similar payment trajectories but reduced magnitude. From these results, both CCfD and CfD schemes can bridge the early cost gap between e-fuels and fossil fuels, while enabling a gradual transition from public subsidy to private sector cost recovery. IPS-PtL appears to reach economic viability faster and with a lower fiscal burden than DAC-PtL, reinforcing its role in early-stage market development.

The CCfD scheme is a more flexible tool for decarbonising the aviation sector, as they encourage producers not only to

adopt e-fuels but also to pursue more efficient, lower-emission production techniques. Moreover, this approach aligns with the UK's broader climate goals by promoting a “carbon value” framework that supports deep decarbonisation rather than simply fuel substitution. This analysis further highlights the importance of setting a strategic exit point for both schemes based on their economic tipping point. For the CfD scheme, the tipping point also depends on the source of CO₂ and kerosene tax. Without kerosene tax, there is no tipping point before 2054 for DAC CO₂ (Fig. 20). At higher kerosene tax, the tipping point and exit point can be achieved by 2040 for DAC CO₂. Whereas for CO₂ from IPS, the exit point is by 2045 even without kerosene tax (Fig. 21), reducing to 2039 with a higher tax on kerosene. An exit strategy that aligns with the economic tipping point is crucial for maintaining fiscal responsibility, as it prevents long-term dependence on subsidies and allows e-fuels to compete independently in the market. These findings align with literature such as Meckling et al. (2021), which argues for time-bound subsidies that taper off as technologies achieve scale and cost-efficiencies.

From Fig. 20, kerosene prices rise steadily with tax (~£1500–£3500/tonne), while strike prices ensure cost stability for e-SAFs. Taxation and subsidies narrow price gaps, reducing reliance on government support over time. Government payments peak at £2000–£2500 million annually, with industry contributions gradually increasing from £200–£800 million. Notably, post-2040, industry payments surpass £500 million, signalling reduced public financial burden. In later years, total costs stabilise, illustrating improved economic viability of e-SAFs as carbon pricing and policy interventions drive market alignment with kerosene.

From Fig. 21, Kerosene prices increase steadily due to the tax, while strike prices ensure price stability for e-SAFs. Early gaps between strike prices (£2,000–£2,500/tonne) and kerosene prices (£1000–£1500/tonne) highlight SAF's higher initial costs, which narrow over time. Government payments dominate initially, peaking at £1.2–£1.4 billion annually by 2040, with industry contributions rising to ~20–25% of total costs. By 2055, industry payments exceed £300 million, demonstrating a shift towards cost parity and reduced government dependence as SAF adoption scales up. Periodic strike price reviews should be conducted to reflect current market realities and avoid over-subsidisation as e-fuel costs decrease. This aligns with the findings of Richstein and Neuhoff (2022), who advocate for dynamic policy instruments that adjust to technological progress, thereby maximising policy impact while controlling public expenditure.

Discussions and limitations

Market-based policy interventions can improve the economic viability of e-fuels in both global shipping and local aviation. Each case study explores different facets of market-based policy tools ranging from carbon taxes, emissions trading schemes, subsidies, Contracts-for-Difference (CfD) to Carbon Contracts-for-Difference (CCfD) to show how these mechanisms can close the cost gap between e-fuels and conventional fossil fuels. The findings reveal the importance of a strategic policy mix, not only to reduce production costs but also to create a stable financial environment that encourages investment and supports long-term decarbonisation

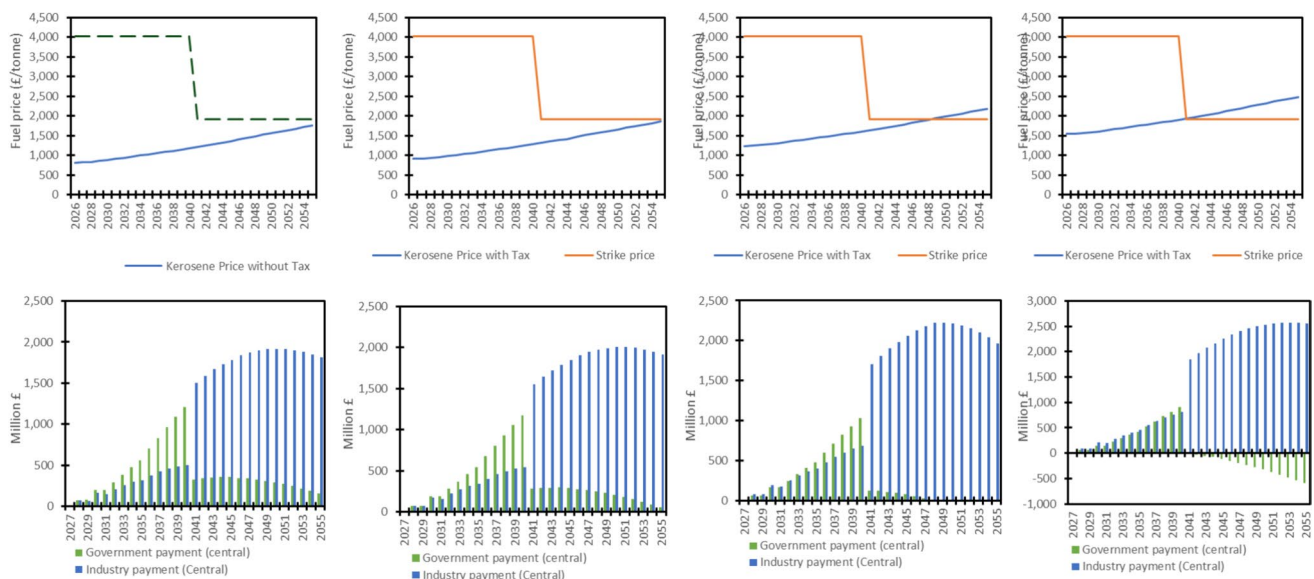


Fig. 20 Impact of kerosene tax on the economic tipping point for DAC-based PtL fuels where the market mechanism is the CfD scheme. This figure examines how kerosene taxes influence the economic viability timeline of PtL fuels using DAC CO₂

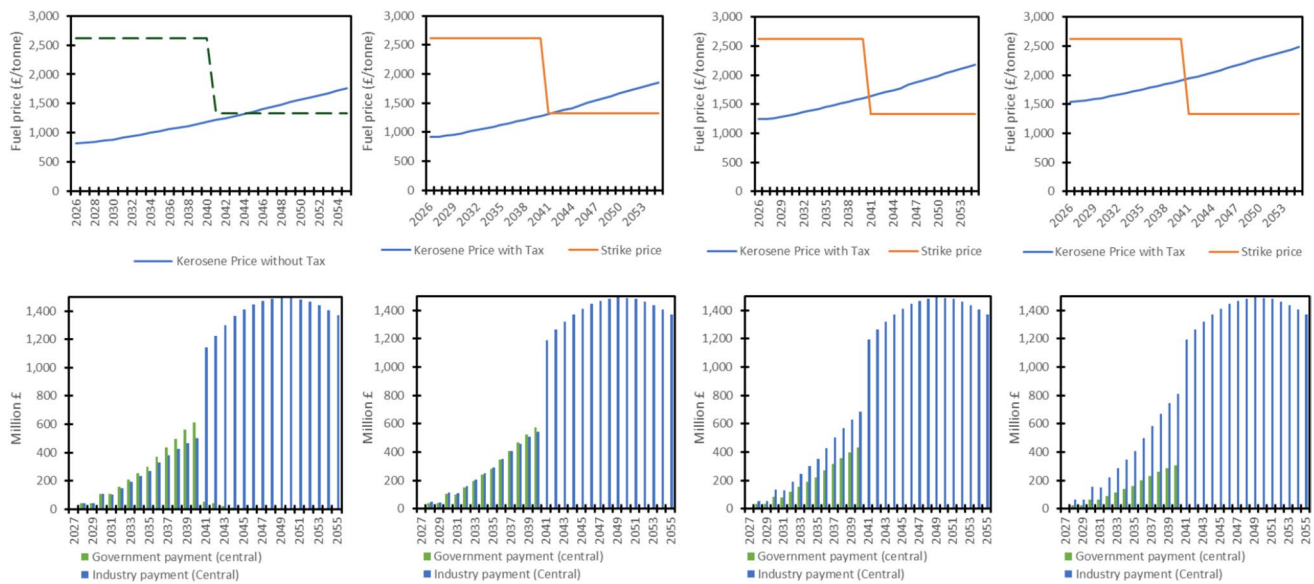


Fig. 21 Impact of kerosene tax on economic tipping point for IPS-based PtL fuels (for the CfD scheme). Displays the effect of kerosene tax levels on achieving cost parity for PtL fuels produced with industrial point source CO₂

goals. In the first case study, focused on global shipping, a mix of carbon taxes, subsidies, and an emissions trading scheme (ETS) demonstrates how these combined policies help address the high production costs associated with e-Ammonia and e-Methanol. The analysis shows that when carbon taxes and subsidies are used in tandem, they not only increase the cost of traditional fuels but also reduce the effective cost of e-fuels, making them a more competitive option. While a standalone carbon tax would have needed to be extremely high to make e-fuels competitive, introducing subsidies and ETS reduced the necessary tax level significantly. These results align with existing literature on the role of layered policy approaches in encouraging the adoption of low-carbon technologies, which is especially important in a sector like shipping, where fuel costs directly impact global trade logistics. The second case study on advanced sustainable aviation fuels (SAF) in the UK emphasises the potential of CfDs to create a secure financial structure that supports SAF production. A carefully set strike price of £800–£1,000 per tonne of SAF was shown to be effective in meeting the financial needs of producers while also making SAF more affordable for the aviation sector. The study also illustrates the importance of integrating CfDs with the UK's Aviation ETS and Air Passenger Duty (APD), two aviation-specific revenue streams that can sustainably fund SAF subsidies. This dual-source funding not only strengthens public support for SAF by ensuring that the aviation industry bears a significant portion of the cost but also minimises reliance on public funds. In the third case study, the role of CCfDs and CfDs in making e-fuels economically viable for UK aviation is evaluated. While traditional CfDs provide a fixed strike

price, CCfDs offer a more targeted approach by tying financial support to actual carbon reductions achieved by e-fuel producers. This model not only stabilises revenue but also encourages producers to prioritise environmentally friendly production methods, resulting in greater overall carbon savings. Additionally, the study emphasises the importance of setting an exit point for both schemes, ensuring that government support diminishes as e-fuel technologies mature and production costs decrease. The common thread across all three case studies is the importance of designing policies that balance short-term financial support with long-term sustainability. Each study highlights the need for initial financial incentives, such as subsidies or CfDs, to offset high production costs and reduce investor risk. However, the studies also show the need for setting clear exit strategies for these policies, ensuring that as production costs decline, the market gradually assumes the financial responsibility for sustaining low-carbon fuels. Another insight from these case studies is the potential for industry-specific funding sources, such as the Aviation ETS and APD in the UK, to create a sustainable financial framework for e-fuel production. Well-designed policy interventions can make e-fuels viable alternatives in hard-to-abate sectors. One key limitation across the case studies is the uncertainty in the cost data. For instance, in the first case study on global shipping, cost estimates for e-Ammonia and e-Methanol were used to determine necessary subsidy and tax levels. However, actual production costs for synthetic fuels can vary widely depending on factors like energy prices, feedstock availability, and regional differences in manufacturing infrastructure. The third case study on CCfDs and CfDs for UK aviation e-fuels also reveals

limitations related to the implementation of dynamic, flexible policy models. Although the study advocates for an adaptive strike price within the CCfD scheme to reflect market and technological conditions, practical implementation of such a flexible model is challenging. Adjusting strike prices over time requires a responsive regulatory framework and timely, accurate data on production costs and market demand conditions that are not always met in policy environments. Finally, whilst our focus is on economic instruments there are other non-economic barriers. For instance, infrastructure limitations for e-fuel production, storage, and distribution remain a challenge, especially in the maritime sector.

Conclusions

This research addresses the economic challenge in decarbonising aviation and shipping by exploring how market-based policy interventions can enhance the economic viability of e-fuels, which are otherwise prohibitively expensive compared to conventional fuels. The novelty of this research lies in its application of targeted policy models, namely, Contracts-for-Difference (CfD), Carbon Contracts-for-Difference (CCfD), and mixed policy approaches comprising subsidies, carbon taxes, and emissions trading schemes to systematically reduce costs and stimulate investment in e-fuels for these hard-to-abate sectors. This research demonstrates how a structured, sector-specific policy mix can close the cost gap between e-fuels and fossil-based alternatives, encouraging the adoption of low-carbon fuels using insights from three case studies: global shipping, advanced SAF for UK aviation, and e-fuels for UK aviation. A novel temporal market penetration optimisation model was developed for e-fuels.

In the global shipping sector, the results show that e-Ammonia and e-Methanol currently cost \$900–\$1200 per tonne, higher than Heavy Fuel Oil (HFO) at \$400 per tonne. A standalone carbon tax of \$100 per tonne of CO₂ is insufficient to make e-fuels competitive, as only 10–15% of demand is triggered. However, a combined approach of carbon taxes (\$33.6–\$162.8 per tonne CO₂) and subsidies (\$32.3–\$79.15 per MWh) reduces the cost of e-Ammonia and e-Methanol by 24% and 29%, respectively. The findings

also indicate that emissions reductions of up to 8.2 Mt CO₂ annually can be achieved when integrating these policies effectively, demonstrating a clear pathway to price parity.

In the UK aviation sector, the study reveals that Power-to-Liquid (PtL) fuels cost £800–£1000 per tonne, while conventional kerosene costs approximately £300 per tonne. Implementing CfD schemes with strike prices of £900 per tonne can make PtL fuels competitive by 2035, reducing government support costs by up to 30% by 2040. Additionally, Carbon Contracts-for-Difference (CCfDs), tied to emissions reductions of 60–70% relative to kerosene, can bring PtL production costs down further while achieving a total CO₂ abatement of 4.5–6 Mt annually. Under a kerosene tax of £200 per tonne, economic tipping points for PtL fuels are accelerated by approximately 5–8 years, making large-scale adoption feasible sooner.

For global shipping, this model was used to evaluate the combined impact of carbon taxes, subsidies, and an emissions trading scheme (ETS) on e-Ammonia and e-Methanol. In the advanced SAF case, a CfD model provided a stable strike price for producers, supported by revenues from the UK's Aviation ETS and Air Passenger Duty (APD). In the third case study, both CCfD and CfD policies were assessed for e-fuels (using CO₂ from DAC and CO₂ from industrial point sources), with a focus on creating a flexible strike price linked to emissions reductions. Each model is grounded in real-world data, aiming to show the financial feasibility of e-fuels under optimal policy conditions. Therefore, layered policy mechanisms can distribute costs and share financial responsibility, making e-fuels more accessible and financially viable for both sectors. This research provides a clear roadmap for policymakers aiming to accelerate the adoption of sustainable fuels. Future work would build on this foundation by exploring the infrastructure and supply chain requirements for large-scale e-fuel adoption.

Appendix A: general model assumption for case study 1.

See Tables 1, 2 and 3

Table 1 General assumptions

Parameter	Value/Description	Source
Carbon intensity of HFO	81.18 MtCO ₂ /EJ	IRENA (2021)
Fuel demand data years	2030, 2040, 2050	IRENA (2021)
Fuel price data	Global average, interpolated	IRENA (2021)
ETS free allowance phase-out	100% (2025)–0% (2034)	ICAP (2023)
ETS policy start year	2027 (aligned with MEPC timeline)	World Bank (2024)
CCfD contract length	15 years	IEA (2023)
Revenue usage from carbon pricing	Fully reinvested into clean fuel subsidies	World Bank Blogs (2023)
Fuel emissions (e-fuels)	Assumed zero at point of use	

Table 2 Fuel demand and price assumptions (interpolated from IRENA (2021) the below assumptions align with the shipping decarbonisation pathway in Fig. 1

Year	e-Ammonia demand (EJ)	e-Ammonia Avg. price (\$/MWh)	e-Methanol demand (EJ)	e-Methanol Avg. price (\$/MWh)	HFO Avg. price (\$/MWh)
2023	0.00	173.00	0.00	203.50	35.20
2024	0.00	168.50	0.00	198.00	37.30
2025	0.06	163.50	0.00	194.50	39.40
2026	0.65	160.20	0.00	191.50	44.43
2027	0.95	157.00	0.00	188.50	46.54
2028	1.15	154.00	0.00	185.50	48.65
2029	1.35	151.00	0.00	182.00	50.76
2030	1.60	148.00	0.00	179.00	52.86
2031	1.75	145.00	0.00	176.00	54.97
2032	1.85	144.50	0.00	175.50	52.86
2033	2.00	142.00	0.25	170.50	50.76
2034	2.10	140.50	0.40	166.00	54.80
2035	2.20	138.50	0.65	161.50	53.88
2036	2.35	136.00	0.80	157.00	57.85
2037	2.45	134.00	1.00	152.50	56.93
2038	2.60	132.00	1.15	148.50	58.04
2039	2.75	130.00	1.30	144.50	59.15
2040	2.90	128.00	1.45	140.50	60.30
2041	3.05	126.00	1.60	136.50	61.40
2042	3.20	124.00	1.75	132.50	62.50
2043	3.35	122.00	1.90	128.50	63.65
2044	3.50	87.50	0.85	122.50	62.50
2045	1.55	128.70	1.20	161.50	55.55
2046	1.70	125.30	1.60	151.20	56.60
2047	2.00	120.00	2.00	141.50	57.65
2048	2.15	116.00	2.15	132.00	58.70
2049	2.45	109.70	2.45	109.70	58.85
2050	3.50	87.50	3.50	122.50	62.50

Table 3 Validation of average fuel price assumption based on reported values of price ranges for e-ammonia and e-methanol

Year	e-Ammonia Price Range (\$/MWh)	e-Methanol Price Range (\$/MWh)
2023	70–210	60–200
2024	68–200	58–190
2025	65–195	55–185
2026	63–190	53–180
2027	60–185	50–175
2028	58–180	48–170
2029	56–175	46–165
2030	54–170	44–160
2031	52–165	42–155
2032	50–160	40–150
2033	48–155	38–145
2034	46–150	36–140
2035	44–145	34–135
2036	42–140	32–130
2037	40–135	30–125
2038	38–130	28–120
2039	36–125	26–115
2040	34–120	24–110
2041	32–115	22–105
2042	30–110	20–100
2043	28–105	18–95
2044	26–100	16–90
2045	24–95	14–85
2046	22–90	12–80
2047	20–85	10–75
2048	18–80	8–70
2049	16–75	6–65
2050	15–70	5–60

Appendix B: general model assumption for case study 2.

See Tables 4 and 5

Table 5 Modelled fuel mix for mandate trajectory options 1–3, under high and low feedstock availability assumptions (DfT 2023)

Option 1—Low feedstock (Megatonnes of fuel)					
Year	Mandate level	HEFA	Gas-FT	AtJ	PtL
2025	0.06	0.01	0.05	0.00	0.00
2026	0.28	0.01	0.14	0.00	0.00
2027	0.42	0.01	0.17	0.08	0.01
2028	0.65	0.01	0.14	0.08	0.01
2029	0.88	0.01	0.11	0.08	0.02
2030	1.13	0.01	0.05	0.07	0.02
2031	1.20	0.01	0.05	0.06	0.03
2032	1.28	0.01	0.05	0.06	0.05
2033	1.35	0.01	0.05	0.05	0.06
2034	1.43	0.01	0.05	0.05	0.09
2035	1.50	0.01	0.05	0.04	0.12
2036	1.58	0.01	0.05	0.04	0.17
2037	1.68	0.01	0.05	0.04	0.24
2038	1.80	0.01	0.05	0.03	0.34
2039	1.93	0.01	0.05	0.03	0.48
2040	2.05	0.01	0.05	0.03	0.67
Option 2—Low feedstock (Megatonnes of fuel)					
Year	Mandate level	HEFA	Gas-FT	AtJ	PtL
2025	0.23	0.01	0.05	0.00	0.00
2026	0.42	0.01	0.14	0.00	0.00
2027	0.53	0.01	0.17	0.08	0.01
2028	0.72	0.01	0.14	0.08	0.01
2029	0.92	0.01	0.11	0.08	0.02
2030	1.13	0.01	0.05	0.07	0.02
2031	1.23	0.01	0.05	0.06	0.03
2032	1.35	0.01	0.05	0.06	0.05
2033	1.47	0.01	0.05	0.05	0.06
2034	1.59	0.01	0.05	0.05	0.09
2035	1.71	0.01	0.05	0.04	0.12
2036	1.85	0.01	0.05	0.04	0.17
2037	2.01	0.01	0.05	0.04	0.24
2038	2.22	0.01	0.05	0.03	0.34
2039	2.44	0.01	0.05	0.03	0.48
2040	2.66	0.01	0.05	0.03	0.67

Table 4 Assumptions table

Parameter	Value/Range	Source
Kerosene price (2025)	£808/tonne	US EIA (2023)
SAF price multiplier (β)	2.0–5.0 in 2025; 1.2–2.8 by 2040	DfT (2023d); ICF (2023)
ETS aviation emissions	9.3 MtCO ₂ /year	DfT (2022)
APD baseline revenue (2025)	£3.6 billion	OBR (2023)
APD growth rate (g _{APD})	2.5%/year	Based on passenger forecasts
Mandate target (M ₂₀₂₅)	0.23 Mt (10% of jet fuel by 2030)	DfT Jet Zero Strategy

Table 5 (continued)

Option 3—High feedstock (Megatonnes of fuel)					
Year	Mandate level	HEFA	Gas-FT	AtJ	PtL
2025	0.46	0.14	0.05	0.00	0.00
2026	0.60	0.15	0.22	0.00	0.00
2027	0.74	0.17	0.48	0.08	0.01
2028	0.91	0.19	0.63	0.08	0.01
2029	1.07	0.21	0.76	0.08	0.02
2030	1.24	0.22	0.92	0.08	0.02
2031	1.41	0.22	1.07	0.08	0.03
2032	1.60	0.22	1.26	0.08	0.05
2033	1.79	0.23	1.43	0.08	0.06
2034	1.99	0.23	1.59	0.08	0.09
2035	2.20	0.23	1.77	0.08	0.12
2036	2.45	0.23	1.96	0.08	0.17
2037	2.73	0.23	2.18	0.08	0.24
2038	3.07	0.24	2.41	0.08	0.34
2039	3.47	0.24	2.67	0.08	0.48
2040	3.88	0.24	2.89	0.08	0.67

Appendix C: general model assumption for case study 3.

See Table 6

Table 6 Data input table for modelling

Parameter	Value(s)
Contract duration CD	15 years
ER (emissions reduction per PtL)	DAC-PtL: 1.0 tCO ₂ /tPtL; IPS-PtL: 0.75 tCO ₂ /tPtL
α_t	Central Mandate: grows to 3.5% by 2040 (see forecast)
RP_t^{fuel}	Market kerosene price (forecasted)
$RP_t^{\text{CO}_2}$	UK ETS CO ₂ price: low £30, central £100, high £435 (increases over time)
L_t	Kerosene tax scenarios: £100, £425.50, £725 per tonne
QK_t	Approximately 96.5% in 2040 (complement of PtL mandate)
J_t	UK jet fuel demand forecast (decreasing post-2040 due to efficiency policies)
PtL production prices	DAC-PtL: £5756 (central), IPS-PtL: £3437 (central)
SP_t^{fuel}	Optimised to minimise CfD cost, subject to $SP_t^{\text{fuel}} \geq \text{LCOF}_t$
$SP_t^{\text{CO}_2}$	Optimised to ensure PtL producer cost recovery via CCfD

Author Contribution GO wrote the manuscript, co-developed the methodology, EG performed the analysis for the e-fuels for aviation case study, SG performed the analysis for the e-fuels for global shipping case study, TT performed the analysis for the advanced SAF for aviation case study, SB supervised the work and contributed to the analysis of EG's case study.

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Data Availability All datasets analysed and generated are provided in the appendix.

Declarations

Conflict of Interests The authors declare no competing interests.

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