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Executive Summary

Context

Over the last three years, expansive energy transition and climate mitigation policy frameworks have been deployed on both sides of the Atlantic. They seek to reduce emissions from a wide range of economic sectors, including electricity generation, transportation, industry, and buildings.

Within the transportation sector, battery electric vehicles (EVs) are widely regarded as the primary tool for addressing the majority of emissions. However, aviation and maritime applications are likely to require fuels for combustion engines for the foreseeable future.

This report will examine the actions taken by the United States (US) and the European Union (EU), two regions commonly at the forefront of climate policy, to support the deployment of lower-greenhouse gas (GHG) fuel options in aviation and marine applications.

In the US, the primary policy measures include the Bipartisan Infrastructure Law (BIL), and the Inflation Reduction Act (IRA). Earlier federal regulations include the renewable fuel standard (RFS). State level frameworks, include the Low Carbon Fuel Standards (LCFS) in California and similar regulations Oregon and Washington State. These rules support the deployment of low-carbon fuels, primarily targeting on-road applications. They have limited impact on aviation and shipping, where demand for low-carbon fuels is likely to be most resilient, as these sectors are harder to electrify directly.

In the EU, policy tools were developed under the EU Green Deal and the Climate Law. These policies combine infrastructure funding enabled by the NextGenerationEU instrument with carbon pricing, regulatory requirements, and funding schemes to stimulate innovation and manage social impacts. The Fit for 55 package added important revisions and new measures. Some of these were also strengthened after the release of the REPowerEU plan. Importantly, for aviation and shipping, policies also include sector-specific fuel switching mandates via in the ReFuelEU Aviation and FuelEU Maritime regulations. With the Fit for 55 package, maritime transport joins aviation in the EU Emission Trading System for carbon pricing.

Aim of This Analysis

This report evaluates the global impact of US and EU policy frameworks on future uptake of sustainable fuels in the aviation and maritime sectors and suggests avenues for policy improvements.

To do so, we analyze current policy measures meant to stimulate the use of lower-carbon alternative aviation and maritime fuels. Factors taken into consideration include life-cycle emissions and cost assessment available in relevant literature. These are overlayed with a quantitative characterization of key policy tools.

Key Findings

United States

The BIL and IRA provide unprecedented monetary incentives via tax credits and other mechanisms. In most cases, they provide a specified amount of credit for every unit of energy or material produced. Often, they are conditioned on the recipient meeting GHG reduction thresholds or indexed to the level of GHG reduction provided. These policies have been stimulated a major investment shift towards clean energy in the US, garnering private funding to complement public spending.

Despite these remarkable results, the BIL and IRA only partially close the cost gap between petroleum-based fuels and lower-carbon alternatives for aviation and shipping. Federal US policies are also limited in time. Biofuel credits under the IRA do not extend beyond 2027, even if similar volumetric biofuel blending credits in the past were routinely extended. Hydrogen credits remain in place for facilities placed in service before the end of 2032, and RFS requirements are quantitatively set one to three years ahead of time. This limited policy predictability does not support much needed long-term investment decisions focused on fuel pathways that have lowest emission profiles and good scalability potential. Such certainty will be necessary to deeply decarbonize transportation beyond 2030.

In the absence of complementary policies at federal level, such as carbon pricing and regulatory requirements, or a federal LCFS, the remaining cost gaps suggest that deployment of low-carbon fuels in shipping or aviation, where they are especially important for decarbonisation and energy diversification, will be limited.

The risk of cost gaps is significant for energy carriers requiring new infrastructure for transport, storage, and distribution. These include hydrogen and some of its derivatives—in particular, ammonia and methanol.

Overall, prospects of sustained domestic demand for low-carbon fuels in the US are limited under the current policy framework. This creates barriers to long-term reductions of GHG emissions and increases in energy diversification over time. This challenge is exacerbated by state-level LCFS programs that only include a very small part of total shipping and aviation fuel demand, at present. The much larger road transportation sector will likely absorb the deployment of sustainable fuels in the near-term and leverage the competitive electrification option later. Distributors of shipping and aviation fuels may be able to tap into the road credit pool at a lower cost than switching fuels, unless the LCFS is subdivided into sectorial compliance pools. There is a substantial risk that fuel providers will prioritize short-term cost savings by buying compliance credits from on-road fuels rather than investing in options that have longer-term scale up potential, but greater risk and higher capital requirements.

European Union

The EU policy framework has greater capacity to mobilize demand for both shipping and aviation fuels than the US framework. This is due to mandates combined with strong non-compliance penalties in both the RefuelEU Aviation and FuelEU Maritime regulations. This differs from subsidy-focused US BIL and IRA policies and RFS and LCFS alternative fuel policies, as these lack requirements for low-carbon fuel uptake in aviation and maritime sectors.

Although the scope currently excludes international aviation and only covers half of extra EU maritime voyages, both shipping and aviation are included in the Emission Trading System (ETS). This system provides a clear price signal to support investments in energy efficiency and reinforces the cost competitiveness of low-carbon fuels. The possibility of raising funds for governments through the ETS carbon price develops resources that can be reinvested in the promotion of innovation. In the EU, this takes place via the Innovation Fund and instruments like the hydrogen bank. Revenues from carbon pricing also support social protection and enhanced cohesion across the EU. In aviation, this takes place through sustainable aviation fuel (SAF) allowances. The allowances support airlines by covering part of the price gap for SAF placed on the market.

Overall, this suggests that the EU policy framework offers greater predictability than the US framework. EU rules assure the business community that investments in low-carbon fuels will be supported by demand, thus stimulating supply and leading to emission reductions.

The EU policy supports supply-side investments to scale up low-carbon fuel availability with a focus on domestic production. Supplies are mobilized by a framework that de-risks investments through careful planning for applicants that seek access to innovation funding. The European Climate, Infrastructure and Environment Executive Agency (CINEA) provides guidance while the European Investment Bank (EIB) provides financial and technical advice, in this context. This results in stronger governmental steering of investments to reduce GHGs.

Europe's barriers to scale up renewable energy, combined with a policy focus on the reduction of fossil energy dependence, may justify the careful planning and coordination for renewable energy projects. However, the additional planning and coordination required by the EU Innovation Fund can slow the pace of project development. This can result in negative consequences on domestic value generation and job creation from low-carbon technologies.

Combined Policy Effects

The disbursement of US IRA tax and LCFS credits is easier compared to EU Innovation Fund and Hydrogen Bank mechanisms. Because of this, US policies can support sizable investments to produce lower-carbon alternative fuels at-scale. On the other hand, the weaker US policy framework for generating low-carbon fuel demand in shipping and aviation may limit the adoption of these fuels domestically.

Some of the fuels supported by US policy (e.g., ammonia and synthetic fuels) may be readily exported to the EU at competitive costs. Nevertheless, EU regulations restrict the cases where this option is viable. This stems from differences in sustainability criteria used in the EU and elsewhere and in the regulatory treatment or life-cycle carbon accounting between different jurisdictions. Further restrictions arise the exclusion, in the EU, of fuels produced from installations that received support in the form of operating or investment aid, such as that provided by the US IRA, from those that can qualify to meet the RefuelEU Aviation and FuelEU Maritime (as well as other Renewable Energy Directive) mandates.

These restrictions are meant to level the playing field for investments made in the EU and elsewhere for supplies destined to the EU. They underscore a desire from policymakers to reduce risks of supply disruptions and price increases that may emanate from changes in policy decisions that take place beyond the EU borders. However, these rules may also slow the pace of investment and low-carbon fuel supply, overall.

Taken together, these considerations highlight the importance for the EU and the US to strengthen their dialogue regarding low-carbon fuels for aviation and shipping. To achieve climate goals, it is essential to balance domestic and diversified supplies, ensure consistent developments on the demand side, and enable both regions to have access to lower cost low-carbon maritime and aviation fuel options, at scale.

Key Policy Decisions

The US and EU have a shared interest in ensuring that policies lead to increased availability of clean energy carriers for aviation and shipping at lower costs. These goals demand a combination of regulations, incentives, and penalties in the near and longer term, alongside compelling emissions reduction and sustainability requirements. On some issues, such as the ones discussed above, policymakers can find guidance from the emerging consensus in the scientific and public policy literature. Where no such consensus exists, policymakers may have flexibility to adopt approaches based on local considerations.

Several key decision-making points are:

- **Whether to prioritize diversity in the fuel portfolio or focus on a single fuel.** No single fuel or fuel production system has emerged as the clear favorite for marine or aviation applications. Policies could support numerous low-carbon primary energy sources for shipping and aviation fuels or encourage the market to consolidate around a limited number of fuel options. Each option has pros and cons. A diverse fuel pool can help maximize competitive cost-reduction and local high-efficiency production options while also supporting energy diversification. Focusing on a smaller number of fuels maximizes the interoperability of the fueling systems and reduces the need for multiple sets of infrastructure and powertrain technology. Some fuels, especially those that need to be stored and transported at cryogenic temperatures (e.g., liquid hydrogen) have particularly high infrastructure costs. They require high utilization to approach cost-effectiveness. Committing to such infrastructure entails stranded asset risks if the chosen fuel does not persist in the market. In each circumstance, a strong focus on robust GHG and environmental assessment is required to ensure that all options support decarbonization.
- **Whether to maximize near-term GHG benefits or optimize the long-term trajectory towards carbon neutrality.** Some fuels, such as currently available biofuels, yield modest reductions in GHG emissions when substituted for petroleum fuels. However, they may lack a feasible pathway to attain zero or near-zero GHG emissions over their full life cycle, limiting their value towards long-run carbon neutrality goals. While electricity is an exception, most fuels that have a clear pathway to zero or near-zero emissions are years away from commercial-scale deployment. Investments in these fuels may help meet long-term goals efficiently but offer little GHG benefit until production can occur at scale. Policy makers have the flexibility to choose whether to prioritize partial near-term emissions benefits or the most efficient trajectory towards lower and even net-zero emissions. In some cases, win-win approaches that support both may be feasible. However, when they are not, policymakers will have to resolve this tension. It is important that accurate GHG assessments underpin decisions, and that these trade-offs are made in a transparent fashion. In pursuing either option, policymakers must consider the risk to investors of stranded assets from misleading or incomplete guidance and maintaining investor confidence with stable policy signals.
- **Balance regulatory requirements, pricing mechanisms, incentives, and other policy measures.** Multiple policy structures can support the decarbonization of the transport sector, including aviation and marine fuels. Combining several measures into a portfolio approach can balance the need for rapid decarbonization and the risk

of economic harm or regressive effects from increased costs. Regulation maximizes the predictability of outcomes. Associated costs are typically passed through to consumers, following the “polluter pays” principle. Incentives can result in lower costs to the consumer, rather than larger margins for producers, if they are implemented through competitive mechanisms. Incentives may also have a greater near-term economic and employment benefit than carbon pricing. Incentives can mitigate start-up costs for new technologies, but they need to be fiscally sustainable. If financed by carbon pricing, incentives can help secure economic sustainability while also providing important price signals to stimulate both energy efficiency and diversification investments.

Policy Recommendations

The following recommendations account for the key decision-making considerations identified above and build on the specific insights arising from the key findings outlined earlier:

1. **Better integrate carbon pricing in the US policy framework.** Current US policies include carbon prices in a few states, but not at the federal level. Current policy actions—especially subsides and public funding for infrastructure—have partially closed the cost gap between petroleum and alternative fuels. A carbon price could help fully close the gap, while raising revenues to fund innovation and incentives. It would be helpful in sectors with fuels subject to lower taxes than road transportation. It could also help close the cost gap with unabated fossil options in the longer term, creating favorable conditions for low-carbon fuels. If significant imports of marine or shipping fuels are anticipated, their emissions should be subject to the carbon price.
2. **Support market stability by adopting long-term policies for US low-carbon aviation and shipping fuels.** Alternative fuel production requires a decade or more of policy predictability for investments to recoup their capital expenditure. Setting concrete policy actions at least a decade out will significantly improve the case for investment in this sector.
3. **Adopt sector-specific regulatory requirements to generate demand for lower-carbon fuels in the US.** Sector-specific binding requirements, such as volumetric blending or GHG reduction mandates, paired with compelling non-compliance penalties, can mitigate the risk of seeking compliance strategies in other sectors of the economy.
4. **Integrate hydrogen and its derivatives in sector-specific regulations in the US**. Current policies do not include regulatory requirements for hydrogen and its derivatives (i.e., ammonia, methanol, and other synthetic fuels). Due to the relevance of specific pathways of low-carbon hydrogen and its derivatives in delivering deep emission cuts, policies should feature specific requirements for these types of fuels, similar to what is already integrated in the RefuelEU Aviation regulation.
5. **Introduce minimum thresholds for non-compliance penalties for sustainable aviation fuels in the EU.** The current approach in RefuelEU Aviation sets minimum non-compliance penalties at twice the price gap between SAF and the fossil fuel benchmark without minimum thresholds. The prices of SAF and fossil jet fuel are set by producers and are influenced by a variety of market conditions. In some circumstances, the price gap may be small enough that companies would prefer to pay for noncompliance rather than investing in SAF production capacity. This risk is especially significant in the near term, where low-cost hydrotreated lipids (e.g., based on waste oils and fats) may

make up a significant fraction of the SAF pool, leading to a small price gap between SAF and fossil jet fuel. Effective non-compliance penalties for SAF are crucial for supporting supplies of alternative sustainably produced fuel technologies. Sustainable alternatives are likely to be more expensive than initial least-cost technologies, but they offer a better and more scalable pathway to deep decarbonization.

6. **Improve regulatory requirements for hydrogen-based fuels in shipping in the EU, reducing uncertainties on specific requirements**. The current approach of the FuelEU Maritime regulation includes mandates for the use of hydrogen and its derivatives but only in a way that is conditional to the lack of supply. This conditionality discourages investments in this space. While there is uncertainty about which hydrogen derivative will ultimately emerge in the commercial market, it is quite certain that at least one such derivative will be required to meet decarbonization targets.
7. **Expand access to EU Innovation funds for hydrogen-based aviation and shipping fuels.** Low-carbon hydrogen supplies for aviation and shipping fuels can be prioritized, given the expectation of durable long-term demand. Going forward, disbursements could also benefit from a transition away from the current project-based approach to a leaner market-based approach. SAF allowances would also benefit from mechanisms enabling longer term certainty, rather than yearly allocations, and lower exposure to risks.
8. **Provide measures to support long-term investments.** Developing low carbon fuel production capacity often requires long-term offtake agreements, but these can be challenging to secure given technology, market, and policy uncertainty. Policies to support such long-term agreements, such as contracts-for-difference (CfDs) or contracts-for-carbon-difference (CCfDs) can help facilitate necessary long-term agreements. Book-and-claim accounting, provided it is based on rigorous GHG assessment and verification, can provide flexibility for new producers to develop necessary supply chains while also making fuel suppliers available from a wider pool of offtakers. Supporting the establishment of markets or exchanges for policy instruments, like carbon credits, or for trading of alternative fuels themselves, can also help support a smooth and efficient transition away from fossil fuels.
9. **Set and maintain strict sustainability requirements to avoid misleading policy and market signals.** Setting and enforcing strict sustainability standards will best support long-term goals by reducing the risk that policies will need to be revised or rolled back. While the desire to move fast is understandable, the principle of “first, do no harm” is applicable, here. To support this, GHG and other environmental assessments of fuels must be robust, empirically focused, and include indirect effects, especially indirect land use change (ILUC). GHG and environmental assessments must be updated to reflect the latest science.
10. **Support global alignment and mutual recognition of life-cycle GHG emission accounting and criteria used for defining sustainability for aviation and shipping fuels.** International cooperation can help set standards, find areas of scientific or policy consensus, and reduce the costs and complexity to decarbonize complex international supply chains. This is especially valuable for the certification of biofuels, hydrogen and its derivatives. Given their international nature, mutual support is especially relevant for aviation and shipping services. Due to challenges in the pace of intergovernmental decisions, the support of a global alignment should not exclude EU- and US-specific progress.

11. **Further explore power and biomass to liquid (PBtL) production systems and their integration in low-carbon fuel policies.** Biofuels have typically been considered a separate technological and regulatory issue from fuels made using renewable electricity. However, there may be opportunities to use renewable electricity and electrolytic hydrogen to maximize the yield of biofuel production systems or reduce emissions associated with the production of hydrogen from conventional means. Processes based on the recovery of concentrated streams of CO_2 and their conversion into fuels as renewable fuels of non-biological origin (RFNBOs) are also relevant, here. Due to the complexity of production pathways and related certification of PBtLs, the integration of dedicated clearinghouses or equivalent mechanisms, such as those already established in the EU and the United Kingdom (UK), can enable progress toward PBtL becoming part of the aviation and shipping fuel mix.

1. Context

Transportation, energy, technology, and innovation policy frameworks are rapidly evolving in recent years as governments mobilize to respond to climate and energy security challenges. This action follows clear and repeated warnings regarding the impacts of climate change (IPCC, 2022), the loss of biodiversity (IPBES, 2019), and rising geopolitical tensions.

Major initiatives have been developed in recent years by governments, in particular in the European Union (EU) and the United States (US), to respond to these challenges (Bordoff and O'Sullivan, 2022). These initiatives aim to shape the adoption of crucial clean energy technologies. Ongoing changes include a proliferation of batteries and variable renewable electricity sources like solar and wind, unprecedented rates of deployment, reductions in unit costs—especially in China, and increased economic competitiveness of these technologies with fossil fuels. These changes have major implications for the development of future industrial systems (IEA, 2023a).

This report reviews major technology-oriented policy tools that have been recently developed in the US and the EU and their relationship with low-carbon fuels in aviation and shipping.

- Section 2 outlines policy characteristics and then dives deeper into instruments relevant to aviation and shipping.
- Section 3 analyses policy impacts. We review the environmental performance and costs of different technologies, focusing on options with significant GHG emission abatement potential and/or a wide rate of adoption at present. Fuel production and infrastructure needs for transportation, storage, and distribution are included, along with a quantitative assessment of the policy impacts on costs.
- Section 4 builds on the analysis to combine costs and policy impacts. We evaluate how existing and proposed policy structures could affect the rate of deployment for these technologies. We model the 2030 time-horizon and consider longer-term implications.
- Section 5 offers policy recommendations based on our analysis of policy impacts. We suggest policy adjustments to align transatlantic measures and make them more effective.

2. Description of Key Policy Instruments

2.1 General Policy Frameworks

2.1.1 United States

In the US, key policies recently enacted include the Infrastructure Investment and Jobs Act, most commonly known as the Bipartisan Infrastructure Law (BIL) of 2021 (US Congress, 2021) and the Inflation Reduction Act of 2022 (US Congress, 2022).

The BIL is a massive "once-in-a-generation" investment in infrastructure, competitiveness, and communities. It aims to ensure a durable and equitable economic recovery post Covid and following other emergency response policies, in particular the American Rescue Plan of 2020 (The White House, 2022). It provides billions of dollars to modernize the electricity grid, build a nationwide network of electric vehicle chargers, strengthen battery supply chains, expand public transit and passenger rail, invest in new clean energy and emissions reduction technologies, improve resilience in physical and natural systems, and clean up legacy pollution in communities while creating new, high-quality jobs (The White House, 2023a).

The Inflation Reduction Act (IRA) confirms EPA's authority to regulate GHG emissions under the Clean Air Act (Dotson and Maghamfar, 2022) and focuses on monetary incentives. It provides an extension of existing tax credits for alternative fuels and a comprehensive benefits package that supports technology development and infrastructure building. Framed as a 10-year plan, it was further defined by a series of implementation actions by the Internal Revenue Service, many of which are still pending (IRS, 2022). The IRA changed a wide range of tax laws to stimulate investment in low-carbon energy technology production and manufacturing, strengthen supply chains for critical minerals and efficient energy-use appliances, and create well-paying jobs and new economic opportunities for workers at a time of major technological transitions (The White House, 2023a).

The IRA also provides billions of dollars in grant and loan programs and other investments for clean energy and climate action. It also includes tax provisions offering bonus credits to projects that are located in low-income communities or energy communities, pay prevailing wages and use registered apprentices, or meet domestic content requirements (The White House, 2022).

The IRA and the BIL complement transportation- and biofuel-specific regulatory requirements that were already in place well before 2021 both at the federal level and in some states. These include Renewable Fuel Standard (RFS) and the Low Carbon Fuel Standard (LCFS).

The RFS is a key federal policy that supports the development, production, and use of low-carbon, domestically produced renewable biofuels destined to the transportation sector (EPA, 2023a).[1] It is currently the only regulatory requirement in place at the federal level to establish requirements on applicable volumes and percentages of renewable fuels. It is

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[1] The RFS issues Renewable Identification Numbers (RINs). One RIN is equivalent to one ethanol-equivalent gallon of renewable fuel (EPA, 2007). RINs are necessary to certify compliance for obligated parties. RINs have a two-year life span and only 20% of the year credits can be transferred to the next year (EPA, 2007).

focused on biofuels, including cellulosic biofuels,[2] biomass-based diesel,[3] other advanced biofuels and conventional renewable fuels.[4,5] These fuels generally include ethanol, biodiesel, renewable diesel and biogas.[6] They qualify for different subcategories, based on their GHG emission profile with a life-cycle perspective considering land use change.

A summary of the mandatory requirements regarding the sales of fuels covered by the RFS, expressed in percentage of gasoline and diesel demand and referring to the time period from 2010 to 2025, are reported in Table 1.[7] Failing to meet these requirements leads to civil penalties, resulting in strong incentives to meet the regulatory requirements.[8]

Table 1. Renewable fuel requirements under RFS

Year	Renewable fuel standard (%)	Including:		
		Cellulosic biofuel standard (%)	Biomass-based diesel standard (%)	Advanced biofuel standard (%)
2010	8.25	0.004	1.1	0.61
2015	9.52	0.069	1.49	1.62
2020	10.82	0.32	2.3	2.93
2025	13.13	0.81	3.15	4.31

Note: Percentages are reported only every five years for simplicity, but the RFS has annual requirements. Shares calculated with respect to gasoline and diesel demand. They are expressed in volume terms, integrating a correction based on energy content differences between ethanol and biomass-based diesel. Source: EPA, 2023a.

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[2] Cellulosic biofuel is required to have life-cycle emissions at least 60% less than the baseline fuels (EPA, 2007).

[3] This includes fuels produced from animal fat and vegetable oils as a replacement for diesel fuel. It includes biodiesel and renewable diesel. To receive credit, fuels are required to have life-cycle GHG emissions at least 50% less than the baseline fuels, as are fuels in the "advanced" category (EPA, 2023a). Biodiesel is a fuel (commonly called an ester, or fatty acid methyl esters [FAME]) produced from renewable fats, oils, and/or greases and that meets a dedicated technical ASTM standard, D6751 (McCormick & Moriarty, 2023). Renewable diesel is a hydrocarbon produced most often by hydrotreating and also via gasification, pyrolysis, and other biochemical and thermochemical technologies (US DOE, n.d.). Unlike biodiesel, renewable diesel meets specifications that are aligned with those of petroleum diesel (ASTM D975).

[4] This is the portion of the total renewable fuel volume requirement that is not required to be advanced biofuel (EPA, 2023a). It shall achieve a minimum 20% reduction in GHGs in comparison to the gasoline or diesel which it displaces, except for cases where it is produced in a facility or facility expansion that commenced construction before the end of 2007 (EPA, 2023a). In practice, most of this category consists of ethanol made from corn.

[5] Hydrogen is also covered in the 2023 action setting standards until 2025, but only as a derivative of biogas (EPA, 2023a). The 2023–2025 proposed rule included a comprehensive program governing the generation of RINs from renewable electricity produced from biogas that is used in electric vehicles, but this was not integrated in the final version of the rule (EPA, 2023a).

[6] Renewable natural gas—an upgraded form of biogas, essentially indistinguishable from fossil-based natural gas that can be distributed via the natural gas commercial pipeline system—is also covered by the RFS (EPA, 2023a).

[7] The RFS integrates flexibility mechanisms for small entities, which can comply by trading renewable fuel certificates (RINs) rather than by actual renewable fuel blending (EPA, 2023a). Up to 20% of the mandatory blending for an obligated party can also be met using previous-year certificates. The ability to carry over a deficit in a given year is also possible, as long as this is not limited to one year (EPA, 2023a).

[8] These were up to USD 37,500 in 2015 per day for each violation, plus the economic benefit of not complying with the standards (Congressional Research Service, 2015, Code of Federal Regulations, 2023).

The Low Carbon Fuel Standard (LCFS), a state law first implemented in California, is intended to reduce the life-cycle carbon intensity (CI) of transportation fuels. Fuel producers generate credits or deficits depending on whether their reported CI is below or above a mandatory threshold.[9] The target CIs for the overall fuel consumed gradually decrease every year, up to a 20% reduction by 2030 relative to the baseline year of 2010 (CARB, 2020), with a proposed increase to a 30% reduction (CARB, 2024a). The CI level in California effectively decreased by 12.6% between 2010 and 2022 (CARB, 2024b).[10] Similar to California, Oregon and Washington State have adopted LCFS-like policies in an effort to expedite the use of low-carbon fuels (CARB, 2023). These are the Clean Fuels Program in Oregon and Clean Fuel Standard in Washington State.

The redistribution of revenues occurs via a market mechanism, enabling producers of fuels that generate credits to sell them to producers of fuels that are subject to deficits. Prices are set by the market mechanisms in all the LCFS-like policies. They are currently ranging between USD 50 and 120/t CO_2, depending on the state (CARB, 2024b, Oregon DEQ, 2024 and Washington State Department of Ecology, 2024). Non-compliance penalties applicable in the LCFS framework essentially consist of obligations to purchase credits at the ceiling price of USD 200/t CO_2, inflation adjusted, in all states.[11]

2.1.2 European Union

In the EU, major policy initiatives include the Green Deal Communication of 2019, the Climate Law of 2021, the NextGenerationEU instrument, the Fit for 55 package, proposed in 2021, the RePowerEU plan of 2022, and the Green Deal Industrial Plan of 2023.

The Green Deal defines a growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient, and competitive economy, where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use (European Commission, 2019). The same communication refers to the importance of an inclusive and just transition allowing the EU to protect, conserve and enhance its natural capital, as well as the health and well-being of citizens from environment-related risks and impacts.

The Climate Law, established in 2021 following the strategic lead already included in the European Green Deal communication, requires the EU to achieve carbon neutrality by 2050 and to reduce GHG emissions by 55% by 2030 (compared to 1990 levels) (European Union, 2021a). This is binding legislation and hard to reverse, as it enacts the EU commitment to comply with the Paris Agreement and enshrines this obligation into law.[12]

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[9] Credits from LCFS can be combined with federal credits, RINs and IRS tax credits, making it more attractive to sell alternative fuels in California (Pavlenko, 2022).

[10] The LCFS also has a credit banking system and a credit clearance market (CCM) to balance credits and deficits (Stillwater Associates,, 2018).

[11] The baseline for inflation adjustments is 2016 in California (CARB, n.d.a), 2018 in Oregon (Oregon DEQ, 2022 and Washington State Legislature, n.d.) and In the very unlikely case of major dysfunctional developments in the markets (or in case of fraud), penalties could technically reach USD 1,000/t CO_2 (California Code of Regulations, 2024).

[12] Its revision would need a new legislative proposal by the Commission, followed by negotiations/agreement to be reached in the Council and a majority vote in the Parliament. The revision would also imply that the EU revokes its commitment to comply with the Paris Agreement.

NextGenerationEU is a major temporary economic recovery instrument. It has been funded for the first time by joint borrowing, with more than EUR 800 billion, which enables some Member States to access credit at lower rates.[13] The purpose is to help repair the immediate economic and social damage brought about by the coronavirus pandemic while ensuring alignment with policy objectives outlined in the European Green Deal and coherence with the Climate Law. It tops up the EUR 1.211 trillion EU budget for the years 2021 to 2027 (European Commission, 2021c). A substantial 30% of its budget is dedicated to fighting climate change (European Commission, n.d.a). This is also the case for more than 37% of the Recovery and Resilience Facility (RRF), the centerpiece of NextGenerationEU, which makes available EUR 723 billion in loans and grants. This aligns with commitments initially outlined in the Green Deal for the InvestEU fund by directing major shares on investments towards climate action and with the "do no significant harm" principle. This principle applies across the EU Sustainable Finance framework to avoid a misalignment between investments and key policy objectives (ESMA, 2023).[14] The NextGenerationEU includes, across Member States, expenditures dedicated to the deployment of infrastructure needed for the delivery of low-carbon energy to transport vehicles.[15]

The Fit for 55 package aims for a reduction of GHG emissions by at least 55% by 2030 compared with 1990. Its implementing policies convert many of the measures foreseen in the European Green Deal into concrete pieces of legislation. This includes a revision of the EU Emission Trading Scheme and several regulatory requirements on energy efficiency and renewable energy. The Fit for 55 package was proposed by the European Commission in July 2021 (European Commission, 2021a) and it is, in 2024, largely finalized.[16] The policies included in the package cover all sectors of the economy and encompass a wide range of tools. Regulatory requirements and economic/financial policies will kick start and scale up the process. Their implementation will prompt deep transformations across many aspects of European society, industry, and the economy. Many of the policy proposals included in the Fit for 55 package are intended to accelerate changes in vehicle powertrain technologies and the energy vectors that they use. Overall, these and other complementary policies address emissions from a life-cycle perspective, even though specific measures target specific and regulated entities. These policies are intended to provide regulatory certainty in line with the middle-term climate ambition and to encourage the development of strategic alliances to deploy the value chain across Europe and beyond. Importantly, the Fit for 55 package takes a

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[13] Before NextGenerationEU, the European Commission already issued bonds, for instance to finance loans to EU Member States and third countries, including up to EUR 100 billion for the SURE programme to support jobs and keep people in work during the COVID-19 pandemic (European Commission, n.d.a).

[14] Based on the Sustainable Finance Disclosure Regulation, the principle refers to investments in economic activities that do not significantly harm environmental and social objectives and follow good governance practices (European Union, 2019 and ESMA, 2023). The EU taxonomy for sustainable activities details further criteria for economic activities that are aligned with a net zero trajectory by 2050 and the broader environmental goals other than climate (European Commission, n.d.b).

[15] In parallel, the Commission intends to raise up to 30% of the NextGenerationEU funds through the issuance of green and social bonds and use the proceeds to finance green policies. The first green bond issuance took place in October 2021 (European Commission, 2021b). Remaining share are raised using multiple instruments, including EU-Bonds, with maturities ranging between 2 and 30 years, and EU-Bills, which have shorter maturity, below one year (European Commission, n.d.c).

[16] The main exception being the revision of the Energy Taxation Directive (ETD), due to the lack of the required unanimity in the European Council.

multi-faceted approach by applying a variety of tools to incentivize measures aimed at decarbonization.

Key policy instruments contained in the Fit for 55 package include:

- a reform of the EU Emission Trading Scheme,
- the introduction of a Carbon Border Adjustment Mechanism,
- the application of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) for flights departing the European Economic Area,
- the possible extension of the EU ETS—which applies to intra-EEA flights17,
- the integration of maritime transport in the EU ETS including 50% of emissions from extra-EU voyages,
- the introduction of a separate EU ETS for road transport and buildings paired with a Social Climate Fund,
- an update to the 2003 Energy Taxation Directive (not finalized),
- the recast of the EU's Renewable Energy Directive (RED) integrating specific regulations for aviation (RefuelEU Aviation) and shipping (FuelEU Maritime),
- the introduction of a regulation on tailpipe CO2 emissions for cars and vans and the announcement of a similar one, to be finalized later, on trucks,
- the introduction of a regulation on alternative fuel infrastructure, updating an earlier Directive (issued in 2014), and
- the recast of the energy efficiency directive.

REPowerEU has the stated aim to reduce the EU's dependence on Russian fossil fuels while continuing to tackle the climate crisis (European Commission, 2022a). Actions meant to increase the resilience of the EU-wide energy system include enhanced energy savings, an accelerated roll-out of renewable energy, and the diversification of gas supplies. These actions will complement near-term changes in behavior. This initiative is related to the war waged by Russia in Ukraine in addition to the Green Deal and the Climate Law. This is reflected by security-related considerations that dovetail with the focus on climate action. Ultimately, the REPowerEU Plan was implemented through amendments to the initial policy proposals of the Fit for 55 package due to the importance of energy efficiency and energy diversification already contained in these same proposals.[18]

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[17] Should the ICAO Assembly fail to strengthen CORSIA by the end of 2025, in line with the ICAO's long-term global aspirational goal towards meeting the objectives of the Paris Agreement, or should the states applying carbon pricing to aviation represent less than 70% of international aviation emissions, the EU ETS should be extended to apply to emissions from departing flights from the EEA, starting in 2027 (European Union, 2023a). This will effectively work in a way that is very similar to the carbon border adjustment mechanism (CBAM) by applying a carbon price beyond Europe, in the absence of international progress.

[18] Importantly, one of the changes is an increase from the originally proposed 40% to 42.5% and aiming for 45% of the share of renewables in the final energy consumption of the EU, included in the recast of the Renewable Energy Directive (European Union, 2023b). The same text increases revised upwards the 2030 objective to a 14.5% reduction in life-cycle GHG emissions intensity or a share of renewable energy within the final consumption of energy in the transport sector of at least 29%. The revision of the Renewable Energy Directive also includes a requirement that 42% of the hydrogen used for final energy and non-energy purposes in industry by 2030, and 60% by 2035, is a renewable fuel of non-biological origin. This excludes transport fuels and biofuels, which are covered by sector-specific requirements and minimum life-cycle GHG emission abatement thresholds, indirectly inducing increases in low-carbon hydrogen.

The Green Deal Industrial Plan (European Commission, 2023a) complements other implementing tools outlined in the European Green Deal communication. The Industrial Plan aims to scale up EU manufacturing capacity for net-zero technologies including materials supply chains. Key pieces of legislation developed in the context of this plan include:

- The Net-Zero Industry Act (European Commission, 2023b) which identifies goals for net-zero industrial capacity and provides a regulatory framework suited for quick deployment.
- The Critical Raw Materials Act to ensure sufficient access to materials, like rare earth minerals, that are vital for manufacturing the technologies to underpin the low-carbon economy (European Commission, 2023c).
- The reform of the electricity market design (European Commission, 2023d).
- Revised Guidelines on State aid for climate, environmental protection, and energy (CEEAG).[19]
- A revision to the General Block Exemption Regulation (GBER), which enables Member States to directly implement aid measures without having to notify the Commission for approval.

2.1.3 Other supportive policy and business structures

In addition to policies like incentives, regulatory requirements, or carbon pricing, several supportive structures may help facilitate the transition to lower-GHG technologies, including those in the aviation and marine shipping sectors. Some of these structures have emerged from the business community and others from public policy. All can be applied to problems relating to alternative fuels. They include power purchase agreements (PPAs) and book-and-claim accounting, which have been used in the utility industry for many years, and Advance Market Commitments (AMC), which have been applied to challenges like vaccine development for emerging diseases. They also include CfDs, which are increasingly used in the EU to support the early scale up of supplies of low-carbon electrolytic hydrogen and its derivatives that would otherwise struggle to see market demand materializing.

While some of these instruments are part of the toolkit independently deployed by project developers and financiers in a variety of sectors, policymakers must determine whether and to what degree such instruments will be welcomed by a policy. California’s LCFS, for example, allows book-and-claim accounting to facilitate delivery of low-carbon energy that is used as an input to a fuel production system in some, but not all, cases.

This section will briefly discuss some of these structures, particularly those that have been applied to alternative fuel or related challenges. An exhaustive discussion of all potentially helpful policy and business structures is beyond the scope of this report, as is a quantitative analysis of all possible impacts they could have on the economics of lower-carbon aviation and marine fuels.

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[19] These widen the categories of investments that single Member States can support to cover new areas (clean mobility, resource efficiency, biodiversity) and the technologies that are aligned with the Green Deal. Based on this revision, aid can be granted for up to 100% of the funding gap where aid awards are based on competitive bidding (with targeted exceptions, e.g., due to limited participants), including via Contracts for Difference (European Commission, 2022b).

2.1.3.1 Offtake agreements

Offtake agreements, or PPAs, are long-term contracts between low-carbon electricity producers and offtakers, which purchase the energy, guaranteeing a primary revenue stream to recover the capital costs and earn a return from the investment (World Bank, n.d.). Historically, PPAs are rooted in the need by energy-intensive industries (e.g., aluminum smelters) to source their electricity from low-cost, predictable sources such as hydropower and, more recently, wind (European Commission 2022c). Their main adopters also include the chemical industry and major technology companies (Commission de Régulation de l'Energie, 2022). They have already been used by hydrogen producers (Casey, 2023) and, in the EU, they are also increasingly popular with big companies, small and medium-sized enterprises, and local authorities (Engie, 2021).

Offtake agreements can be leveraged by end-users, including aviation and shipping low-carbon fuel users, to gain access to hydrogen or hydrogen derivatives at a negotiated price. The agreements also allow producers of these energy carriers to secure a long-term, low-risk, primary revenue stream from the same negotiated price. These contracts could also directly link low-carbon electricity producers with energy end-users, allowing large-scale and long-term contracts while minimizing transaction costs. Renewable energy purchase agreements are already providing industry and businesses with direct access to cheap electricity, while ensuring stable prices to project developers. This includes developers involved in the conversion of electricity into hydrogen and its derivatives. Such arrangements bypass the need to wait for financial support from governments (European Commission 2022c). Provisions to ensure that offtake agreements related to electrolytic hydrogen production are not double counted, fulfil additionality/incrementality, temporal matching, and deliverability/geographical correlation conditions have already developed in the EU. Similar measures also apply to hydrogen tax credits in the US.[20]

2.1.3.2 Contracts for difference

Contracts for difference (CfDs) are typically multi-annual (e.g., 15-year) contracts stipulated between a low-carbon electricity producer and a governmental entity where both parties agree on the remuneration of electricity generation at a given and fixed "strike price," irrespective of the variability of the electricity price on the market. They are therefore capable of reducing risk by providing certainty on the price for the producer, which can then more effectively plan its investments. CfDs also allow governments to minimize costs to support low-carbon electricity generation, effectively remunerating them in cases where the market price of the electricity exceeds the strike price. In this respect, they are more sophisticated and effective than options such as capital grants and subsidies (Pavlenko et al.,

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[20] In the EU, the delegated regulation setting out detailed rules for the production of RFNBOs as transportation fuels already foresees the use of PPAs and frames it under the additionality/incrementality, temporal matching and deliverability/geographical correlation conditions required for hydrogen and RFNBOs to be aligned with broader climate and energy policy objectives (European Union, 2023h). The same regulation clarifies that guarantees of origins (GOOs) certifying that electricity is from renewable sources can be used to demonstrate compliance only if the three conditions are fulfilled. The Renewable Energy Directive already ensures that guarantees of origin for the renewable electricity needed for the RFNBO production are not double claimed (European Union, 2023h). Similar provisions, aiming to avoid double counting and to avoid indirect negative impacts from hydrogen production from electrolysis are also already taken into consideration in the US, where the use of energy attribute certificates (EACs—the US equivalent of European GOOs) is also to be considered conditional to the respect of the additionality/incrementality, temporal matching and deliverability/geographical correlation conditions for the access to IRA hydrogen tax credits (US DOE, 2023d).

2017). They are also complementary to other instruments, such as AMCs, already used to fund vaccines and carbon capture (CGD, n.d.).[21]

The instrument used by governments to cover the cost of CfDs is typically a levy applicable to the overall electricity supply, which could well take the form of a carbon price. To date, CfDs have been effectively used to support the deployment of large-scale, low-cost and low-carbon electricity generation capacity, in particular in the United Kingdom (Watson & Bolton, 2023). They have also gained a lot of interest recently in the EU, given the huge variations in the marginal cost of electricity generation from natural gas.

Carbon Contract for Difference (CCfD) apply when electricity generation from fossil fuels is subject to carbon pricing. In this case, the price differential is between a strike price and the fossil fuel price plus the carbon price. This integrates carbon pricing and any variability in the impact of carbon prices into the calculation used to determine CfD payouts. Differences in amounts of energy subject to carbon pricing and low-carbon fuels entering the market can ensure that the overall system is financially self-sustaining. This mechanism is similar to the LCFS in California, where relatively small charges applied to a large body of fuel can be aggregated to provide high per-unit incentives for a comparatively smaller volume of low carbon fuels.

In aviation and shipping, there are expectations that low-carbon fuel prices will remain higher than the fossil fuel benchmark for some time. In this case, the need to shift energy sources can be effectively addressed by the use of CfDs or CCfDs, depending on whether or not a carbon price is applied.[22] For example, targeting them on forms of energy that deliver high life-cycle GHG emission benefits or complementing or eventually substituting purchase agreements.

CCfDs can be paired with clear, transparent, and ambitious qualifying requirements such as additionality/incrementality, temporal matching and deliverability/geographical correlation. Due to the above characteristics and their competitive nature—they are awarded through auctions—CCfDs are well suited to distribute EU carbon pricing revenues.

In the US, CfDs with clear sustainability requirements could complement or eventually replace IRA credits meant to stimulate investments in low-carbon fuel production capacity and reduce the risk that policy-related incentives do not translate into cost reductions for energy end-users. CfDs could also help bridge the issue of the limited regulatory requirements (in terms of volumes to be supplied or shares of total demand) for low-carbon shipping and aviation fuels, because they could be paired with auctions clearly attached to specific volumes of supplies. This could offer better predictability for budgetary requirements attached to the policy, in comparison with the IRA. This is because the regulator determines the volume of fuel for which to provide CfDs. Securing larger demand through regulatory action in the US could add solidity to the current policy framework, as it

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[21] AMCs are likely better suited for earlier phases of technological development and deployment and for cases where the differences in cost structures are not as relevant as in the case of low-carbon fuels. In particular, the operational costs of renewable energy are very low, while they are high for fossil energy. Contrary to CfDs, AMCs enable governmental remuneration if the marginal cost of producing the fuel from one of the pathways increases. This allows revenues to be redistributed to the most-affected stakeholders.

[22] For CfDs, a complementary mechanism enabling budget increases, as needed to cover the price differential, is also necessary. CCfDs can leverage carbon pricing revenues, for this purpose.

could be paired with a broad spectrum of supply options. This could increase the overall resilience of the system.

In shipping and aviation, key economic industries that could mobilize investments through offtake agreements, given their interest in abundant low-cost and low-carbon fuel supplies, include aircraft and ship operators, i.e., airlines and shippers or charterers. Actors that could benefit from CfD or CCfDs, as receivers of public funds to help them mobilize investments, include clean aviation and shipping fuel suppliers. The effectiveness of offtake agreements and CfDs could be maximized if they are paired with measures that enable greater flexibility on the way the fuels are delivered to the market, especially in the early phase of deployment. For example, book and claim mechanisms can assist sellers and buyers in coordinating decarbonized value chains (Box 1).

To avoid the risk of unfairly excluding cost-effective suppliers at the advantage of subsidized competitors, it is also important that CfDs and CCfDs are developed in a way that excludes—or at least integrates—corrections due to differences across policy frameworks internationally, e.g., for production incentives or other forms of industrial support. Internationally aligned mechanisms regarding life-cycle GHG emission accounting and additionality/incrementality, temporal matching, and geographical correlation/deliverability are also important to ensure that CfD and CCfDs are coherently applied across borders.

Box 1. Book and Claim

Book and claim mechanisms are accounting practices that that can help decouple sustainability claims from the physical flow of goods by connecting suppliers and buyers by a contract—regardless of whether the energy or energy carrier involved is physically delivered to the specific buyer—still ensuring that the physical delivery has taken place on the market. They are often used in situations where a common energy carrier, such as one used for electricity or natural gas, conveys goods across a shared transmission and delivery (T&D) network.

The low-carbon attributes of energy injected into a network can be sold via contract and transferred, with a traceable paper trail, to an energy end-user. This allows a high level of environmental integrity to be guaranteed without requiring that the specific low-carbon forms of energy arrive at the location of end use. The book and claim agreement tracks the delivery of a specified amount of low-carbon energy onto a common-carrier T&D network and allows the contracted recipient to withdraw an equivalent amount of energy, less any T&D losses. The withdrawal is considered to be fully identical to what was delivered. These transactions are often described as trades of the environmental attributes of energy. For example, the low-carbon status of electricity produced by wind and solar generation is traded, even where flow conditions on the T&D system do not actually deliver the specific units of energy. In other instances, this might include the specific biogenic methane molecules in the case of biomethane, or the units of electrical charge generated by renewable electricity.

Book and claim mechanisms can also be applicable to fuels. For example, by allowing suppliers to transfer the environmental attributes of their fuel to locations without requiring physical delivery. So long as the environmental attributes being traded do not vary depending on where the fuel is consumed, this transfer yields the same global emissions impacts at lower cost than systems that require physical delivery. Most GHGs produce their warming impacts on global scales: the location where a tonne of CO2 or methane is emitted has little impact on its warming potential. Many alternative fuels produce local air quality co-benefits, however, and the distribution of these may be impacted by book and claim accounting. In the case of aviation and marine fuels, book and claim accounting may offer the potential to increase net air quality benefits, by allowing for jurisdictions to claim the GHG benefits of alternative fuels that are physically delivered to, and therefore provide air quality benefits to, locations with worse air quality challenges.

To be increase low-carbon production, the book and claim mechanism needs to ensure that payments by the buyer are used effectively. As supply scales up, the system enables the maximization of benefits because the mechanism favors investments in locations with the least-cost supply. For the same reason, the scheme may lead to uneven dynamics across geographies, with greater supply costs for areas with lower potential, and vice versa. This could lead to distortions of competition. For this reason, the EU RefuelEU Aviation regulation is open to the possibility to integrate a system of tradability of sustainable aviation fuels "incorporating elements of a book and claim scheme" up to the end of 2034 (European Union, 2023). In doing so, the regulation acknowledges both the near-term relevance to kick off supplies and longer-term risk for uneven availability.

In Europe, recommendations have been developed with the aim to favor good practices on a book and claim mechanism for the European SAF market. These include: (1) the adoption of harmonized SAF sustainability standards and certification processes, (2) the incorporation of book and claim into legal frameworks related with the "Union database,"[23] (3) the implementation of a registry of trusted partners to ensure credibility to avoid double counting and other frauds, and (4) the development of monitoring and tracking schemes (FCA, 2024). Existing book and claim certification systems such as the Roundtable on Sustainable Biomaterials (RSB, n.d.) or International Sustainability and Carbon Certification (ISCC, n.d.) can help SAF traceability rules and independent auditing measures.

2.2 Sector-Specific Policies: Aviation & Maritime

In addition to economy-wide climate and energy efficiency policies, many jurisdictions have adopted policies that affect transportation across modes as well as policies for the aviation or maritime sectors, specifically. These latter policies are paired with instruments aiming to lower cost and increase the sustainable supply of low-carbon fuels. This section will review aviation and maritime sector-specific policies, adopted in the US and the EU.

2.2.1 United States

In the US, aviation and shipping specific policies are focused on scaling production of energy low-carbon aviation and/or shipping fuels by bringing down their production costs (US GAO, 2023). This is similar to the general approach to decarbonizing the economy overall. The policies are complemented by measures aiming to enhance the energy efficiency of equipment used in aviation and shipping, such as aircraft, shipping vessels, airports, and ports.

The IRA includes grants and loans to accelerate the production and use of SAF and to reduce GHG emissions from the aviation sector (Table 2). The most relevant is the USD 245 million Fuelling Aviation's Sustainable Transition – SAF (FAST-SAF) grant program. These grants

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[23] This is meant to ensure the tracing of liquid and gaseous transport fuels that are eligible for being counted towards the share of renewable energy in the transport sector in any EU Member State.

target projects related to production, transportation, blending, and storage of SAF (The White House, 2022). This program is paired with FAST-Tech, another USD 46 million grant program focused on aviation technology.

For shipping, the EPA received USD 3 billion in funding to provide grants to port authorities and other eligible entities for the purchase and installation of zero-emission port equipment and technology. The Higher Blend Infrastructure Incentive Program allocates USD 0.5 billion to grants for storage and distribution facilities for transportation fuels. This includes maritime, road, and rail applications running on biofuels (The White House, 2022). The manufacturing of low- or zero-emission vessels is addressed by a USD 3 billion Advanced Technology Vehicle Manufacturing Loan Program.[24]

Table 2. IRA grant programs for aviation and shipping.

Program	Entity in charge	Sector	Amount (billion USD)	Section
Fuelling Aviation's Sustainable Transition – SAF (FAST-SAF)[25]	DOT, FAA	Aviation (fuels)	0.2445	40007 (a)(1)
Fuelling Aviation's Sustainable Transition – Technology (FAST-Tech)[26]	DOT[27]	Aviation (aircraft)	0.0465	40007 (a)(2)
Grants to Reduce Air Pollution at Ports	EPA	Maritime (ports)	3	60102
Advanced Technology Vehicle Manufacturing Loan Program	DOE	Road, rail, maritime (vessels)	3	50142
Biofuel Infrastructure and Agriculture Product Market Expansion (Higher Blend Infrastructure Incentive)[28]	USDA	Road, rail, maritime (biofuels)	0.5	22023
Advanced Energy Project Credit	Treasury, DOE	Cross-cutting	10	13501

Note: All monetary values are in 2023 USD. "Cross-cutting" refers to all sectors, not just transportation and, within it, aviation and shipping. Source: The White House, 2022, US DOE, 2023a

Different IRA credits are applicable to aviation and shipping. There are multiplying factors for facilities that meet prevailing wage and registered apprenticeship requirements. In aviation, the IRA introduces SAF credits (Code § 40B) (The White House, 2022, US Congress, 2022). Credits are focused on bio-based pathways and are conditional to levels of GHG emission reduction. They are only available for SAF capable of cutting GHG emissions for more than 50%,[29] and exclude those derived from feedstocks exposed to significant risks of inducing

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[24] The USD 27 billion Greenhouse Gas Reduction Fund for zero-emission technology (not included in Table 2) also covers cross-cutting projects that reduce GHG emissions and other air pollution, without a specific focus on aviation or maritime transportation (EPA, 2024; The White House, 2022).

[25] Projects of production, transportation, blending, and storage of SAF are eligible (The White House, 2023b).

[26] Low emission aviation technologies are eligible (The White House, 2023b).

[27] The FAA also supports the development of new aircraft and engine technology through the Continuous Lower Energy, Emissions, and Noise (CLEEN) program (FAA, 2023).

[28] The fund aims to encourage the sale and usage of higher ethanol and biodiesel blends (USDA, 2023).

[29] Based on the latest available indications, IRA credits are available for fuels that meet the 50% requirement based on the most recent Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) standard, or approval by the EPA under the Renewable Fuel Standard (RFS) (US Department of the Treasury,

land use changes, such as palm oil or palm-derived intermediates (IRS, 2023). SAF credits were applicable from January 2023 to the end of 2024.

The IRA extended other biofuel credits that could technically be applicable to the maritime sector until 2024. These fuels include alternative fuels, second-generation biofuels, and renewable diesel. From 2024 through 2027, the IRA Clean Fuel Tax Credits (Code § 45Z) are applicable to SAFs and other bio-based fuels (The White House, 2022, US Congress, 2022). They include options suitable for maritime transportation. For SAF, this includes up to 1.75 USD/gallon of credits (12.5 USD/GJ), provided the production facilities meet prevailing wage requirements.

A complementary (and stackable) tax credit, specifically applicable to SAF and available to airlines, rather than fuel producers (in an attempt to bridge the risk that credits remain with producers, was also introduced in the State of Illinois, in 2023 (Illinois Department of Revenue, 2023, Barkley et al., 2023 and Argus, 2023). The credit amounts to 1.5 USD/gallon (10.8 USD/GJ) and it is available from 2023 to 2032. It applies to pathways that cut emissions by at least 50% (based on the same accounting methods allowed for the IRA credits). Developed in the context of the Invest in Illinois Act, it introduces selective conditions pointing towards the development of pathways based on domestic biomass resources, with a focus on corn ethanol (including waste gases from conventional conversion plants) and alcohol to jet SAF production pathways.[30]

Hydrogen producers can also receive the Clean Hydrogen Production Credit (Code § 45V) under the IRA (The White House, 2022, US Congress, 2022). These credits range from 0.6 to 3 USD/kg for facilities that meet prevailing wage and registered apprenticeship requirements (and one fifth of that for those that do not), depending on the life-cycle GHG emission intensity of hydrogen production. CO_2 utilization, sequestration and direct air capture (DAC) are also eligible for different levels of credits (Code § 45Q) (The White House, 2022, US Congress, 2022). Hydrogen credits are applicable to all fuel options requiring hydrogen as a feedstock, including aviation and maritime fuels such as synthetic kerosene, synthetic hydrocarbons and ammonia. Credits for DAC are also applicable to the case of synthetic hydrocarbons, as they require DAC for their low-carbon production. These are not stackable with 45V credits in cases that rely on natural gas as a primary source of hydrogen (The White House, 2022, US Congress, 2022).[31]

2023a). A modified version of the GREET model also enables qualification for IRA credits, in the US. This integrates GHG reduction strategies such as carbon capture and storage, renewable natural gas, renewable electricity, and a pilot on the use of Climate Smart Agriculture (CSA) practices for SAF feedstocks (US Department of the Treasury, 2024, US DOE, 2024). It also aims to address critiques regarding the accounting of risks of indirect land use change (see O'Malley and Pavlenko, 2023 and Pavlenko, 2023).

[30] The Act requires local production from biomass resources as of 2028, allowing fossil-based gases as a feedstock prior to that date, enabling earlier investments in waste gas to ethanol/chemical conversions – similar to those developed by LanzaTech (LanzaTech. 2017) – and also suitable for alcohol to jet conversion – in line with technologies developed by LanzaJet (LanzaJet, n.d.) or Gevo (Gevo, n.d.), amongst others. The Act also limits credits available for biofuel pathways from soybean oil, it excludes palm oil residues (palm fatty acid distillates) and pathways based on co-processing of oleochemical feedstocks with others not derived from biomass.

[31] As this case requires reformation with CCS or methane pyrolysis for the hydrogen to be low carbon. Producers of hydrogen and hydrogen-based fuels need to choose between the 45V or the 45Q (CCS) if hydrogen is sourced from natural gas. It can stack 45V and 45Q credits from DAC for electrolytic hydrogen from low-carbon electricity.

The Advanced Energy Project Credit (Code § 48C) covers investments in advanced energy projects via the re-equipment, expansion, or establishment of industrial or manufacturing facilities with equipment designed to reduce GHG emissions by at least 20%, or whose purpose related with processing, refining, or recycling of critical materials (The White House, 2022). The part related with GHG emission saving in industrial/manufacturing facilities includes equipment designed to refine, electrolyze, or blend any fuel, chemical, or product which is renewable, or low-carbon and low-emission. This part is also relevant for low-carbon aviation and shipping fuels. In particular, manufacturing of equipment needed for low-carbon SAF is considered as one of the energy supply chain and manufacturing priority areas (US DOE, 2023a).

The BIL has several programs to support carbon capture and utilization (CCU), carbon capture and storage (CCS), hydrogen, and clean energy more broadly. These programs have direct or indirect relevance for aviation and shipping.

- For aviation, direct funding for clean energy and climate-related projects is limited to specific cases, such as fuel storage facilities owned by the FAA under the USD 5 billion Facilities and Equipment Program and energy maintenance (The White House, 2022). Other funding, available via the USD 0.1 billion Airport Infrastructure Program, targets more generically the improvement of safety, security, and terminals at airports.
- For ports, the Port Infrastructure Development Program Grants, totaling 2.25 billion USD, include some items of relevance for sustainability, such as port electrification and bunkering facilities for ocean-going vessels and charging infrastructure, amongst others (The White House, 2022).

Regional clean hydrogen hubs, subject to an allocation of USD 8 billion, are meant for grants, contracts or other agreements regarding projects that demonstrate production, processing, delivery, storage, and end-use of clean hydrogen – meeting requirements defined in a specific guidance standard[32] – through regional clean hydrogen hubs. Their relevance for aviation and shipping depends on the specific project and is technically possible if the hubs cover relevant hydrogen end-uses (e.g., as an energy carrier or as a feedstock for aviation and/or shipping fuel production). California's hydrogen hub, called ARCHES, has convened a workgroup to evaluate the potential applications of hydrogen in aviation, and advise the project participants on how best to support development in this space. Similar considerations apply for the Carbon Capture Demonstration Projects Program and Carbon Capture Large-Scale Pilot Programs.

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[32] Included in Section 40415 and updated based on US DOE, 2023b, establishing a target of 4.0 kg CO_2e/kg H_2 for life cycle emissions related to hydrogen production. This limit is based on a "well-to-gate" system boundary that includes upstream energy inputs, upstream transport, and hydrogen production, and excludes downstream storage and transport, service, and end-of-life emissions.

Table 3. BIL grant programs related to aviation and shipping.

Program	Lead Entity	Sector	Amount (billion USD)	Section
Airport Infrastructure Program[33]	DOT, FAA	Aviation	0.1	Division J, Title VIII
Facilities and Equipment	DOT, FAA	Aviation	5	Division J, Title VIII
Port Infrastructure Development Program[34]	DOT	Maritime	2.25	Division J, Title VIII
Regional clean hydrogen hubs[35]	DOE	Cross-cutting	8	40314
Carbon Capture Demonstration Projects Program	DOE	Cross-cutting	2.537	41004
Carbon Capture Large-Scale Pilot Programs[36]	DOE	Cross-cutting	0.937	41004

Note: All monetary values are in 2023 USD. "Cross-cutting" refers to all sectors, not just transportation and, within it, aviation and shipping. Source: The White House, 2022

Due to similarities between the production of renewable diesel and currently available forms of SAF, jet fuel has qualified as biomass-based diesel under the RFS since 2010. It must achieve at least a 50% reduction in life-cycle GHGs in comparison to petroleum-based fuels to do so (EPA, 2023a). Despite these regulations, little SAF has been produced to date: SAF makes up less than 0.1% of the jet fuel consumed by major airlines in the US (EPA, 2023a, Boyles, 2023, US GAO, 2023b) or on international routes, falling under the scope of work of the International Civil Aviation Organization (ICAO). Jet fuel is also only brought in the RFS as an opt-in solution because the required shares of renewable fuels under the RFS are calculated as a percentage of gasoline and diesel demand. (Code of Federal Regulations, 2024)

While there are no binding requirements to move towards SAF in aviation, a non-binding goal to scale up SAF by 2030 and meet 100% of aviation fuel demand with SAF by 2050 is included in the Sustainable Aviation Fuel Grand Challenge roadmap (Box 2).

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[33] The grants (USD 25 billion) for the aviation infrastructure program by DOT are prepared for the improvement of safety, security, and terminals at the airports.

[34] Projects, such as Port electrification and hydrogen refueling infrastructure will be eligible for this fund (The White House, 2023b).

[35] Seven hubs, including California, the Mid-Atlantic, the Gulf Coast, and others, were chosen on October 13, 2023 and four projects were about green hydrogen production (The White House, 2023).

[36] US DOE announced 9 winners (Carbon Credits, 2023).

Box 2. The SAF Grand Challenge Roadmap

The SAF grand Challenge roadmap, developed as a memorandum of understanding by the Departments of Energy, Transportation, and Agriculture (US DOE, 2022), frames collaborative efforts to achieve three main objectives:

- expanding SAF supply and end use to achieve 10% of projected aviation jet fuel use by 2030 and 100% by 2050,
- reducing the cost of SAF,
- enhancing the sustainability of SAF.

SAFs need to be capable of achieving a minimum of a 50% reduction in life-cycle greenhouse gas emissions (GHG) compared to conventional fuel, in line with RFS indications and IRA credit targets.

The roadmap lays out six action areas: feedstock innovation, conversion technology innovation, building supply chains, policy and valuation analysis, enabling end use and communicating progress, and building support.

Sustainable liquid and gaseous fuels, including biofuels, ammonia, hydrogen, and methanol are also cited as promising alternatives in the 2023 US National Blueprint for Transportation Decarbonization, alongside electrification, renewable energy and carbon capture (US DOE, 2023c). The Blueprint refers to the Zero-Emission Shipping Mission (ZESM) goals to ensure that 5% of the global deep-sea fleet can use zero-emission fuels by 2030, at least 200 of these ships primarily use these fuels across the main deep-sea shipping route, and 10 large trade ports covering at least three continents can supply zero-emission fuels by 2030. It also mentions R&D support and engagement in international fora like the IMO, but firm requirements to effectively move towards tangible shifts are very limited in the federal regulatory framework. Renewable fuel used in ocean-going vessels cannot account for compliance under the RFS,[37] even if, since 2010 (with further clarifications in 2023), this exclusion only applies to fuels used to power large ocean-going vessels[38] (EPA, 2023a). As in the case of aviation, the fuel mix in the US maritime sector consists almost exclusively of options derived from oil (heavy fuel and marine diesel oil) or natural gas (Taylor et al., 2022).

In aviation, all the low carbon fuel standards (**LCFS**) and similar programs (currently operational in California, Oregon and Washington State) consider jet fuel as an opt-in solution, similar to the RFS (CARB, 2020, Oregon Secretary of State, n.d., Washington State Department of Ecology, 2023). Conventional jet fuel does not generate deficits, but SAFs will be entitled to generate credits if opt-in. In California, CARB started to include SAFs produced by approved pathways in 2019 in the LCFS framework.[39] The opt-in treatment of SAF in the LCFS limited credits from their market introduction, as SAF accounted for 0.3% of all LCFS credits in California, in 2021. The lack of price competitiveness has been assessed as a key barrier, in this respect (O'Malley, 2023, US GAO, 2023a). A current proposal could bring fossil

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[37] This is due to the fact that fuel used in ocean-going vessels is explicitly excluded from the Clean Air Act's definition of transportation fuel (EPA, 2023a).

[38] The 2010 clarification was part of the rulemaking that created the RFS2 regulatory program. The 2023 clarification adds the notion that large ocean-going vessels also rely on very large engines as their primary propulsion system. These are "Category 3" reciprocating marine engines, with a specific displacement at or above 30 L per cylinder (EPA, n.d.).

[39] As of 2023, CARB approved more than 40 alternative jet fuel pathways with CI levels from 19 to 62 g CO_2e/MJ, all based on hydrotreated fats, oils and greases (CARB, n.d.b).

aviation fuel used for intrastate flights into the program as a deficit-generating regulated fuel, starting in 2028 (CARB, 2024).

For maritime transportation, the LCFS in California and Oregon exempt large vessels from obligations on carbon intensity of the fuels they use,[40] like the RFS. This includes container ships, tankers and bulk vessels.[41] The LCFS in the State of Washington explicitly exempts marine fuel (Oregon Secretary of State, n.d., Washington Washington State Department of Ecology, 2023).[42]

2.2.2 European Union

In the EU, key policy tools include requirements regarding the progressive integration of low-carbon fuels in the mix used by aircraft and ships (via the RefuelEU Aviation and the FuelEU Maritime Regulations, nested in the Renewable Energy Directive) and the integration of both aviation and maritime transportation in the Emission Trading Scheme (ETS).

The inclusion of maritime transportation is part of a significant reform of the EU ETS that was approved in 2023[43] Its scope is not limited to intra-EU voyages, but it covers also 50% of those to/from an EU port.

For aviation, the inclusion in the ETS dates back to 2012 (European Union, 2008) and it applies to flights within the European Economic Area (EEA). Changes introduced with the 'Fit for 55' package align with what has been adopted for carbon border adjustment mechanism (CBAM) and the ETS reform for industry. Prior to this reform, free permits were allocated to industries with strong international competition in order to limit carbon leakage, including aviation.[44] Following the reforms introduced with the 'Fit for 55' package, free emission allowances for intra-EEA flights are progressively phased out, starting in 2024 and achieving completion by 2026 (European Union, 2023c). The same reforms also give the Commission the option to extend the scope of the ETS to emissions from departing flights from the EEA, starting in 2027, if the ICAO Assembly fails to strengthen CORSIA by the end of 2025 (European Union, 2023c).

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[40] Criteria for exemption include a length of 400 feet or more, a gross tonnage of 10,000 gross tons or more, or a marine compression-ignition engine with a per-cylinder displacement of 30 L or more (CARB, 2020, Oregon Secretary of State, n.d.).

[41] Separately from LCFS, CARB has issued new vessel regulation of ocean-going vessels at berth, including emission controls of Cruises (CARB, n.d.c). In 2020, NO_X was the most significant pollutant in marine environments, accounting for 19% of the total NO_X emissions in California (CARB, 2022, EPA, 2023a).

[42] In California, the Ports of Los Angeles, Long Beach and Shanghai have also recently announced an implementation plan to accelerate emissions reductions on one of the world's busiest container shipping routes. As part of the plan, stakeholders involved will begin deploying ships capable of significantly reducing life-cycle emissions by 2025 and they will work together to demonstrate, by 2030, the feasibility of deploying fuels with strong life-cycle GHG emission reductions to supply them (Port of Los Angeles, 2023).

[43] The broader reform of the EU ETS includes the phase out of free allocation in some sectors (cement, aluminum, fertilizers, electricity, hydrogen and iron and steel), accompanied by the phase-in of CBAM, and similar instruments (further discussed in the following part of the main text) for aviation. The EU ETS reform also includes a more ambitious reduction target (62%) by 2030 in comparison with previous versions of the System and revised parameters for the Market Stability Reserve (MSR), which is the main instrument for addressing supply and demand imbalances and bolstering its resilience to external shocks.

[44] Carbon leakage is a situation that can arise when companies transfer production to other countries that have more relaxed emissions requirements in order to save costs. While emissions in the more regulated jurisdiction nominally decline, they actually just shift to a new jurisdiction, and may even increase in aggregate (European Commission, n.d.).

This follows earlier attempts to take an approach similar to maritime transport: the initial proposal for the 2012 ETS reform, which brought aviation in the EU ETS, was already designed to include all flights departing from or arriving at an airport in the European Economic Area (EEA), but was then replaced with a temporary reduction in the scope to cover only intra-EEA flights, to give ICAO time to reach an effective worldwide agreement (Rao, 2023). A similar development took place during the trilogue negotiations of the aviation files in the 'Fit for 55' package, with the Parliament calling for an inclusion of emissions from extra-EEA flights (European Parliament, 2022).

This extension would be similar to the 50% coverage of voyages already integrated in the ETS for maritime transportation, a feature that is most likely reflecting lower expectations for progress on global carbon price at the IMO. An extension of the aviation ETS beyond intra-EEA flights would effectively work in a similar way to CBAM, applying a carbon price beyond Europe alone, based on the need to protect the continent from risks of carbon leakage.

An important function of the revised ETS is an increased capacity to raise funds to be reinvested in technological development and social protection measures. In aviation, a part of the ETS revenues – estimated close to EUR 2 billion (O'Malley, 2024) – can be used to cover the cost of 20 million 'SAF allowances' made available to airlines between 2024 and 2030, and possibly (pending a decision by the Commission) up to 2034 (European Union, 2023c). These allowances consider the mandates to deploy SAF developed under the RefuelEU Aviation regulation (discussed below) and are meant to cover at least part of the price differential that exists between SAF and the fossil kerosene fuel benchmark[45] (net of fuel taxes and the carbon price), helping to manage compliance costs in an early deployment phase for SAFs, while also supporting early adopters, without eliminating price signals from fuel taxes and carbon pricing. SAF allowances are restricted to the EU ETS scope, i.e., intra-EEA flights (at least until 2026). The specific mechanisms enabling the distribution of these allowances will need to be defined in delegated acts by the European Commission (European Union, 2023c).

The Innovation Fund, summarized in Box 3, is another important policy instrument meant to facilitate progress on climate-related technologies. It has a focus on energy and industry, and is one of the world's largest funding programmes for the deployment of net-zero and innovative technologies (European Commission, n.d.e). It targets the demonstration and commercialisation of innovative low-carbon technologies and processes, including, but not limited to, solutions that have relevance for aviation and shipping fuels.[46] Importantly, contributions obtained via the Innovation Fund are not considered as state aid in the EU. Even if this is a key instrument, much needed to overcome disadvantages of being a first-mover on a new technology, the Innovation Fund can only bring a partial contribution in comparison with the overall investments needed for the transition. For example, investment needs in aviation alone are estimated to reach USD 40-50 billion annually for the aviation sector alone (MPP, 2023): this corresponds to the size of the whole Innovation Fund budget for 2020-2030, which isn't reserved solely for aviation.[47] This means that a successful shift

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[45] 50% to 100%, depending upon the fuel pathway used and the location of SAF delivery. 100% applies to small airports in islands of less than 10,000 km^2, 95% applies for RFNBOs, 70% applies to hydrogen or advanced biofuels, and 50% to other eligible SAFs (European Union, 2023c).

[46] As its scope covers CCU, CCS, renewable energy generation and energy storage.

[47] Assuming a price difference of EUR 1.5 between low-carbon fuels and the fossil-based benchmark and 26.6 billion liters of fuel demand, means that 40 billion would just cover the price difference for 5% of the total.

can only happen if the Innovation Fund and other policy tools help mobilizing significant flows of private investments.

Box 3. Innovation Fund and other European Union Funding Entities

The Innovation Fund was established by the Directive that established the ETS (European Union, 2003) and further defined in a series of delegated acts (European Commission, n.d.f). Its total funding depends on the carbon price, and it is estimated to be about EUR 40 billion from 2020 to 2030.[48] The Innovation Fund provides support through grants and project development assistance. Projects applying to calls for regular grants are to be selected based on effectiveness of greenhouse gas emissions avoidance, degree of innovation, project maturity, replicability and cost efficiency. The European Climate, Infrastructure and Environment Executive Agency (CINEA) is the implementing authority for the scheme. It is in charge of administrative aspects, from managing the calls for proposals to providing guidance and support for applicants, signing grant agreement, disbursing the grants, monitoring the technical/financial management of projects, providing expert technical support to project promoters and ensuring visibility of the programme. The European Investment Bank (EIB) is responsible for providing and managing project development assistance (PDA), which consists of financial and technical advice services to improve project maturity. The EIB is also in charge of monetizing the Innovation Fund allowances from the EU ETS and managing the Innovation Fund revenues.

Grants by the Innovation Fund cover up to 60% (and 100% with competitive bidding) of capital and operational costs minus revenues over the first ten years of operation for the projects supported[49].

This support can be combined with other support programmes, including:

- **InvestEU**, which facilitates access to finance and investments in European companies and projects simpler, more efficient and more flexible. The programme consists of three components: the InvestEU Fund, the InvestEU Advisory Hub and the InvestEU Portal. The InvestEU Fund aims to mobilize more than EUR 372 billions of public and private investment through an EU budget guarantee of EUR 26.2 billion, bringing together the multitude of earlier EU financial instruments (European Commission, n.d.j). The InvestEU Advisory Hub provides advisory support, technical assistance, and including capacity building to public and private entities, including project developers. The InvestEU Portal brings together investors and project promoters on a single EU-wide platform, in an attempt to link up companies and potential investors.
- **EU Important Projects of Common Interest (IPCEI)** are enabled by the Treaty on the Functioning of the EU (European Commission, 2017) and currently cover, in addition to a road and rail link between Denmark and Germany, microelectronics, batteries, hydrogen, cloud infrastructure and services and hydrogen infrastructure (European Commission, n.d.k).
- **The Connecting Europe Facility (CEF):** Established by a Regulation in 2021, the CEF is a key EU funding instrument in delivering the European Green Deal and an important enabler towards the EU's decarbonization objectives for 2030 and 2050 (European Union,

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[48] This assumes a carbon price of EUR 75/t CO_2, 530 million ETS allowances auctioned, in total.

[49] Up to 40% of the grant can be given based on predefined milestones before the whole project is fully up and running.

2021b). It supports the development of high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy and digital services, based on projects identified along priority corridors and thematic areas. Its focus is on cross-border projects. It has an energy budget (focused on TEN-E projects) of EUR 5.84 billion in the 2021-27 period, a transport budget (focused on TEN-T projects) of EUR 25.81 billion, including EUR 11.29 billion for cohesion countries, both managed by CINEA (CINEA, n.d.).

- **Horizon Europe research funds:** Horizon Europe is the EU's key funding programme for research and innovation. with a budget of EUR 95.5 billion (European Commission, n.d.l). It tackles climate change, helps to achieve the UN's Sustainable Development Goals and boosts the EU's competitiveness and growth. The programme facilitates collaboration and strengthens the impact of research and innovation in developing, supporting and implementing EU policies while tackling global challenges. It supports creating and better dispersing of excellent knowledge and technologies
- **The Modernisation Fund** was established in 2020 (European Union, 2020a). It is a dedicated funding programme to support, via the EIB, 10 lower-income EU Member States (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia) in their transition to climate neutrality by helping to modernize their energy systems (renewable energy generation, energy storage, energy networks, re-skilling in carbon-dependent regions) and improve energy efficiency.
- **The Just Transition Fund** is addressed to EU regions that are most affected by transition towards a climate-neutral economy, to back productive investments in small and medium-sized enterprises, the creation of new firms, research and innovation, environmental rehabilitation, clean energy, up- and reskilling of workers, job-search assistance and active inclusion of job-seekers programmes, as well as the transformation of existing carbon-intensive installations when these investments lead to substantial emission cuts and job protection (European Commission, n.d.m).

The first EUR 800 million competitive bidding under the Innovation Fund was launched through a pilot auction that was operationalized in November 2023 and closed in February 2024, awarding EUR 720 million to several renewable hydrogen projects, with end-uses foreseen that include maritime transport, adding to chemicals, fertilizer production and steel (European Commission, n.d.n). The next auction will be launched towards the end 2024.

The auctions for hydrogen/RFNBO production are also key elements of the European Hydrogen Bank. The Bank was announced in September 2022, following earlier work in the European Hydrogen Strategy (European Union, 2020b), and defined in a Communication in March 2023 (European Union, 2023d). It aims to unlock private investments in hydrogen value chains in the EU and in third countries by connecting renewable hydrogen supply with the emerging demand by European off-takers and thus to establish an initial market for renewable hydrogen.

The Hydrogen Bank is expected to address four investment challenges: scaling up manufacturing capacities for electrolyzers, scaling up new hydrogen production capabilities, opening new demand sectors for renewable and low-carbon hydrogen and developing dedicated hydrogen infrastructure. It is based on four pillars, which will be implemented by the European Commission: two new financing mechanisms to support renewable hydrogen production within the EU and internationally, increased demand visibility by linking with off-takers, Member State initiatives and existing data centers, and a coordination role to streamline access to different funding instruments for Member States and project developers, including the European Regional Development Fund (ERDF) and the Just Transition Fund (JTF), as well as the InvestEU Fund.

While volumes of low-carbon fuels in aviation and maritime transportation in the EU are also very low, similar to the US, recent legislative updates introduced regulatory requirements regarding the progressive integration of low-carbon fuels in the mix used by aircraft and ships. These arise from the RefuelEU Aviation and FuelEU Maritime regulations, complementing and adding specific regulatory requirements to the Renewable Energy Directive,[50] which was recast as part of the Fit for 55 package and following the REPowerEU plan.

- RefuelEU Aviation sets new rules that oblige fuel suppliers to deliver in airports with traffic above 800,000 passengers/year or 100,000 t/year an increasing share of SAF, including biofuels, recycled carbon fuels and synthetic aviation fuels (Table 4). To reduce the risk of leakage through “tankering”—a behavior in which aircraft load more fuel than necessary at airports with fewer regulations or fees on fuel than at more regulated airports—aircraft operators serving these airports will be required to uplift at the same airports no less than 90% of the fuels they need (European Union, 2023d). SAF supplied to operators in EU airports needs to grow from 2% by 2025 to 6% by 2030, and up to 70% in 2050. A sub-obligation for synthetic aviation fuels (including hydrogen and derivatives obtained from renewable or nuclear electricity – i.e., renewable fuels of non-biological origin [RFBNOs] – requires shares of 1.2% in 2030, 2% in 2032, 5% in 2035 and then up to 35% in 2050 (European Union, 2023d). A 10-year flexibility mechanism (during which aviation fuel suppliers may supply higher shares of SAF in certain airports to compensate for lower shares in other airports) intends to support the SAF industry to develop production and supply capacity.[51] Compliance is to be ensured on an annual basis. In addition to setting SAF mandates, the ReFuelEU Aviation regulation also creates a new flight labelling program for the performance of flights, to reflect the expected carbon footprint and CO_2 intensity per passenger kilometer (European Union, 2023d).
- FuelEU Maritime focuses its requirements on the GHG intensity of energy used on board of ships larger than 5,000 gross tonnes, these are currently responsible for 90% of the GHG emissions from maritime transportation. Only half the energy used for extra-EU voyages will be subject to the regulation. It also mandates the use of onshore power supply by passenger and container ships in the main EU ports (European Union, 2023e). Life-cycle GHG intensity of the energy falling within the scope of the regulation shall decline by 2% in 2025 compared to the 2020 baseline, by 6% in 2030 and, shall progressively reach an 80% reduction by 2050. Synthetic hydrogen and its derivatives, including renewable fuels of non-biological origin (RFNBOs) and recycled carbon fuels, will be receive double credit when counting towards the requirement until 2033. Moreover, a 2% RFNBO sub-target will apply in 2034 and beyond if the share of RFNBOs in the maritime bunker fuels is less than 1%

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[50] With RefuelEU Aviation adopted as a *lex specialis* of the Renewable Energy Directive (European Union, 2023d).

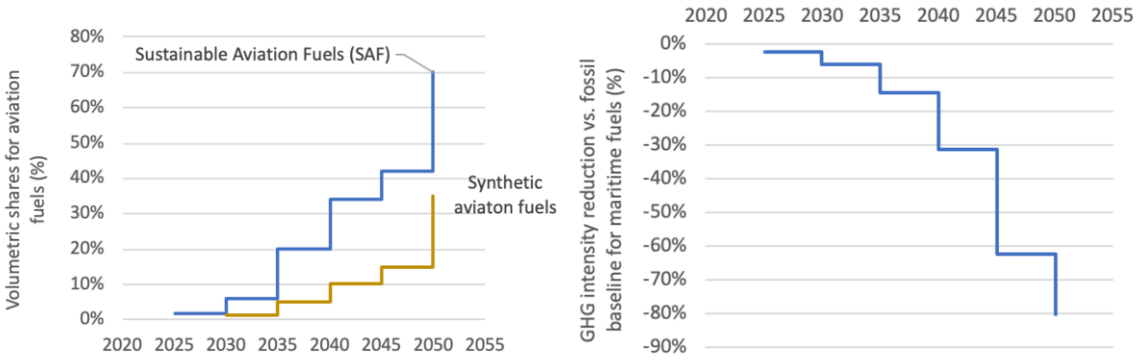
[51] The regulation is also open to enhancements, including elements of a book and claim scheme. These could help offtakers connect directly with suppliers, enabling long-term contracts for fuel supplies (European Union, 2023d).

by 2031. A reward factor for wind-assisted propulsion is also foreseen. Flexibility mechanisms include banking and borrowing of compliance surpluses between (yearly) reporting periods and pooling of compliance across multiple ships and for the companies controlling them.

Similar to the RFS and the LCFS in the US, the RefuelEU Aviation and FuelEU Maritime regulations are reliant on life cycle GHG emission accounting (with system boundaries limited to energy used in feedstock supply and conversion facilities), even if RefuelEU Aviation sets volumetric rather that GHG emission reduction targets. Land use change issues are addressed requiring compliance with sustainability criteria developed in the Renewable Energy Directive and the exclusion of feedstocks presenting a significant risk of indirect land use change (ILUC) from those that enable fuels to count for the mandatory requirements.

Figure 1 contains a summary of the regulatory requirements in the RefuelEU Aviation and FuelEU Maritime regulations, while Table 4 and Table 5 provide an overview of the fuels considered by each of them.

Figure 1. Regulatory requirements in RefuelEU Aviation and FuelEU Maritime.



Note: synthetic aviation fuel shares for 2030 to 2034 need to exceed annual values of 0.7%/year and reach an annual average of 1.2% across the 5 years. Source: European Union, 2023d and European Union, 2023e

Table 4 and Table 5 show that both regulations exclude fuels obtained from food and feed crops and biomass-derived from primary or highly biodiverse ecosystems, nature protection areas, endangered ecosystems, wetland, heathland, peatland and continuously forested areas. All fuels must meet minimum life-cycle GHG emission abatement thresholds vs. a fossil fuel benchmark, currently 65% for biofuels.[52]

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[52] This is consistent with the fact that they leverage the provisions of the Renewable Energy Directive, as the Directive includes a 7% cap for food and feed crops used in road transport and criteria protecting land with high biodiversity value and land with high-carbon stock.

Table 4. Types of fuels allowed in RefuelEU Aviation.

	Category	Subcategory	Requirements
SAF	Aviation biofuels	Biofuels	Produced from used cooking oil and animal fats unfit for human or animal consumption (the feedstocks listed in Part B of Annex IX of RED)
			Produced from other feedstocks, except food and feed crops, as defined in RED intermediate crops, palm fatty acid distillate and palm and soy-derived materials, and soap stock and its derivatives[53] Not made from feedstocks from land with high biodiversity and carbon stocks. Minimum 65% life cycle GHG reduction.
		Advanced biofuels	Produced from algae, agricultural waste, biomass fraction of MSW, forestry and forest-based industry waste, manure, bagasse, palm oil mill effluent, non-food cellulosic material, ligno-cellulosic material except saw and veneer logs (the feedstocks listed in Part A of Annex IX of RED).
	Recycled carbon aviation fuels		Compliant with life-cycle accounting and emissions savings criteria of the delegated acts under the RED. No carbon from fossil origin after 2040 for RCFs. Minimum 70% life cycle GHG emission benefit.
	Synthetic aviation fuels	Renewable hydrogen	
		Renewable fuels of non-biological origin (RFNBOs)	
		Low-carbon hydrogen (nuclear)	
		Synthetic low-carbon aviation fuels (nuclear)	

Sources: European Union, 2023d, European Union, 2018 and European Union, 2023g.

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[53] The RED defines food or feed crops as starch-rich crops, sugar crops or oil crops produced on agricultural land as a main crop but excluding residues, waste or ligno-cellulosic material and intermediate crops, such as catch crops and cover crops, provided that the use of such intermediate crops does not trigger demand for additional land.

Table 5. Types of fuels allowed in FuelEU Maritime.

	Category	Requirements
Renewable and low-carbon fuels	Biofuels	Excluding food and feed crops, as defined in RED Not made from feedstocks from land with high biodiversity and carbon stocks. Minimum 65% life-cycle GHG requirement.
	Recycled carbon fuels (RCFs)	Compliant with life-cycle accounting and emissions savings criteria of the delegated acts under the RED. No carbon from fossil origin after 2040 for RCFs. Minimum 70% life cycle GHG emission benefit.
	Renewable fuels of non-biological origin (RFNBOs)	

Sources: European Union, 2023e, European Union, 2018 and European Union, 2023g.

RefuelEU Aviation also excludes explicitly intermediate crops,[54] palm fatty acid distillate, palm- and soy-derived materials, soap stock and its derivatives (European Union, 2023d, European Union, 2023e). Contrary to the Renewable Energy Directive and Fuel EU Maritime, Refuel EU Aviation integrates forms of hydrogen and its derivatives derived from non-fossil energy (and therefore including renewable and nuclear energy, but excluding natural gas with CCS), as long as they deliver life-cycle GHG emissions savings of at least 70% compared to the fossil fuel benchmark (European Union, 2023f).

Accounting methodologies developed in the context of the Renewable Energy Directive and used in RefuelEU Aviation and FuelEU Maritime define conditions related with additionality (or incrementality), temporal correlation/matching and deliverability to avoid inducing increases in GHG emissions in the rest of the energy system.[55] They define also requirements on the sourcing of CO_2 sources, excluding the possibility to rely on concentrated carbon streams of fossil origin after 2040 (European Commission, 2023e).

PBtL fuels are subject to separate accounting approaches for the biofuel and the RFNBO/hydrogen-related shares (European Commission, 2024a).

Both regulations include non-compliance penalties. For aviation, these are at least double the price difference between conventional fuels and the average of the low-carbon alternatives, with differentiated values for SAF and synthetic fuels (European Union, 2023). For shipping, non-compliance fines equal EUR 2,400 per tonne of very low-sulfur fuel oil

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[54] Intermediate crops are any crop grown outside the main growing season (Badino & Mukhopadhaya, 2022). They include food and feed crops that are allowed as an exception in the Renewable Energy Directive, provided that the use of such intermediate crops does not trigger demand for additional land (European Union, 2018). They also include cover crops, grown as a form of sustainable land management for soil cover or other environmental purposes). The exclusion accounts for the lack of guidance on how Member States should interpret and implement the condition of triggering “demand for additional land" and the risk that all biofuel produced from intermediate crops could be certified as not from food and feed crops, diverting feedstocks with current uses to SAF production and, through that, leading to indirect GHG emissions, as long as a replacement material is necessary for the initial use.

[55] These may also have served as a model for policies in the US, as shown by the recently proposed regulations on the Clean Hydrogen Production Credit established by the Department of Treasury (US Department of the Treasury, 2023b).

(VLFSO) energy equivalent (Safety4Sea, 2023 and European Union, 2023). This value is comparable to those introduced for aviation and it is significantly higher than technical estimates of low-carbon fuel production costs.

Complementary policies deployed in the EU also include waivers for SAF and low-carbon shipping fuels in the updated Guidelines on State aid for climate, environmental protection, and energy (CEEAG) (European Union, 2022), their inclusion in the Net Zero Industry Act as strategic net zero technologies (European Council, 2024), facilitate access to finance EU sustainable finance taxonomy (European Union, n.d.), as well as SAF-related capacity building projects in Africa and India and corridors focused on low-carbon shipping fuels under the Global Gateway flagship projects (European Union, n.d.).

3. Technology Analysis and Policy Characterization

The effectiveness of policy interventions often depends on their quantitative impact on the economics of fuel or energy production. This section will assess the impacts of current policy measures meant to stimulate the use of lower-carbon alternative aviation and maritime fuels, based on life-cycle emission values and cost assessment available in relevant literature, overlaying these with assumptions reflecting the policy impacts.

3.1 Technology Analysis

The selection of representative fuels, considered alongside their life-cycle emissions and the primary energy requirement per unit of fuel energy delivered to the vehicle are shown in Table 6. Table 7reports production costs, in a near-term (now), medium-term (2030) and long-term framework (post 2040). Table 8 contains estimates of infrastructure-related costs for the fuels requiring specific investments to be transported, stored and distributed (due to incompatibility with existing infrastructures). These reflect the cost of transporting, storing and distributing fuels, the need for specific facilities for different forms of alternative energy (e.g., ammonia, methanol, hydrogen), and the impacts of different usage rates of these facilities on the unit costs of the fuels (i.e., on the cost of each energy unit delivered to aircraft and/or ships). Table 9 combines the information of Table 7 and Table 8 in a total cost of fuel delivery to aircraft and ships.

Covered fuels include biogenic and non-biogenic fuels for both aviation and shipping. This reflects a wide range of options currently being considered as alternative candidates to fossil fuels. In broad terms, this includes:

- Biofuels, derived from biogenic materials which may include food and feed crops (i.e., conventional biofuel feedstocks, generally used in biochemical and oleochemical conversion pathways), energy crops, agricultural and forestry waste and other forms of biogenic waste (i.e., advanced biofuel feedstocks, suitable for biochemical, thermochemical and oleochemical conversion pathways).
- Hydrogen, derived from electrolysis (in centralized or decentralized production units) and from natural gas, in centralized production units involving methane reforming with carbon capture and storage or methane pyrolysis processes. For these pathways, low-carbon primary energy – renewable electricity, or low-carbon biomethane or synthetic methane – is required to maximize GHG reductions.
- Recycled carbon fuels (RCFs) combine hydrogen with carbon obtained from the combustion of carbon-containing fuels (including, in principle, both of non-biogenic and fossil fuels) or other waste gases, to make new hydrocarbon fuels. RCF production would most commonly utilize CO and CO_2 from the waste gas stream. The carbon is thereby recycled for additional uses as an energy carrier before it is released. EU policy specifies that RCFs must rely on non-biogenic carbon (if they use biogenic carbon, they counterintuitively fall within the pool of RFNBOs).
- E-fuels, combining low-carbon electrolytic hydrogen and non-renewable carbon streams (requiring CO_2 from biogenic sources or from Direct Air Capture [DAC]) as

feedstocks and deriving their energy from renewable (or nuclear, in cases like synthetic aviation fuels) electricity.

There may also be opportunities to improve the yield or conversion efficiency of biofuel production systems by integrating renewable electricity, or inputs produced using renewable electricity, especially electrolytic hydrogen, in processes referred to as power and biomass to liquids (PBtL).[56] Key examples include the use of low-carbon hydrogen in oleochemical biofuels production pathways[57] and the use of low-carbon hydrogen as both a feedstock and energy input.[58] However, due to limited data availability, PBtL fuels are excluded from the quantitative analysis of this report and only considered in qualitative fashion. Additional research, and deployment of demonstration facilities could help demonstrate whether PBtL lives up to its potential.

Assessment of costs, life-cycle carbon intensity, and energy efficiencies focus on low-carbon options, in line with the focus of policy action intended to foster their development. Sources of life-cycle emission estimates (as well as energy ratios) and costs reflect the detailed review developed in Trinomics (2023), with targeted updates, as summarized in Annex 1.

For biofuels, cost estimates reflect ranges of feedstock prices observed in the global market to date, including effects related to the recent price increases and excluding the case of feedstocks grown on marginal land because available cost estimates for feedstock prices do not reflect these conditions.[59] Central estimates for production costs of biofuels take into consideration mid-point values of ranges available from different sources. The costs of biofuel feedstocks are not assumed to evolve (in real terms) over time, with respect to the ranges observed in the past. On the other hand, technological progress and in particular energy efficiency enhancements also translate in biofuel production cost savings, going forward.

For hydrogen from renewables and its derivatives (e-fuels), the analysis focuses specifically on options reliant on low-carbon, low-cost electricity (in the range of 0.02 to 0.1 USD/kWh). This excludes cases with low load hours for electrolyzers (i.e., cases where electrolyzers would run on otherwise curtailed electricity), and it is therefore reflecting circumstances with greater low-cost, low-carbon renewable or nuclear electricity production potential.[60]

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[56] The same concept applies also to gaseous fuels, enlarging the scope of PBtL fuels to PBtX, e.g., synthetic methane. At present, many biomass production systems obtain some of their needed energy or hydrogen from the input biomass. While this reduces required inputs to the production process, it typically means that some of the carbon embodied in the input biomass is lost, most commonly as CO_2. Supplying energy or hydrogen made from zero-carbon sources means the biofuel process can be optimized to maximize the conversion of carbon into useful fuels or products. Early studies, mostly using models of the production system, indicate promise, but as yet few examples exist to validate modelled results.

[57] These include hydrotreated vegetable oils (HVO), commonly referred to as renewable diesel, and hydroprocessed esters and fatty acids (HEFA), for jet fuel.

[58] Similar to those developed by LanzaTech (Lanzatech. 2017).

[59] While feedstock production on marginal and degraded land can have significant environmental benefits (e.g., soil organic carbon, nutrient management, and erosion), the feasibility and cost of biofuel feedstock production on such land is highly uncertain. Without policy frameworks to measure and reward the provision of ecosystem and other environmental services, biofuel cost estimates used here should therefore be considered optimistic, especially in jurisdictions that enacted stricter sustainability guidelines.

[60] Electricity used for low-GHG fuel production needs to conform with additionality/incrementality, deliverability, and temporal correlation conditions introduced in the EU and proposed in the US. This in line with recommendations issued by the International Renewable Energy Agency in the case of renewable electricity (IRENA Coalition for Action, 2022).

Higher electricity costs are considered for decentralized hydrogen production, due to lower likelihood of abundant and highly available low-carbon electricity in these circumstances (in comparison with centralized production in sites selected for their optimal low-carbon electricity availability: these are also the siting options more likely to be considered for e-fuels). Decentralized hydrogen (not considered for e-fuels) is also paired with lower infrastructure costs in comparison with hydrogen from centralized production. Hydrogen and e-fuel production costs decline moving forward, reflecting a case where the policy push enables technology learning and increased availability of low-cost renewable electricity, thanks to continuous investments on the supply side. Central estimates take into consideration mid-point values of ranges available from different sources (as outlined in Annex 1), paying specific attention to internal consistency of life-cycle, energy efficiency and cost considerations to make sure that there is internal consistency for the different fuel production pathways taken into consideration.

For fossil-based hydrogen (with CCS), GHG emission estimates reflect best theoretical practices, needing very low methane leakage rates, allowing a 70% GHG reduction vs. a baseline without CCS, using 100-year global warming potentials. For methane pyrolysis, the focus is on the combined use of natural gas as a feedstock and renewable electricity for the process, leading to strong GHG emission savings. Costs (further detailed in Annex 1) reflect IEA estimates for CAPEX and OPEX, excluding energy inputs (IEA, 2019a). Estimates shown in Table 7 and Table 9 also account for natural gas price ranges. These span from current values in the US market in the low-end (2.1 USD/MMBtu, or 8 USD/MWh, or USD 2.2/GJ) to sustained price increases for natural gas, reaching 120 USD/MWh, or USD 33/GJ[61]) for estimates at the high-end of the production cost range. In the case of pathways reliant on natural gas inputs, central values are at 25 USD/MWh, and therefore close to 7 USD/GJ.

Ranges are wider for hydrogen pathways based on natural gas (due to the wide variation of feedstock prices) and for energy carriers that are not widely used today, and therefore require dedicated infrastructure for transportation, storage, distribution and refueling.

For recycled carbon fuels (RCFs), estimates of GHG emission savings reflect cases where carbon is of fossil origin. Energy use and costs reflect lower requirements with respect to e-fuels, thanks to the reliance on concentrated CO_2 streams.

Fuels requiring new infrastructure are subject to wider total cost ranges. This is because low transport, storage and distribution infrastructure utilization can have major impacts on the unit cost of energy carriers requiring dedicated infrastructure investments, especially if they are in a gaseous state at ambient pressure and temperature (and in particular in the case of hydrogen, which comes also with energy-intensive requirements, especially in cases requiring liquefaction). Circumstances characterized by more conservative assumptions regarding infrastructure utilization are currently mainly reflected in the higher cost estimates. Central estimates reflect a rather positive perspective regarding fuels needing new/dedicated transportation, storage and distribution infrastructure to be delivered to aircraft and ships, corresponding to circumstances that are rather optimistic (and not necessarily likely to occur, at scale) on the capacity of all stakeholders to bridge investment risks still faced by these types of fuels.

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[61] Note that these values are well below the peaks observed in 2022 and 2023 in the EU, which exceeded USD 50/GJ in 2022 and reached USD 100/GJ before the winter of 2023 (IEA, 2022a; Trading economics, n.d.).

Table 6. Life-cycle emissions energy efficiencies of fuel production.

	Sector	GHG emissions (g CO_2/MJ)			Primary MJ/MJ of fuel produced		
		Before 2030	Near-term (2030)	Long term (post 2040)	Before 2030	Near-term (2030)	Long term (post 2040)
Fossil fuels	Aviation and maritime	90	90	90	1.2	1.2	1.2
Biofuels							
Biofuels - Biochemical - Conventional (cereals)	Maritime	57	56	55	1.8	1.7	1.7
Biofuels - Biochemical - Conventional (sugar cane)	Maritime	35	35	35	2.8	2.7	2.7
Biofuels - Biochemical - Advanced feedstocks	Maritime	25	24	23	3.0	2.9	2.7
Biofuels - Biochemical (ATJ) - Conventional (cereals)	Aviation	72	64	61	2.2	2.0	1.9
Biofuels - Biochemical (ATJ) - Conventional (sugar cane)	Aviation	44	40	39	3.5	3.1	3.0
Biofuels - Biochemical (ATJ) - Advanced	Aviation	29	27	25	3.8	3.3	3.0
Biofuels - Oleochemical - Medium ILUC risk	Aviation and maritime	60	60	60	1.5	1.4	1.3
Biofuels - Oleochemical - Low ILUC risk	Aviation and maritime	31	31	31	1.5	1.4	1.3
Biofuels - Thermochemical - Advanced feedstocks	Aviation and maritime	20	20	19	1.8	1.7	1.6
Hydrogen							
Hydrogen - Low-carbon electricity, requiring H transport	Possibly aviation, unlikely maritime	9	9	8	1.7	1.6	1.5
Hydrogen - Low-carbon electricity, decentralized H production on-site	Possibly aviation, unlikely maritime	9	8	8	1.6	1.5	1.4
Hydrogen - Fossil based (CCS), requring H transport	Possibly aviation, unlikely maritime	27	27	27	1.9	1.7	1.5
Hydrogen - Fossil based (methane pyrolysis), requring transport	Possibly aviation, unlikely maritime	11	10	10	3.2	2.9	2.6
E-liquids							
E-fuels - Liquid hydrocarbons	Aviation and maritime	15	14	14	2.7	2.6	2.5
E-fuels - Methanol	Posibly maritime, unlikely aviation	13	12	12	2.4	2.3	2.2
E-fuels - Methane	Posibly maritime, unlikely aviation	12	11	11	2.1	2.0	1.9
E-fuels - Ammonia	Posibly maritime, unlikely aviation	11	10	10	1.9	1.8	1.7
Recycled Carbon Fuels (with low-carbon H)	Aviation and maritime	52	52	52	2.3	2.2	2.1

Note: blue identifies comparatively low values, red identifies comparatively high values. Color coding is separately set for life-cycle GHG emissions and energy efficiency (meaning that the darkest red is the highest value across all GHG emissions or energy efficiencies of conversion processes, and darkest blue the lowest, again either for GHG emissions or energy efficiencies of conversion processes). For e-fuels, energy efficiency estimates consider low-carbon electricity as the primary form of energy. Life-cycle GHG emissions assessed attempt to integrate all GHGs and to include ILUC effects. They refer to fuel production and do not include emissions transporting/distributing fuel to end uses.

Source: This assessment, based on relevant literature, as indicated in the main text and further detailed in Annex 1.

Table 7. Fuel production costs.

	Production cost (USD/GJ)								
	Lower bound			Central estimate			Upper bound		
	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)
Fossil fuels (aviation)	20	20	20	20	20	20	20	20	20
Fossil fuels (maritime)	15	15	15	15	15	15	15	15	15
Biofuels									
Biofuels - Biochemical - Conventional (cereals)	18	18	18	20	19	19	21	21	21
Biofuels - Biochemical - Conventional (sugar cane)	18	18	18	20	20	20	22	22	21
Biofuels - Biochemical - Advanced feedstocks	35	33	30	46	42	35	56	52	44
Biofuels - Biochemical (ATJ) - Conventional (cereals)	25	22	20	31	25	23	35	27	26
Biofuels - Biochemical (ATJ) - Conventional (sugar cane)	25	23	20	31	26	24	35	28	27
Biofuels - Biochemical (ATJ) - Advanced	47	40	36	64	53	48	79	64	59
Biofuels - Oleochemical - Medium ILUC risk	34	33	30	37	36	33	48	46	42
Biofuels - Oleochemical - Low ILUC risk	37	35	33	41	39	36	52	50	46
Biofuels - Thermochemical - Advanced feedstocks	46	41	30	51	47	38	56	52	45
Hydrogen									
Hydrogen - Low-carbon electricity, requiring H transport	25	13	8	38	27	19	50	30	25
Hydrogen - Low-carbon electricity, decentralized H production on-site	29	15	9	43	31	22	58	35	29
Hydrogen - Fossil based (CCS), requring transport	10	10	10	21	19	18	72	67	63
Hydrogen - Fossil based (methane pyrolysis), requring transport	14	13	11	30	30	28	156	143	129
E-liquids									
E-fuels - Liquid hydrocarbons	68	53	36	88	63	47	99	71	54
E-fuels - Methanol	64	49	32	83	58	42	92	64	47
E-fuels - Methane	61	46	29	79	54	38	88	60	43
E-fuels - Ammonia	40	30	22	53	38	28	65	47	33
Recycled carbon fuels	54	42	27	74	51	38	83	57	43

Note: blue identifies comparatively low values, red identifies comparatively high values. Color coding is set uniformly across the whole table (meaning that the darkest red is the highest value across the board, and darkest blue the lowest). All monetary values are in 2023 USD. Liquefaction is not included in hydrogen production cost estimates. Feedstock costs for the oil-based benchmark and biofuels are assumed at current levels, going forward.
Source: this assessment, based on relevant literature, as indicated in the main text and further detailed in Annex 1.

Table 8. Infrastructure costs for the fuels considered.

	Infrastructure-related costs (USD/GJ)								
	Lower bound			Central estimate			Upper bound		
	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)
Hydrogen - Low-carbon electricity, requiring H transport	28	30	25	38	37	29	76	76	68
Hydrogen - Low-carbon electricity, decentralized H production on-site	18	17	15	24	23	21	48	44	39
Hydrogen - Fossil based (CCS), requring H transport	17	17	15	26	25	20	37	37	33
Hydrogen - Fossil based (methane pyrolysis), requring transport	17	17	15	26	25	20	37	37	33
E-fuels - Methanol	5	5	5	5	5	5	11	11	10
E-fuels - Methane	9	9	9	10	10	9	22	22	19
E-fuels - Ammonia	8	8	8	13	12	10	18	18	17

Note: blue identifies comparatively low values, red identifies comparatively high values. Color coding is set uniformly across the whole table (meaning that the darkest red is the highest value across the board, and darkest blue the lowest). All monetary values are in 2023 USD.

Source: this assessment, based on relevant literature, as indicated in the text and further detailed in Annex 1.

Table 9. Total delivery costs for the fuels.

	Total costs (USD/GJ)								
	Lower bound			Central estimate			Upper bound		
	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)	Current	Near-term (2030)	Long term (post 2040)
Fossil fuels (aviation)	20	20	20	20	20	20	20	20	20
Fossil fuels (maritime)	15	15	15	15	15	15	15	15	15
Biofuels									
Biofuels - Biochemical - Conventional (cereals)	18	18	18	20	19	19	21	21	21
Biofuels - Biochemical - Conventional (sugar cane)	18	18	18	20	20	20	22	22	21
Biofuels - Biochemical - Advanced feedstocks	35	33	30	46	42	35	56	52	44
Biofuels - Biochemical (ATJ) - Conventional (cereals)	25	22	20	31	25	23	35	27	26
Biofuels - Biochemical (ATJ) - Conventional (sugar cane)	25	23	20	31	26	24	35	28	27
Biofuels - Biochemical (ATJ) - Advanced	47	40	36	64	53	48	79	64	59
Biofuels - Oleochemical - Medium ILUC risk	34	33	30	37	36	33	48	46	42
Biofuels - Oleochemical - Low ILUC risk	37	35	33	41	39	36	52	50	46
Biofuels - Thermochemical - Advanced feedstocks	46	41	30	51	47	38	56	52	45
Hydrogen									
Hydrogen - Low-carbon electricity, requiring H transport	53	43	33	76	63	48	126	107	93
Hydrogen - Low-carbon electricity, decentralized H production on-site	47	31	24	67	54	43	106	78	68
Hydrogen - Fossil based (CCS), requring transport	27	27	25	47	44	38	109	104	96
Hydrogen - Fossil based (methane pyrolysis), requring transport	30	29	26	55	55	48	193	179	162
E-liquids									
E-fuels - Liquid hydrocarbons	68	53	36	88	63	47	99	71	54
E-fuels - Methanol	69	54	37	88	63	47	103	75	57
E-fuels - Methane	70	55	38	89	64	47	109	81	62
E-fuels - Ammonia	48	38	30	65	51	38	83	65	50
Recycled carbon fuels	54	42	27	74	51	38	83	57	43

Note: blue identifies comparatively low values, red identifies comparatively high values. Color coding is set uniformly across the whole table (meaning that the darkest red is the highest value across the board, and darkest blue the lowest). All monetary values are in 2023 USD.
Source: this assessment, based on relevant literature, as indicated in the main text and further detailed in Annex 1.

Table 6 to Table 9 indicate that, excluding policy impacts (discussed below and in the next section):

- Production costs of petroleum based fuels (assuming no change in oil prices, values centered on an oil price of 95 USD/barrel oil paired with a 20% markup from refining and distribution for aviation fuels, and a 25% lower benchmark for shipping fuel[62]) tend to remain lower than those of alternative fuels.[63] This excludes effects of oil price volatility, which can be very significant, as demonstrated by historical development of oil prices, due to supply and demand dynamics influenced by economic and geopolitical factors (beyond the scope of this specific analysis).
- Biofuels are more likely to achieve greater cost competitiveness than other options. Their GHG emission abatement performances depend on the pathway, with better results for fuels derived from waste products, energy crops and cane (net of direct and ILUC effects, which can be very significant). Biofuels also come with significantly higher land use requirements than other alternatives, with values estimated in a range 40 to 220 times higher than the land needed for renewable hydrogen and e-fuels (Bakker et al., 2022).[64] Primary energy requirements of advanced biofuels from biochemical pathways also tend to be higher than for other fuels, and all biomass production is subject to additional uncertainty from the effects of climate change on crop-growing regions and long-term yields.
- Low-carbon electrolytic hydrogen can be produced at lower costs than the fossil fuel benchmark if it is derived from very low-cost, low-carbon electricity. Hydrogen from natural gas from specific pathways, requiring both CCS and low-carbon electricity inputs, can, under specific technical conditions (low methane emissions, strict design of conversion plants, high capture or storage rates), also be low-carbon. It requires natural gas to be available at low costs (comparable to those seen in the US and below those in place in the EU) to compete with the fossil fuel benchmark. Production cost of low-carbon hydrogen from natural gas is negatively affected by the need for CCS and also highly sensitive to natural gas costs.
- All forms of low-carbon hydrogen come with much lower land-use and water requirements than biofuels.[65] Input/Output energy ratios are higher for options based on natural gas than for options reliant on renewable electricity. However, hydrogen from natural gas requires less renewable electricity per unit of energy contained in the hydrogen produced.
- Hydrogen production comes with better energy efficiency and lower land use requirements than its derivatives. However, transportation and distribution of

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[62] Shipping fuels tend to be significantly cheaper than aviation fuels, due to lower fuel quality requirements. The 25% difference between aviation and shipping fuels of fossil origin, as well as the USD 20/GJ and USD 15/GJ, are the same used in IEA (2023b).

[63] The analysis does not consider an increase nor a decrease of the fossil fuel cost, reflecting an agnostic assessment on the oil price developments. This is grounded on the consideration that there are both upwards and downward drivers affecting the oil price, dependent on factors beyond the scope of this report.

[64] Water requirements also tend to be higher, especially for food and feed crops, unless biomass growth can be mainly rainfed.

[65] Electrolytic hydrogen also tends to use less water than hydrogen from natural gas with CCS (IRENA and Bluerisk, 2023).

hydrogen can impose significant energy or economic costs.[66] This is especially challenging if demand for hydrogen across different energy end-uses struggles to scale up, as low demand is paired with significant unit cost increases.[67] The energy balance and operational cost profile of hydrogen is improved if hydrogen pipelines can be built for distribution, compared to systems that require liquefaction, but this requires large volumes of hydrogen to be moved between areas of supply and demand.[68]

- Carbon-containing liquid e-fuels that can be blended with petroleum-based ones have higher production costs than all other fuel options, but no or far lower infrastructure costs than hydrogen. E-diesel or e-kerosene can have low GHG emissions, despite high energy intensity, if they rely on low-carbon primary electricity that would not otherwise feed the grid. They could compete cost-effectively with hydrogen from renewables in cases where the sustainable availability of biofuels and PBtL is constrained. E-fuels can also offer greater GHG emission abatement than most bio-based fuels available at scale.
- E-methane, e-methanol and e-ammonia, which are potential alternative energy carriers for maritime transportation, have lower production costs than e-diesel and higher than hydrogen. Due to its liquid state, e-methanol has lower delivery costs than e-methane, compensating higher production costs and resulting in similar total costs.
- RCFs (using point-source CO and CO_2 produced from liquid or solid waste streams of non-renewable origin or waste processing gases) or carbon-bearing e-fuels based on concentrated streams of biogenic CO_2 (hence included in RFNBOs, by EU definitions) cost less than e-fuels using DAC for carbon (also classified as RFNBOs, in the EU), but more than biofuels. Both RCFs and RFNBOs based on concentrated carbon streams are more energy efficient to produce than biofuels. RCFs and e-fuels require far less land than biofuels (Bakker et al., 2022). RCFs typically come with significantly lower GHG emission abatement capacity than low-carbon hydrogen and DAC-based e-fuels, as they do not rely on biogenic CO_2.
- E-ammonia can become available at production costs in the same range of biofuels and below those of carbon-containing e-fuels but higher than the hydrogen. It is also less energy- and land-intensive than biofuels (Bakker et al., 2022). Life-cycle GHG emissions can be very low if e-ammonia is produced from low-carbon electricity or other forms of very low-carbon hydrogen. Availability and scale advantages derive from the fact that ammonia does not contain carbon. Important challenges, including the feasibility of ammonia as a shipping fuel, where it is most discussed, costs, and the management of its high toxicity remain to be addressed.

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[66] Unless natural gas can be transported and CO_2 is stored locally: this is reflected in the lower infrastructure costs of lower-bound cost estimates, for hydrogen from natural gas.

[67] Such circumstances would make hydrogen the energy carrier with the highest cost, even in the long term.

[68] Pipeline construction also entails significant capital expenses, the need to secure right-of-way and navigate permitting approvals. These challenges are not only relevant for new pipelines, but also for repurposing of existing natural gas infrastructure (ACER, 2021a). For hydrogen from low-carbon electricity, this is also paired with risks due to competing alternatives, both to transport energy—in particular high voltage direct current (HVDC)—and for its end-use—via the direct use of electricity.

PBtL fuels combine features of biofuels (carbon of biogenic origin) and electrolytic hydrogen (reliance on primary renewable electricity) and can be seen as a combination of biofuels and RFNBOs, based on EU definitions. They may be able to come closer to cost competitiveness with the fossil fuel benchmark, especially where supportive policy is in place. The use of primary renewable electricity in the form of electrolytic hydrogen can enable PBtL fuels to be produced with reduced life-cycle GHG emissions (e.g., in the case of hydrotreated oils and fats) or to reduce the amount of biogenic carbon that is otherwise lost as CO_2 (e.g., in RFNBOs reliant on the recovery of CO_2 streams arising from biochemical biofuel production). If the renewable energy and hydrogen have particularly low production costs, this yield increase could come with net savings, in comparison with biofuels. GHG emissions, energy intensities and land use requirements are dependent on the specific feedstock and energy conversion pathway. GHG emissions and energy use can be lower than for biofuels and primary energy requirements are higher than for hydrogen or direct electrification.

Importantly, energy carriers that require a change in infrastructure also need technological developments on the vessel side, leading to increased costs vs. technologies developed for hydrocarbons as energy carriers, in part also due to payload issues. This is not limited to fuel cells (a more energy efficient but costly alternative to combustion engines), but also includes on-board energy storage devices. These devices are especially challenging for hydrogen as an energy carrier, due to the extremely low temperatures needed for its liquefaction (below -253 °C at ambient pressure) or the extremely high pressures needed (more than 35 MPa, and more frequently 70 MPa, in automotive applications[69]) to increase its energy density.[70]

Ammonia and methane also come with higher investment costs on the vessel side, due to their gaseous state at ambient pressure and temperature, and—in the case of ammonia—its toxicity.[71] These same technologies also require major developments in terms of regulations and technical standards.[72]

3.2 Policy Characterization

Production, infrastructure-related and total delivery costs of low-carbon fuels are directly or indirectly affected by the US and EU policy frameworks to promote their deployment in aviation and shipping, discussed in Section 2. The effect of key policy instruments mentioned there are summarized in Table 10 to Table 14.

Table 10 and Table 11 refer to aspects related with the Inflation Reduction Act. Table 10 focuses on information on production credits for SAF, clean hydrogen and fuels produced from concentrated CO_2 streams or direct air capture (DAC). They are applicable to aviation (SAF and hydrogen-based options) or fuels used in maritime transportation (biofuels and all hydrogen-based options). Values in Table 10 for hydrogen reflect the 45V section of the IRA, for all pathways. These are relevant for hydrogen from natural gas. In this case, they cannot be stacked with the 45V credits for hydrogen production. This means that hydrogen from

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[69] See ITF, 2020 for a review of these aspects regarding the case of heavy duty road vehicles.
[70] These same physical constraints pose challenges for the long distance transportation of hydrogen (IRENA, 2022, ACER, 2021b and Kneebone & Piebalgs, 2023).
[71] See Kass et al., 2021 for a review of challenges associated with different fuels for maritime transport.
[72] IMO, 2023 provides a summary of recent and expected developments for the case of maritime transportation, where there is strong interest in hydrogen derivatives, in particular methanol and ammonia, as energy carriers alternative to hydrocarbons.

natural gas needs to select which one applies (on the contrary, e-fuels can leverage both 45V credits for hydrogen and 45Q credits for CO_2 capture and utilization or DAC). Krupnick & Bergman, 2022 show that the 45V credits (used in Table 10) align with a 70% GHG emission abatement for hydrogen. They also show that 45Q credits, applicable to cases with lower life-cycle emission reductions, are lower. Credits for biofuels are available first (up to the end of 2024) as extensions of previous credits, and then through 2027 via the more general Clean Fuel Production Credits, which apply only for pathways with low life-cycle emissions.[73] They are considered here as applicable to maritime transportation, even if most of the maritime transportation fuels fall out of the scope of the RFS and, in California and other LCFS states, also of the LCFS (see discussion in Section 2). SAF incentives are dependent on carbon intensities, valid until the end of 2024, then integrated in the more general clean fuel production credits, applicable after 2025 and until the end of 2027.

Table 11 defines multipliers to be applied to the clean hydrogen credit for hydrogen derivatives including e-fuels; hydrogen-related incentives can significantly affect e-fuel economics because their production requires large amounts of energy in the form of hydrogen with respect to their own energy content. The Table focuses on advanced plants with significant system integration and heat recovery (needed for greater cost effectiveness for direct air capture of CO_2 [DAC]) in place. This type of production facility, described in Soler et al. 2022, informs the values used for the characterization of GHG emission and energy efficiency of these fuels.

The values in Table 11 are used to define how clean hydrogen credits are reflected in the case of hydrogen derivatives, excluding other eventual credits from DAC and CCS. The latter are added only for e-fuels and not for CCS associated with hydrogen production from natural gas.[74]

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[73] The minimum carbon intensity reduction required to be eligible for Clean Fuel Production Credits is 50%. Preliminary guidance regarding the methodology by which this will be assessed has been released, however a final version was not available at the time or writing (IRS, 2024, US Department of the Treasury, 2024, US DOE, 2024). It offers pathways for continued reliance on crop-based feedstocks, subject to the use of climate smart agricultural practices.

[74] Hydrogen production itself can also rely on carbon capture. In such a case, the IRA credit for clean hydrogen production (45V) is non-stackable with those for CO_2 sequestration (45Q) (US Congress, 2022). Soler et. al, 2022 indicate that CO_2 costs contribute for about 3% (for concentrated sources) to 10% (for DAC to e-fuel) of the production cost, considering CO_2 supply costs close to USD 60/t and USD 160/t, respectively, for concentrated sources and DAC. These values are in the same range of the 45Q IRA credits for CCS and DAC for facilities that meet prevailing wage and registered apprenticeship requirements (US Congress, 2022): USD 60/t for CCU from concentrated sources and USD 130/t for DAC for CCU. Soler et. al, 2022 estimate that CO_2 supply has an impact close to 4 USD/GJ in DAC to e-fuel facilities. On this basis, the quantitative analysis of policy impacts developed in the following section, focusing on DAC-based pathways for e-fuels, accounts for 4 USD/GJ of 45Q credits, adding them to the 45V credits related with electrolytic hydrogen from very low-carbon electricity, also needed for e-fuel production. Impacts of IRA credits for other fuels using hydrogen as a feedstock, in combination with CO_2 from concentrated sources (and therefore CCU), are below 1 USD/GJ, according to Soler et. al, 2022. These are factored in the analysis developed here, in combination with 45V credits from electrolytic hydrogen from very low-carbon electricity, in the case of recycled carbon fuels (RCFs).

Table 10. IRA production credits.

Energy/fuel type	Credits			Units	Conditions/Notes
	Before 2030	Near-term (2030)	Long-term (post 2040)		
Ethanol, until 2024[75]	0.5	-	-	USD/gallon	Extension of Tax Credits for Alternative Fuels
Other biofuels, until 2024	1	-	-	USD/gallon	Extension of Second-Generation Biofuel Incentives and Tax Credits for Biodiesel and Renewable Diesel.
Clean Fuel Production Credit (45Z), 2025-27	0 to 1	-	-	USD/gallon	For fuels whose life-cycle GHG emissions are lower than 50 kg CO_2/MMBtu (47.4 g CO_2/MJ), proportional to excess savings
SAF (40B, until end 2024)	1.25 to 1.75	-	-	USD/gallon	From 50% to 100% life-cycle GHG emission reduction vs. fossil fuel benchmark
Clean Fuel Production Credit, SAF (45Z), 2025-27	0 to 1.75	-	-	USD/gallon	For SAF whose life-cycle GHG emissions are lower than 50 kg CO_2/MMBtu (47.4 g CO_2/MJ), proportional to excess savings
Clean hydrogen (45V)	0.6		-	USD/kg H_2	Between 2.5 and 4 kg CO_2e/kg H_2
	0.75		-		Between 1.5 and 2.5 kg CO_2e/kg H_2
	1		-		Between 0.45 and 1.5 kg CO_2e/kg H_2
	3		-		Below 0.45 kg CO_2e/kg H_2
Carbon capture and utilization (CCU) (45Q)	60		-	USD/t CO_2	From concentrated sources, for recycled carbon fuels (RCFs)
	130		-		From direct air capture (DAC), for e-fuels

Note: where relevant, values reflect cases when production facilities meet prevailing wage and registered apprenticeship requirements. All monetary values are in 2023 USD. State-specific credits are not included.
Sources: The White House, 2023, US Congress, 2022.

Table 11. IRA hydrogen (45V) credit multipliers for hydrogen derivatives.

Energy/fuel type	Multiplier
E-hydrocarbon	1.23
E-methanol	1.15
E-methane	1.19
E-ammonia	1.13

Note: accounting for hydrogen feedstock requirements and energy efficiency gaps vs. the production of hydrogen as energy carrier.
Source: based on Soler et al. 2022 and also informed by FVV, 2021, Liu et al., 2020, Bakker et al., 2022, IRENA, 2022a and Bicer at al., 2016.

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[75] Not applied

Table 12 and Table 13 focus on the European policy framework. They summarize aspects related with carbon pricing, via the ETS (reflecting current and expected values for the ETS credits), regulatory requirements in RefuelEU Aviation and FuelEU Maritime (considering a life-cycle accounting, covering well-to-wheel emissions and energy efficiency correction factors) and non-compliance penalties included in these regulations.

Table 12. Carbon pricing and non-compliance penalties in the EU policy framework.

ETS credit price	Currently close to 80 EUR/t CO_2; assumed at 80 EUR/t in 2025 100 EUR/t CO_2 in 2030 and 200 EUR/t CO_2 in 2050. This is applicable to fossil fuels, while biofuels and other fuel options compliant with the Renewable Energy Directive are not subject to ETS CO_2 prices.	
Non-compliance penalty	Aviation	At least twice as high as the difference between alternative and conventional fuel, with differentiated values for SAF and RFNBOs or synthetic fuels (hydrogen and its derivatives)
	Maritime	2400 EUR/t of very low sulfur fuel oil (59 EUR/GJ)

Note: All monetary values are in 2023 USD. Biofuels compliant with the sustainability criteria established by the Renewable Energy Directive are not subject to ETS CO_2 prices (European Commission, 2024b). Biofuels, e-fuels (RFNBOs) and RCFs shall also be treated equally in the ETS (German Emissions Trading Authority, n.d.) and they are not subject to a carbon price, at least until a specific implementing act dealing with RFNBOs and RCFs is adopted (European Union, 2003). For aviation, this excludes the impact of the 20 million SAF allowances. The latter has been estimated at roughly one fifth of the total mandated by RefuelEU Aviation (Berg, 2023), but estimates depend on the fuel considered, its cost and the CO_2 price.
Source: Authors assessment based on European Union, 2023d, European Union, 2023e and Safety4Sea, 2023.

Table 13. Regulatory requirements in the EU policy framework.

	Maritime		Aviation	
Year	**Life-cycle GHG emission reduction**	**RFNBO shares**	**SAF shares**	**RFNBO shares**
2025	2%	-	2%	-
2030	6%	1% by 2031 or 2% by 2034	6%	1.2%
2035	16%		20%	5%
2040	31%		34%	10%
2045	62%		42%	15%
2050	80%		70%	35%

Note: synthetic aviation fuel shares for 2030 to 2034 need to exceed annual values of 0.7%/year and reach an annual average of 1.2% across the 5 years.
Source: European Union, 2023d and European Union, 2023e

Table 14 focuses on California's LCFS, the largest of the LCFS policies in place in the US. This has a similar dynamic to the EU policy framework, combining carbon pricing, GHG emission reduction requirements, on the basis of a life-cycle accounting and energy efficiency correction factors, and non-compliance penalties, but with important exclusions in aviation and maritime.

- Fuels used on ocean-going vessels with engines having cylinder capacities above 30 L are out of the LCFS scope. This means that only a fraction of the fuels included in maritime transportation can receive LCFS credits. This same fraction of fuels is within the scope of sector-wide (not just maritime) regulatory requirements and non-compliance penalties (the same conditions apply in Oregon; maritime is excluded in Washington State).

- As an opt-in fuel, jet fuel can receive LCFS credits but it is not subject to non-compliance penalties (the same conditions apply in Oregon and Washington State).

Table 14. Carbon intensity, pricing and non-compliance penalties in California's Low Carbon Fuel Standard (LCFS).

Carbon intensities	**Reduction of 11.25% in 2023 and 20% in 2030 vs. life-cycle baseline (89 g CO_2/MJ)**
Cap-and-trade and LCFS credit prices	The LCFS credit price is currently close to 50 USD/t CO_2, assumed at 60 USD/t for 2025 and at 80 USD/t CO_2 in 2030.[76] The LCFS credit price is capped at 261 USD/t CO_2 (after adjustment for inflation. A cap-and-trade price is also applicable to emissions for fossil fuels from refining.[77] Values considered here are 40 USD/t CO_2 currently and 50 USD/t CO_2 in 2030.[78]
Non-compliance penalty	The LCFS credit price cap (200 USD/t CO_2, inflation adjusted, starting in 2016 and now beyond 260 USD/t) acts effectively as the non-compliance penalty. A 1,000 USD/t CO_2 could technically be the penalty in a case of major dysfunctions in the market or in the case of fraud. As only a portion of maritime fuel is covered by the LCFS, the credit price cap is what is considered here as the penalty (and only for the part of maritime fuel covered, not for aviation, as it is only opt-in).

Note: All monetary values are in 2023 USD.
Source: based on Huson et al., 2020, CARB, 2023, CARB, 2024c, CARB, 2024b and CARB, 2020.

Infrastructure-related policy impacts are integrated in ranges used for infrastructure cost assumptions (Table 8). Policies aiming to absorb investment costs—as in the case of Investment Tax Credits (ITC) in the IRA (see for instance Sadler, 2023 on SAF) and the BIL and NextGenerationEU support for infrastructure investments—can bring infrastructure costs closer to the lower-bound of the range considered in Table 8 (and therefore also help moving towards the lower bound of Table 9).[79] These policy impacts are not explicitly accounted for here, due to the variability of the impacts that they may have on specific infrastructure investments.

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[76] The LCFS credit price values are consistent with the current prices indicated by CARB, 2024b and the rates of increases shown for carbon prices by CARB & MELCCFP, 2023. While CARB has announced forthcoming amendments to the LCFS, including a higher target and auto acceleration mechanism, that are intended to increase the credit price, recent modelling indicates that they proposed changes are unlikely to achieve this effect (Murphy and Ro, 2024).

[77] For the well-to-tank component, the application of this is different for oil produced in California or imported. The analysis developed here takes a simplified approach, applying the cap-and-trade to 1.2 times the embodied carbon content of the amount of fuel used, converted to CO_2 equivalents.

[78] The cap-and-trade prices considered are consistent with the current prices indicated by CARB, n.d.d and the rate of increase shown for carbon prices by CARB & MELCCFP, 2023.

[79] For simplicity, the combined effect of more (or less) optimistic production costs for different fuels, and more (or less) optimistic infrastructure-related costs, is what determines the ranges characterizing the total cost, in Table 9. Other combinations, such as optimistic production costs and conservative infrastructure costs, fall within the ranges used and are not explicitly represented.

4. Analysis of Policy Impacts

The combined impacts of all parameters summarized in Table 6 to Table 14 and the discussion developed in Section 3 inform the results outlined in this section, which focuses on the analysis of different policy formulations on the cost competitiveness of different fuels, in the current and 2030 timeframe.

Figure 2 to Figure 8 illustrate what happens combining the technical assessments illustrated in Table 6 to Table 9 for forms of energy that are suitable for shipping and/or aviation and the effects of the policy mechanisms summarized in Table 10 to Table 14.

Results are shown focusing on life-cycle GHG emission reductions and cost differentials between a fossil benchmark and the alternative options. This has the advantage of offering a technology-neutral basis for the comparison of different fuel options, with the caveat that some fuels are subject to further differences in costs on the vehicle side (e.g., due to on-board storage and conversion technologies, not factored in in this assessment).

The best options are located on the top-right of the charts because these represent cases with net gains in terms of costs and largest GHG emission savings. Results are presented first (Figure 2 to Figure 6) looking at the 2030 timeframe, and then (Figure 7 and Figure 8) considering a post-2040 cost assessment. Each figure contains two subsets of data: the first refers to maritime transportation, the second to aviation.

Figure 2 reports results in the absence of any policy action for 2030. Figures 2 through 5 show the impact of different policies on costs in 2030:

- Figure 3 reflects changes associated with the IRA, in the US.[80]
- Figure 4 focuses on the impacts of EU policies, combining the ETS integration and the regulatory requirements of RefuelEU Aviation and FuelEU Maritime.
- Figure 5 focuses on the policy framework in place in California, combining a cap and trade and the Low Carbon Fuel Standard (LCFS).
- Figure 6 adds the effect of the IRA (also applicable to California) to Figure 5.

Figure 7 and Figure 8 show the same results as Figures 2 and 4, respectively reflecting policy effects for a post-2040 timeframe. Due to the lack of clear, long-term policy protocols, or even binding GHG targets at the US level, there is insufficient data from which to project long-term impacts of US policy.

Insights from Figure 2 are those already highlighted in Section 3, as the Figure is a graphical representation of the same results shown in Table 6 and Table 9, for 2030.

Importantly, results show significant variability for gaseous hydrogen in comparison with other fuels, reflecting both opportunities (e.g., in cases where feedstock, electricity, transportation, storage and distribution costs are all in the lower end of their range) and

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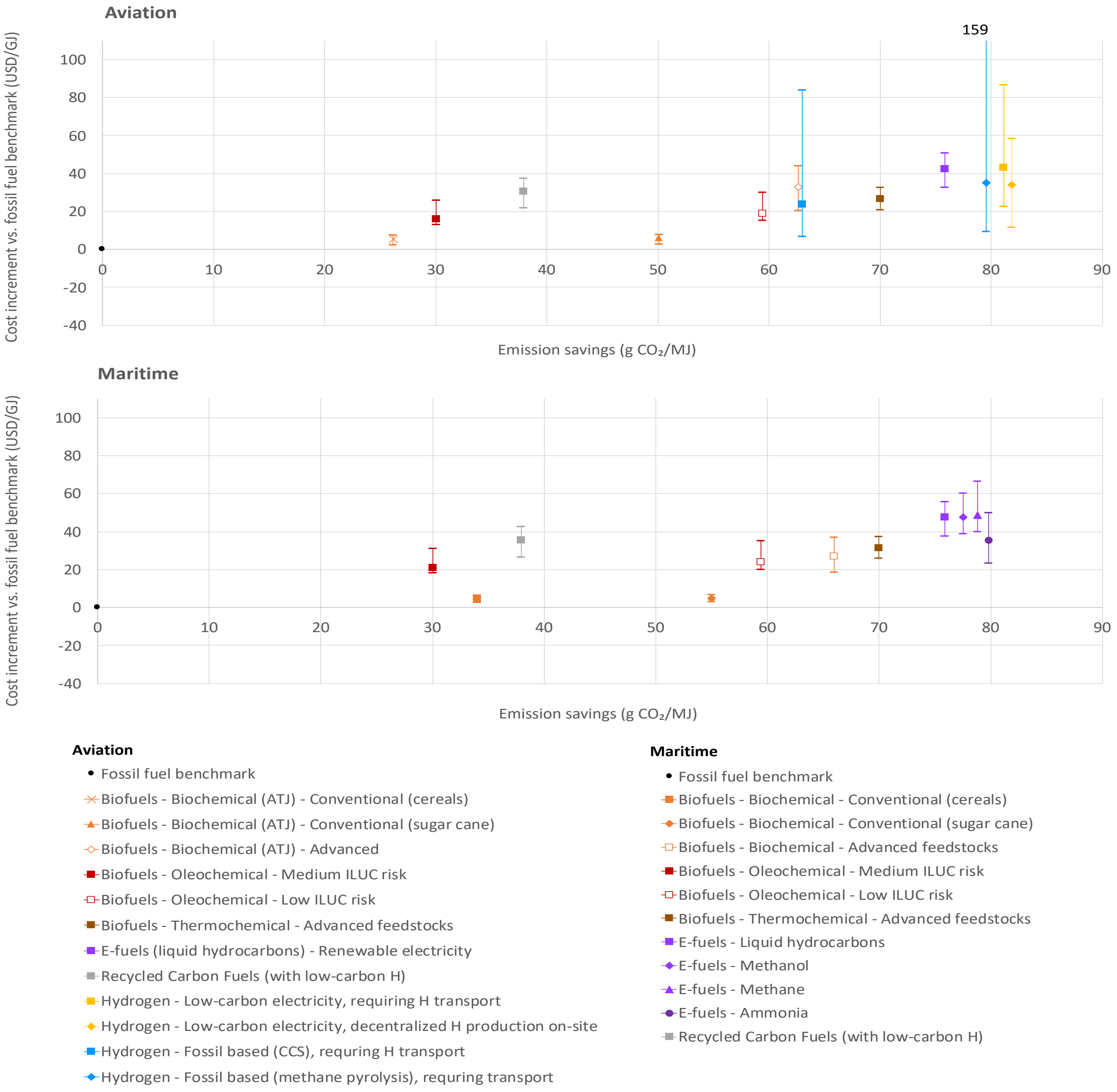
[80] Note that Renewable identification numbers (RINs) are credits used for compliance with the RFS; they have a small and highly uncertain impact on SAF economics, and a minimal impact on marine fuel economics. On the other hand, the SAF credits available in Illinois (available from 2023 to 2032 and targeted to pathways based on domestic biomass resources—namely ethanol based ATJ, after 2028) are additional to what has been considered here and having a cost saving impact equivalent to 10.8 USD/GJ. This is not included in the figures, as it is state-specific.

risks (e.g., in cases where primary energy needed are at the upper end of their range or infrastructure costs struggle to be shared across large production volumes). This is a feature that is not a function of the specific policy framework. It is therefore also visible in Figure 3 to Figure 6, representing specific policy cases.

Figure 2. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, no policy case, near-term (2030).

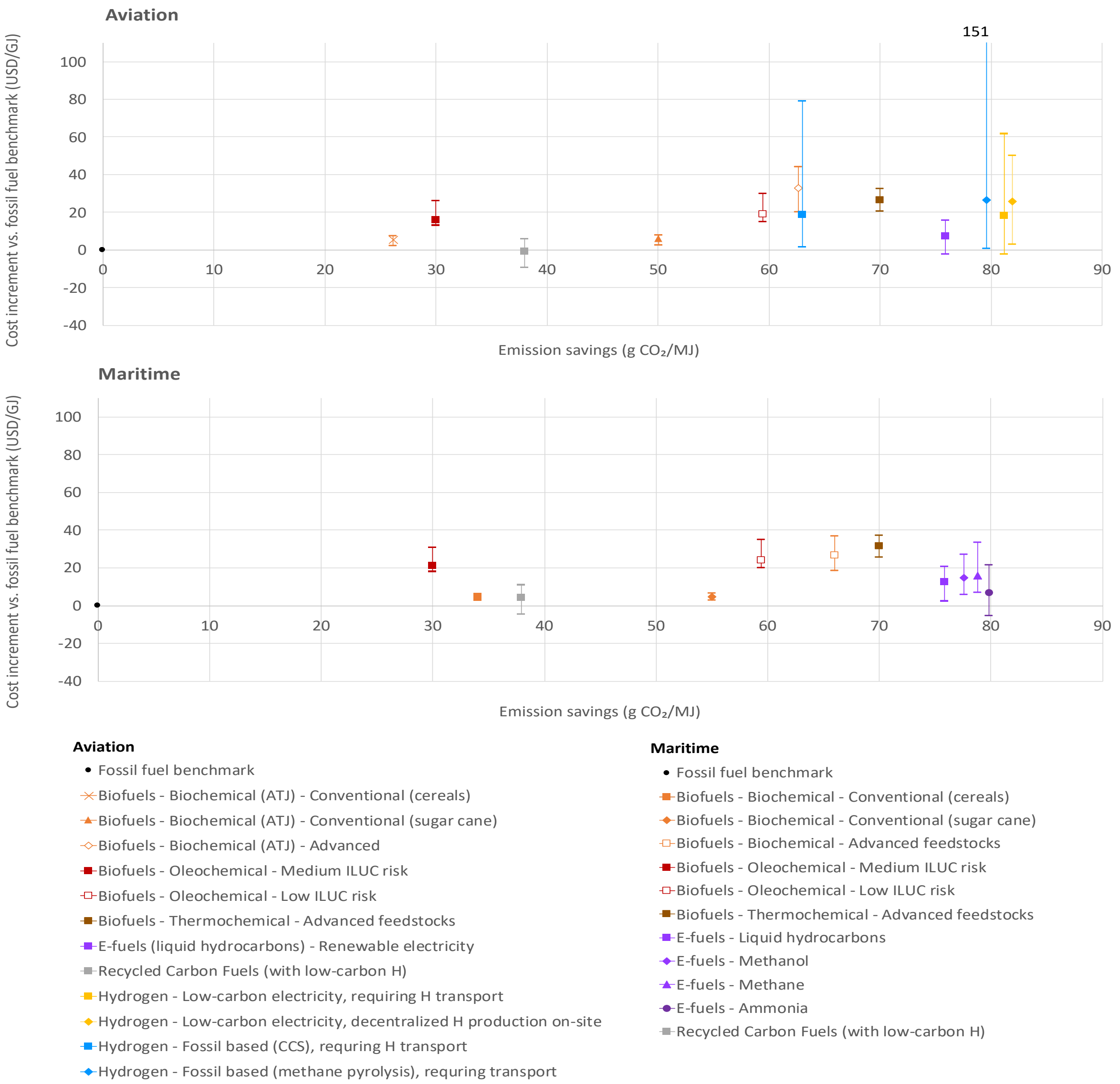


Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. Biofuel pathways from sugar cane are based on production costs in Brazil and they are relevant as import options.
Source: this assessment.

4.1 United States, 2030

Production credits available from the IRA are reflected in the net costs shown in Figure 3. In comparison with Figure 2, IRA credits shift results towards the achievement of cost competitiveness, with stronger impacts for options that have lower life-cycle GHG emissions.

Figure 3. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, showing the impact of production credits available from the IRA, near-term (2030).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9, to which the policy effect (essentially consisting in credits, for the IRA) are subtracted. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. The calculation accounts for hydrogen and carbon needs, as well as specific credits applicable to hydrogen (45V), in particular, in line with the indications outlined in the discussion regarding Table 10 and in the main text. Lower and upper bound are represented at the top and bottom of the whiskers in the Figure, for each fuel. The central estimate is shown by the central marker. No credit is applied to pathways based on sugar cane (only relevant as an imported option, based on production costs in Brazil).
Source: this assessment.

IRA credits have significant impacts on hydrogen and its derivatives, as the hydrogen-based options considered in Figure 3 are capable to meet the best GHG emission abatement foreseen in the legislation[81] and as biofuel or SAF credits are not currently foreseen beyond 2027.[82] Policy effects are generally stronger for pathways that offer greater GHG emission savings. The production of hydrogen from methane reforming with CCS or methane pyrolysis, with low natural gas prices, and hydrogen from renewables at low electricity costs are all capable to achieve cost competitiveness, as shown in Figure A2.2 of Annex 2. The IRA credits ensure that this does not only happen in cases with the most optimistic cost estimates (as in the case of no policies, shown in Figure A2.1).

However, while production cost gaps can be bridged by the IRA incentives, there are still infrastructure costs for hydrogen transport, storage and distribution to overcome. Comparing Figure A2.2 with Figure 3 shows this effect, as the IRA credits help bridge costs gaps between petroleum and lower-carbon alternatives for aviation and maritime fuels. The gap does not entirely close, however, unless primary energy costs are at or near the low end of their possible range and infrastructure utilization rates are at or near the high end of their possible range, thereby spreading costs across a larger base. Differences between production cost and total cost differentials, including infrastructure, are particularly apparent for hydrogen and other options not already used as energy carriers in shipping and aviation.

Absent the materialization of best-case assumptions or other policies complementing the IRA, we would not expect to see significant deployment of lower-carbon fuels in shipping and aviation in the US.[83] Complementary policies that can help eliminate the remaining cost gap for low-carbon hydrogen and its derivatives for shipping and aviation could include the elimination of fossil fuel subsidies, in favor of carbon pricing and other forms of taxation, or targeted measures strengthening incentives for alternative fuels, or the combination of taxation/pricing mechanisms for GHG emission intensive technologies and incentives for low-carbon options; a federal LCFS may also be able to help close the remaining price gap. As cost competitiveness in the near-term cases is only approached in cases with optimistic

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[81] Note that this occurs despite values of life-cycle GHG emissions reported in Table 6 that are not zero, for hydrogen. The reason lies in differences in system boundaries between what determines IRA credits (excluding the construction of the production facilities needed to produce hydrogen and upstream energy, and only limited to operational energy requirements) and the values (detailed in Annex 1) reported in the sources used to characterize different options in Table 6.

[82] In the case the clean fuel and SAF production credits were to be extended, pathways emitting less than 50 kg CO2/MMBtu (47.4 g CO2/MJ) would be subject to credits, but impacts would be capped below 8 USD/GJ for biofuels with 100% emission reductions vs. the fossil benchmark and 12.5 USD/GJ for SAF, meaning that biofuel production pathways based on advanced feedstocks (e.g., reliant on forms of waste that do not risk to increase ILUC, and/or enable net increases in soil carbon storage and have positive impacts on biodiversity), would still be subject to a price premium.

[83] Figure 3 also shows that the additional 10.8 USD/GJ credit introduced in Illinois could support the closure (or at least the narrowing) of the cost gap for ATJ technologies, but only in cases where GHG emissions from feedstock production and the conversion process enabling the production of aviation fuel can be effectively reduced well beyond values emerging from the work of ICAO and other life-cycle assessments, which underpin the assumption used for GHG emission savings in this work and as long as this happens without substantial increases in feedstock and conversion process prices.

cost assumptions additional actions such as the removal of fossil fuel subsides and/or carbon pricing (or both) will be needed to mobilize a transition in the fuel mix.

Regulatory requirements would probably be the most effective instrument capable of mobilizing investments on low-carbon fuel supplies and provide the greatest certainty that GHG emissions reductions would actually occur. Such requirements could level the playing field in terms of cost competitiveness across different end users of the fuels, without hampering opportunities to ensure overcompliance following voluntary action. The economies of scale developed by companies to meet ambitious regulatory requirements could result in lower costs in the long run, but still likely higher than fossil fuels. Limiting end-user cost increases in this kind of scenario would also require that the available opportunities for cost reductions are passed along from producers to consumers (requiring competition and dedicated policy arrangement, especially in cases where price competition between alternative fuel suppliers may be limited. However, there may be significant costs associated with the capital needed for companies to scale up lower-carbon alternatives.[84]

Other policies and market developments are also important to bridge the infrastructure cost gap. The need for infrastructure investments is especially relevant to support new energy carriers, such as hydrogen, ammonia and methanol. This comes with important challenges to achieve scale, as low volumes of alternative fuels result in higher unit costs. Declining costs with increasing volumes of fuel delivered magnify the necessity for large-scale demand to reduce unit costs of infrastructure investments for fuels requiring the deployment of new transport, storage and distribution facilities.

Due to the significant technical challenges associated with transport, storage and distribution of hydrogen, and related costs, it is important to maintain receptiveness to PBtL and hydrogen derivatives, i.e., e-fuels/RFNBOs to complement sustainable biofuels where direct electrification is not cost competitive or technically viable, rather than an exclusive focus on hydrogen alone.[85] Advantages could be largest for options compatible with existing infrastructure (such as sustainably produced biofuels, PBtLs or liquid e-hydrocarbons. Biomethane or e-methane may play a role, but this is likely limited due to infrastructure limitations and low potential production capacity for biomethane).[86]

International coordination is also important in shipping and aviation to mitigate risks for infrastructure-related investments, whether or not they are covered by complementary policies.

4.2 European Union, 2030

Figure 4 summarizes implications from the EU policy framework on aviation and maritime fuels for 2030. The Figure restricts the fuel options to those eligible under the regulatory requirements of RefuelEU Aviation and FuelEU Maritime (excluding food- and feed-based biofuels and only including RCFs and synthetic fuels from renewable and – for aviation –

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[84] Other alternatives include voluntary actions by stakeholders to transition to more expensive low-carbon options (a solution that comes with advantages in terms of reduced climate policy risk, but also disadvantages in terms of scalability and cost competitiveness).

[85] PBtL fuels are indirectly supported by the IRA (as they need low-carbon hydrogen) and implicitly integrated in the RFS via advanced biofuel options, but considered as standalone entities.

[86] Similar considerations apply to other energy end-use sectors., where alternative energy carriers are likely to see direct competition from electrification (e.g., on-road vehicles and in buildings).

nuclear energy[87]). It considers the impact of price signals by the ETS, based on a 100 EUR/t CO_2, applicable to fossil-based fuels and not to alternative options that also qualify for RefuelEU Aviation and FuelEU Maritime regulatory requirements.[88] It does not include the effect of SAF allowances (meant to help close the price gap for aviation fuels, but in a way that is still subject to uncertainties[89]), not the effect of the revisions of the Energy Taxation Directive, proposed in the context of the 'Fit for 55' package but not unanimously agreed upon by the European Council.

Figure 4 shows that the price impacts from the ETS and noncompliance penalties from RefuelEU Aviation and FuelEU Maritime (resulting in vertical shifts in the cost differentials in the Figure, with respect to Figure 2) is not sufficient to close the price gap with the fossil fuel benchmark.

On the other hand, the significant non-compliance penalties introduced by RefuelEU Aviation and FuelEU maritime have very significant implications to generate demand for low-carbon shipping and aviation fuels. The reason is that these penalties generate significant economic impetus to bring alternative fuels to market (within the limits imposed by regulatory requirements), as doing so is far more attractive for regulated entities than paying the penalty.

In Figure 4, the effect of the penalties (shown with the horizontal dashed lines) is similar to an upward offset of the horizontal axis, bringing alternative fuel options into the space of net economic gains (as they are in many cases below the dashed lines) with respect to a scenario in which regulated entities take no action (hence having to pay the penalties). If a fuel's cost penalty (y-axis value) is above the horizontal dashed line for noncompliance penalties, that indicates a situation in which a regulated party would have an economic reason to prefer paying the noncompliance penalty rather than opting for even-more-expensive compliance options.

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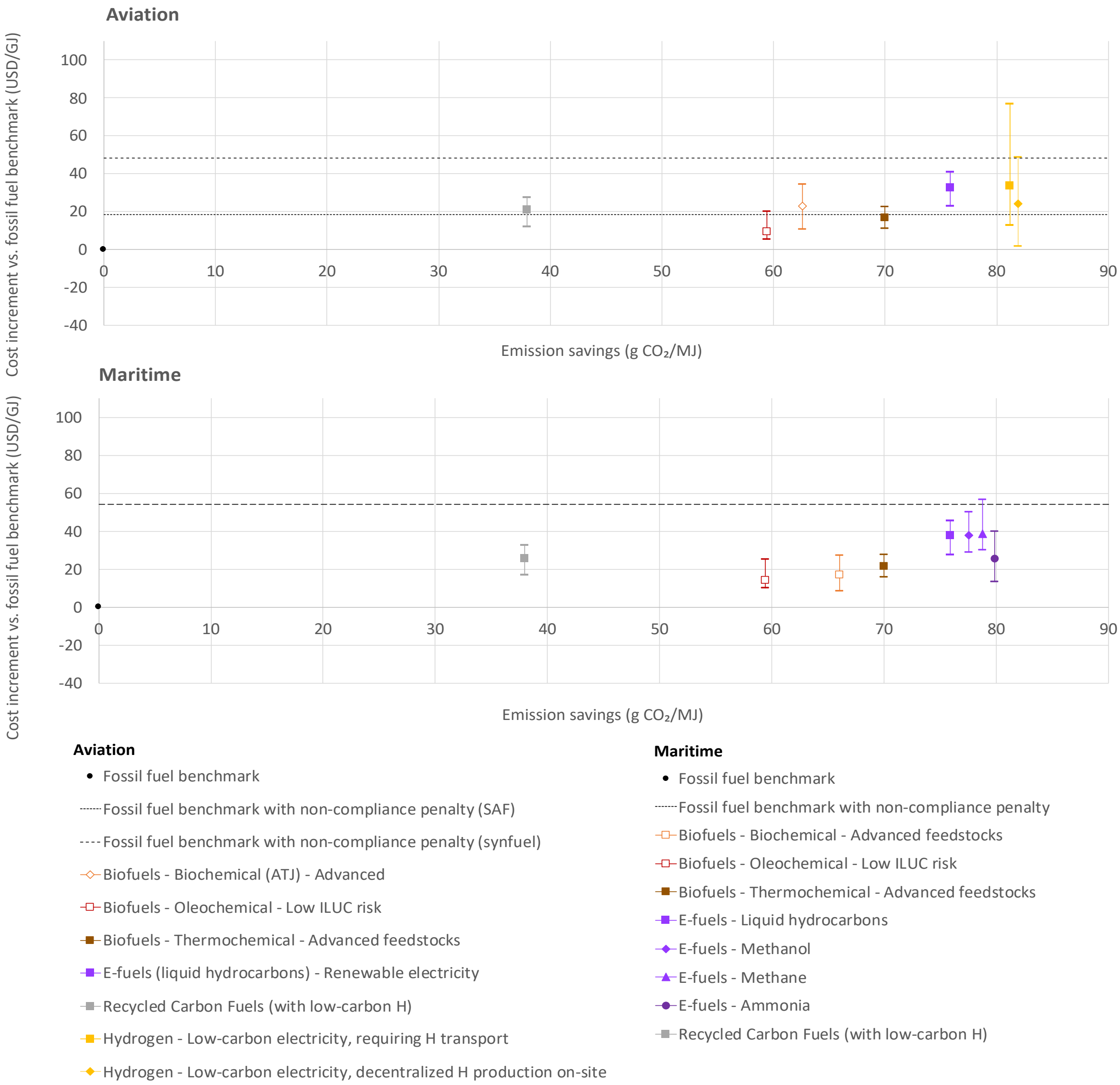
[87] See Table 4 and Table 5 for details.

[88] Biofuels compliant with the sustainability criteria established by the Renewable Energy Directive are not subject to ETS CO_2 prices (European Commission, 2024b). Biofuels, e-fuels (RFNBOs) and RCFs shall also be treated equally in the ETS (German Emissions Trading Authority, 2024) and they are not subject to a carbon price, at least until a specific implementing act dealing with RFNBOs and RCFs is adopted (European Union, 2003). For this reason, this assessment focused on fuel options compliant with RefuelEU Aviation and FuelEU Maritime, alternatives to fossil fuels are not assumed to be subject to carbon pricing (i.e., are considered zero emission, for the purpose of the ETS). For fossil fuels, the carbon price is applied to the life-cycle emissions, as the refinery sector (upstream or aviation and maritime) is also within the ETS scope (as aviation and maritime transportation).

[89] One estimate (mainly considering oleochemical conversion of waste oils and animal fats) considers that SAF allowances could close 20% of the price gap between eligible SAF (Berg, 2023). Another, considering an (unlikely) full allocation of the allowances to synthetic aviation fuels, is close to 80% of their cumulative cost gap (O'Malley, 2024).

Figure 4. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, showing the impact of the EU ETS and non-compliance penalties in RefuelEU Aviation and FuelEU Maritime, near-term (2030).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. Horizontal lines reflect costs imposed by non-compliance penalties in RefuelEU Aviation and FuelEU Maritime, shown in Table 12, based on the central estimate of alternative fuel cost prices (for aviation, the penalty is equivalent to twice the gap between the least cost alternative and the fossil fuel benchmark, for SAF and synthetic aviation fuels, separately). For the 2030 case and synthetic fuels, the line accounts for the arithmetic average of the lowest cost of hydrogen and e-fuels. The effect of SAF allowances is not integrated in this Figure.
Source: this assessment.

Based on the results of Figure 4, the current setup of non-compliance penalties is more effective to yield net economic gains for regulated entities (in particular fuel suppliers) choosing to invest in SAF rather than paying the penalties, in comparison with the IRA, as long as the penalties are more expensive than choosing to invest. However, results are not clear cut for thermochemical and biochemical pathways using advanced biofuel feedstocks, as the cost of production of oleochemical SAF (the cheapest form of biofuels, used to establish the non-compliance penalty) is appreciably lower.

If compared with Figure A2.3 Figure 4 also shows that infrastructure-related hydrogen costs are far from being negligible for aviation, and capable to make fuel costs of hydrogen-powered flights comparable with those of e-fuels.[90]

Feedstock availability remains another challenge that is not well reflected in cost analyses, including this one. Biogenic SAF is also subject to cost-related risks due to the mechanism of the noncompliance penalties, whose value is benchmarked on cheaper, oleochemical, aviation biofuels. As the penalty is based on the gap between fossil fuels and the average aviation biofuel cost (and, at least initially, this will correspond to cheaper options, despite limited scale), investment barriers may apply for oleochemical pathways if feedstock costs rise, as well as for advanced, biochemical or thermochemical, aviation biofuel pathways. As investment delays may arise also in cases where the origin of the feedstock (e.g., used cooking oil) and its conversion into aviation biofuels are located beyond the EU.

Competition with other supplies, resulting in a risk of a lower margins than initially anticipated and lower non-compliance costs, could well be one of the basis of recent decisions to delay investments in the EU in oleochemical aviation biofuel production by BP and Shell (BP, 2024 and Shell, 2024). This could be the case especially in light of signals of significant waste oil feedstock supplies and increased investments in aviation biofuel supplies in China (Biofuels international, 2024).[91]

The adoption of a sufficiently high floor value for the non-compliance penalty for SAF (and aviation biofuels in particular) can help handling these challenges, supporting the idea that the fundamental framework EU policy framework can be effective to induce growth in demand, in line with regulatory requirements.

Net of the effects of mitigating tools (in particular the SAF allowances), compliance with regulatory requirements is likely to come with costs that are likely to be passed to end-users, either in the form of higher airfares or as higher prices for maritime shipping services. Depending on how these costs are distributed across different parts of the society, there may be associated regressive or progressive impacts. As aviation is generally mostly consumed by people with higher income levels, regressive effects are likely to be limited, but attention to and management of these risks will likely be required.

Due to the reliance on carbon pricing, including the phase out of free CO_2 emissions allocations (net of SAF allowances), the EU policy framework also comes with greater capacity to ensure that users of shipping and aviation transportation services respond to price signals in cases where alternative fuels do not reach cost competitiveness, stimulating investments in energy efficiency and other systemic improvements and ultimately helping to increase the overall economic productivity of shipping and aviation services, despite risks to also contribute to an overall contraction of demand.

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[90] For hydrogen, additional costs can also arise from technology changes needed on the aircraft. Regarding infrastructure, usage rates have significant impacts, and novel concepts, including in particular the delivery of filled hydrogen tanks directly to aircraft and swap them with empty ones (Adler & Martins, 2023), are not part of this assessment.

[91] Signals of increased investments also apply to marine biodiesel, in China (Mysteel, 2024).

In aviation, price impacts in case of non-compliance can be limited by the differentiated non-compliance penalties in place for synthetic aviation fuels and aviation biofuels; adding a floor to the non-compliance penalty could help ensure that there are no market conditions under which non-compliance becomes the preferable option.

The mitigation of risks and inflationary pressures induced by price increases, in the EU policy, also depends on the effectiveness of complementary instruments—namely the Innovation Fund and research funds and, for aviation, the effect of the SAF allowances.

4.3 Focus on California, 2030

California's policy framework results from the combination of a cap-and-trade, the LCFS, and the IRA. The latter is applicable at the federal level, and therefore also in the State of California. The former applies a carbon price to industrial installations, including refineries and electricity generation plants, and to the carbon embodied in transportation fuels. It is only applicable to the part of maritime fuels covered by the carbon pricing mechanism (i.e., excluding ocean going vessels with large engines). The LCFS regulates carbon intensity and adds a mechanism attributing credits to transportation fuel technologies that reduce life-cycle GHG emissions below specified, annually declining target, and deficits to fuel options with a carbon intensity higher than that same target. Revenue from credit transactions under this system help incentivize the production and entry into the market for low-carbon fuels, by bringing down their price. The LCFS also creates a motivation for incumbent petroleum fuel providers to help low-carbon fuels enter the market, as that is the only way to generate the credits they need to satisfy their compliance obligation. It is only applicable to the same part of maritime fuels considered for the cap-and-trade, primarily diesel used in harbor craft and small vessels that operate near the shore. For aviation, the LCFS currently allows credit generation by SAF on an opt-in basis; proposed amendments would extend the deficit generating status to cover aviation fuel used within California starting in 2028. The IRA adds a layer of incentives, as discussed above, to the cap-and-trade and LCFS.

The effects of the cap-and-trade and the LCFS (shown in Figure 5 by vertical shifts for each alternative energy option vs. the data in Figure 2, bringing them towards better cost competitiveness) are similar to those induced, in the EU, by the combined effects of the ETS, the RefuelEU Aviation and FuelEU Maritime regulations and the Innovation fund. Differences lie in some of the details, including, in particular:

- The scope of application, which—for the LCFS—includes only a small part of the shipping sector (as it excludes large ocean-going vessels, with engine cylinders larger than 30 L)[92] and only considers aviation as an opt-in solution.
- The partial applicability of non-compliance penalties, as they are not relevant for the opt-in solutions in aviation (and hence not shown in Figure 5) and they only apply to the fraction of maritime transportation within the LCFS scope.
- The cost of non-compliance, far lower than in the EU. In the LCFS, an entity that does not have enough credits to meet its compliance obligation is obligated to purchase

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[92] This is also the case in Oregon, while maritime transportation is excluded in Washington State.

pledged credits at the ceiling price, currently 253 USD/t CO_2 and rising with inflation.[93]

The additional impact of the IRA, shown in Figure 6, leads to a narrowing of the cost gap for all options reliant on hydrogen, either as a feedstock (e.g., in e-fuels) or as an energy carrier. It brings hydrogen used as an energy carrier for aviation (net of the costs that occur on the aircraft side) beyond the cost competitiveness with the fossil benchmark, but only under optimistic assumptions.[94] It also brings ammonia as a shipping e-fuel in the same conditions, again considering optimistic cost assumptions.

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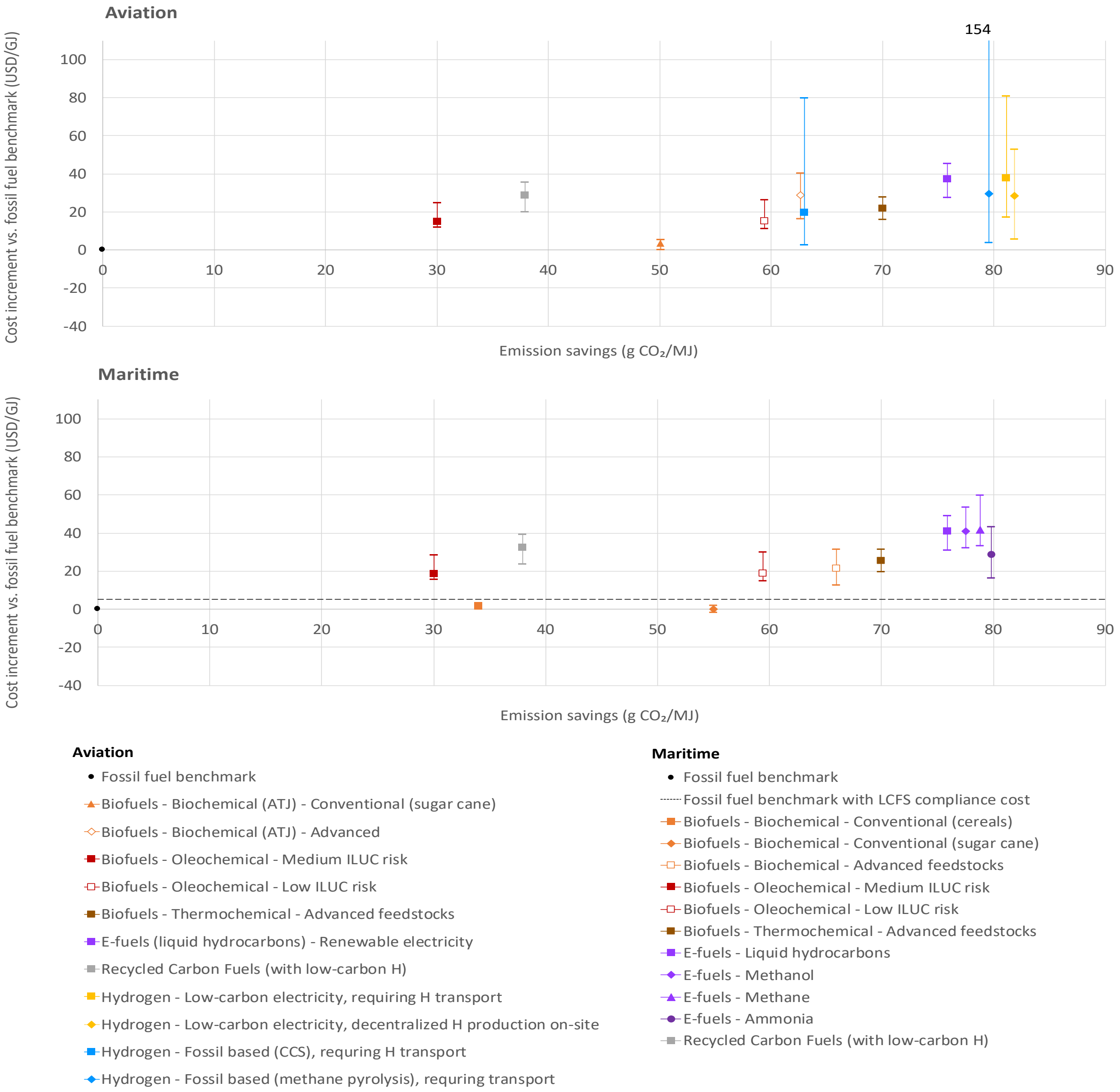
[93] In the extremely unlikely event that an entity cannot or refuses to do so, administrative fines of up to 1,000 USD/t CO_2, similar to noncompliance penalties in the EU for SAF of biogenic origin (if produced at scale) and much lower than the values for hydrogen-based fuels or the maritime sector, would be imposed.

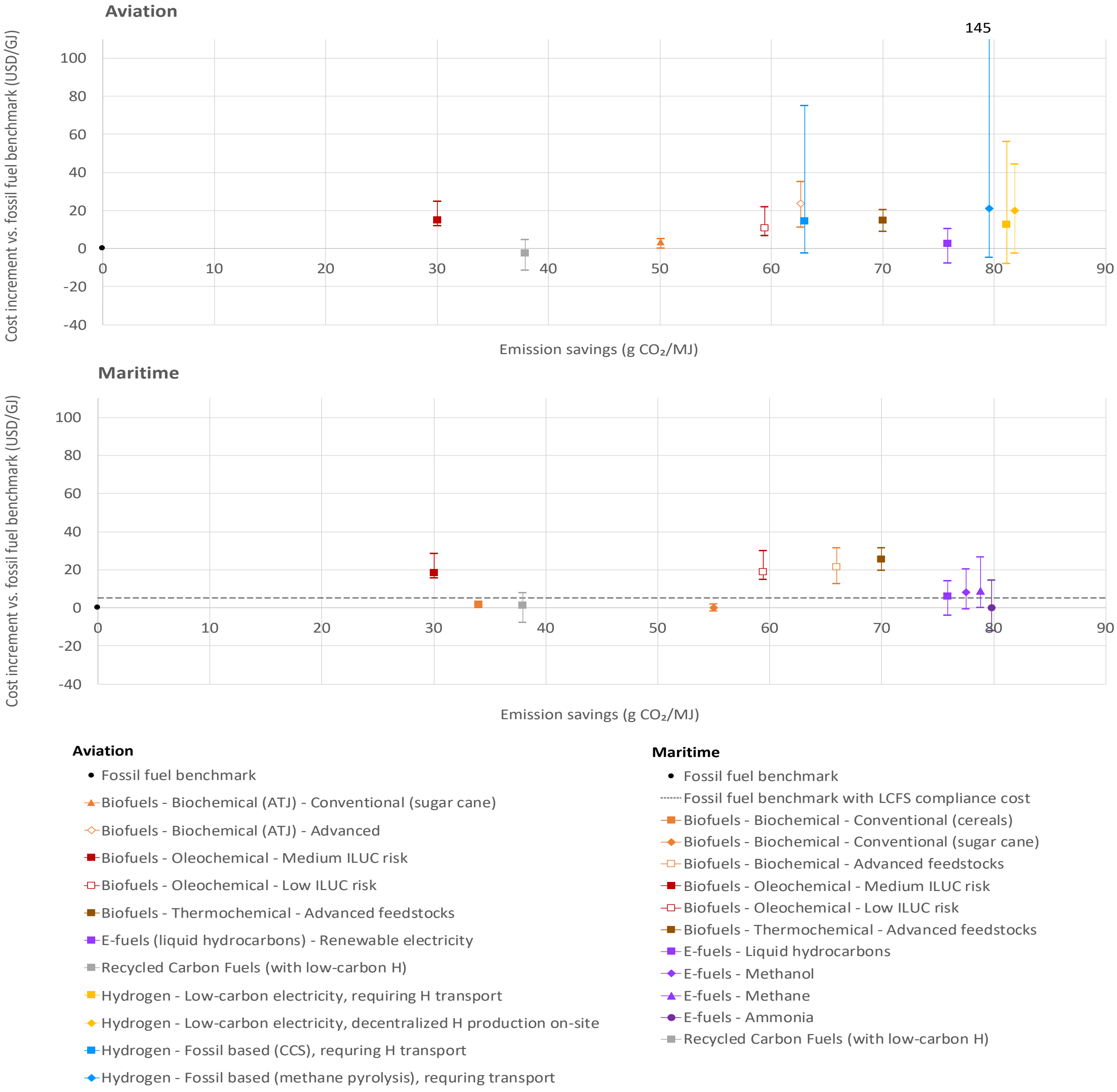
[94] Note that this threshold is exceeded, for electrolytic hydrogen and hydrogen from natural gas with low feedstock costs, if the focus is solely on hydrogen production, excluding infrastructure costs, as shown in Figures A2.4 and A2.5, for cases comparable with Figure 5 (focused on the LCFS) and Figure 6 (combining LCFS and IRA subsidies), respectively.

Figure 5. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, showing the impact of California's LCFS and its non-compliance penalty (where applicable), near-term (2030).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. The values reported for maritime transportation exclude the case of ocean-going vessels with engines with a cylinder capacity of more than 30 L, as the LCFS and the cap-and-trade do not apply in those cases. Cap-and-trade prices are only applied to the fossil benchmark for maritime. Biofuel pathways based on sugar cane are based on production costs in Brazil and they are relevant as import options. In the figure, they are subject to a carbon price, like all other fuel options. Horizontal lines reflect costs imposed by non-compliance penalties in the LCFS, shown in Table 14.
Source: this assessment.

Figure 6. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, showing the impact of California's LCFS and its non-compliance penalty (where applicable), in combination with IRA credits, near-term (2030).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. The values reported for maritime transportation exclude the case of ocean-going vessels with engines with a cylinder capacity of more than 30 L, as the LCFS and the cap-and-trade do not apply in those cases (bringing them back to a policy condition only influenced by the IRA, for the purpose of this analysis). Cap-and-trade prices are only applied to the fossil benchmark for maritime. Biofuel pathways based on sugar cane are based on production costs in Brazil and they are relevant as import options. In the figure, they are subject to a carbon price, like all other fuel options. Horizontal lines reflect costs imposed by non-compliance penalties in the LCFS, shown in Table 14.
Source: this assessment.

The different scope of application of the LCFS clearly limits its effectiveness at supporting low-carbon aviation and marine fuels. The reason is that the much larger road transportation fuel pool widens significantly the focus for alternative fuels producers. The market for low-carbon fuels for on-road vehicles is several times the size of aviation and marine fuels, providing many more opportunities to generate credits via the sale of fuels for on-road vehicles, with associated economies of scale from the larger production volumes.

Since LCFS credits are fungible across all modes of transportation, the volume of credits from on-road applications is likely to dwarf those from non-road ones under the vast majority of market conditions.

The rapid growth of light-duty electric vehicles over the next 1-2 decades, as well as in the availability of renewable diesel, can also create a massive present and future stream of LCFS credits. Even if the scope of regulation for the LCFS were expanded, to a larger fraction of maritime fuels for example, distributors of those fuels would likely find lower-cost pathways to near-term, and possibly long-term compliance by buying credits from on-road fuels rather than investing in the production of novel fuels for their sector. In this case, the GHG reductions required from the marine sector by the LCFS would essentially be displaced into the on-road sector; aggregate emissions across the transportation system may be the same as if the marine sector had directly complied, but there would be no guarantee of actual shifts in the marine sector fuel portfolio.

This scenario could yield lower short-run costs for GHG abatement than if maritime fuel distributors lowered their emissions directly. Total cost to achieve carbon neutrality, however, could be significantly higher because action within smaller sectors may be delayed, requiring a rapid transformation in the future.

This risk can be at least partially mitigated by sub-dividing the LCFS obligation into sectors and restricting the flow of credits across sectors. For example, if aviation and marine fuels were each within their own separate LCFS compliance pool, the option to meet obligations via the purchase of lower-cost, more readily available credits from on-road fuel use would not be available.[95]

Aviation and shipping, especially over long distances, are amongst the cases where investment in hydrogen-based decarbonization options, including hydrogen used as a feedstock for liquid fuel production, could be most beneficial, because they are less likely to have effective direct electrification alternatives than other energy end-uses. For this reason, the lack of focus on these sectors in California's approach emerges as an area that could benefit from policy improvements.

Another difference between California and the EU lies in the mechanism used to redistribute revenues from carbon pricing. The advantage of the market-based approach in place in California lies in its flexibility, self-sustaining nature and ease of access to the funds. A disadvantage is the risk that producers of low-carbon fuels with comparatively low costs, but also limited scale up potential can, in early years of the program, crowd out needed investments in more scalable technologies, or those with a better pathway to zero or near-zero GHG emissions. Some technologies can even have negative life-cycle emissions in

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[95] Allowing limited transfer of credits across pools could be an option as a cost-containment mechanism in this instance. Alternatively, a requirement that a specified fraction of credits come from within-sector fuel consumption could allow a balance between the cost-minimization of fully fungible LCFS credits vs. ensuring that each sector must begin reducing emissions to comply. Ongoing work at the UC Davis Policy Institute seeks to better understand the differences between these approaches (Murphy, 2024).

certain circumstances, such as renewable natural gas from anaerobic digestion of livestock manure, which receives a credit for abating the fugitive methane that would otherwise have been released, or in biochar production, for which biofuels could be a by-product, or in BECCS systems. While technologies with a negative carbon intensity clearly provide value as a climate mitigation measure, the extremely high amount of credit they generate per unit of produced energy means that aggregate compliance can occur across the program via relatively small changes to the fuel portfolio. This can delay necessary investments in more scalable options and lead to a rushed, more expensive transition for the remainder of the market in the future. This disadvantage is stronger in California than in the EU policy framework, as the LCFS includes decarbonization options for land transportation, while the RefuelEU Aviation and FuelEU Maritime regulations are solely focused on aviation and shipping.

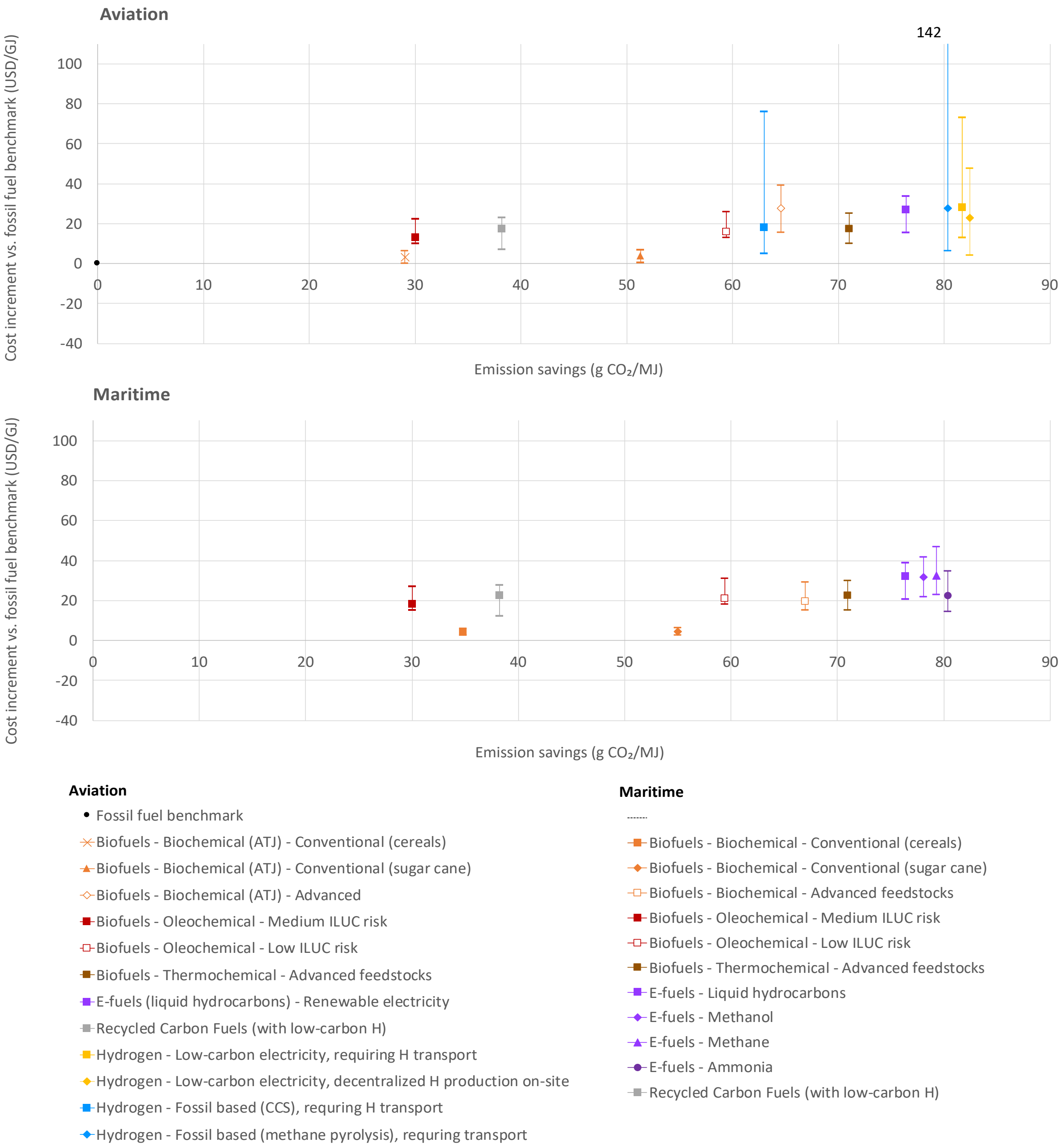
4.4 Post-2040

Figure 7 and Figure 8 show the same type of results of Figure 2 to Figure 6, but with a long-term (post 2040) focus. These Figures offer additional insights on the effects of the policy frameworks considered. In this timeframe, IRA credits no longer apply, while the assumption for the ETS price increases to 200 EUR/t CO_2. Technology costs also integrate energy efficiency and other process-related improvements, as well as scale increases.

The lack of a carbon price in the US and the discontinuation of incentives in Figure 2 is compensated by technology progress. However, Figure 7 shows that the combined effect of these two counteracting drivers does not enable any option to lead to net emission and cost savings, even for technologies that did reach that objective in Figure 3.

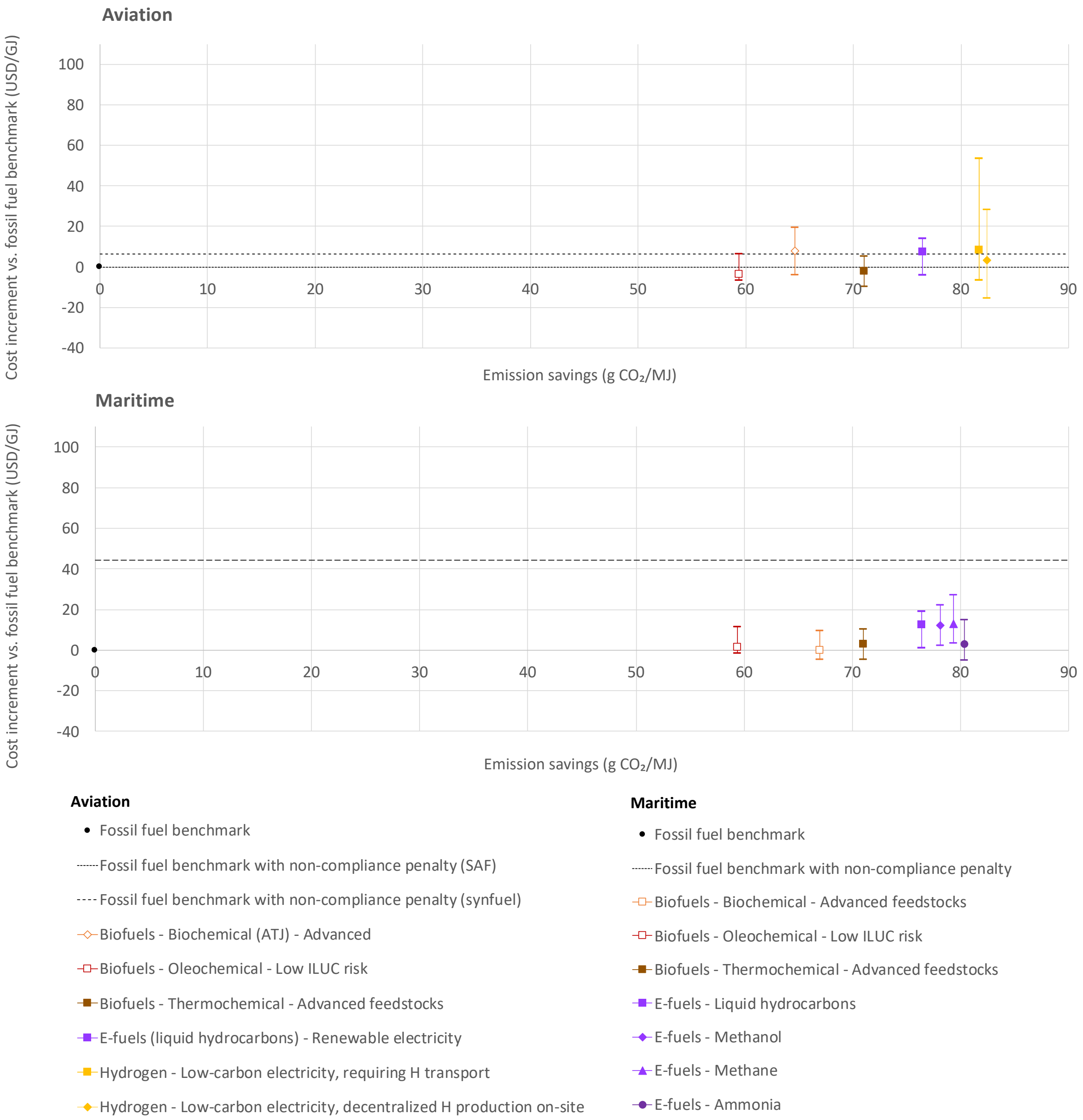
Figure 8 shows that increases in carbon pricing in the EU framework are capable of complementing technological improvements to ensure that several low-carbon alternative energy options become cost competitive, provided they achieve both significant GHG savings and cost reductions. At the same time, non-compliance penalties maintain pressure to ensure that fuels are brought to the market even if costs do not decline. This effect is stronger for maritime fuels because non-compliance penalties in the FuelEU Maritime regulation are fixed, while they adapt to changes in the price gap between the fossil benchmarks and the alternative fuel which will narrow in the case of RefuelEU Aviation (to the point that, as the cost gap for SAF other than synthetic aviation fuels, the penalty goes to zero).

Figure 7. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, no policy case, long-term (post 2040).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings.
Source: this assessment.

Figure 8. Savings of GHG emissions per megajoule and total cost differentials for a selection of shipping and aviation fuels, showing the impact of the EU ETS and non-compliance penalties in RefuelEU Aviation and FuelEU Maritime, long-term (post 2040).



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 9 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Positive cost values reflect a cost premium compared to fossil fuels, negative values represent a cost savings. Options not qualifying for the sustainability requirements under the Renewable Energy Directive or the RefuelEU (which excludes food and feed crops) are not shown. Horizontal lines reflect costs imposed by non-compliance penalties in RefuelEU Aviation and FuelEU Maritime, shown in Table 12, based on the central estimate of alternative fuel cost prices (for aviation, the penalty is equivalent to twice the gap between the least cost alternative and the fossil fuel benchmark, for SAF and synthetic fuels, separately). For the post-2040 case and synthetic fuels, the line accounts for the arithmetic average of the costs of hydrogen and e-fuels.
Source: this assessment.

This means that, especially in the absence of regulatory requirements or cost cuts that exceed those taken into consideration here, the IRA policy framework provides less certainty of emission reductions and may be less effective at motivating sustained investment from industry stakeholders in comparison with the EU policy framework.

Absent an extension in time and scope of the SAF allowances,[96] the EU policy's certainty is likely to impose higher impacts on fuel costs than those in the US. This comes with the disadvantage of costs that will ultimately be passed on to consumers, but also with the advantage of a narrowing cost gap, better price signals, and greater long-term policy certainty. On this last point, the fixed values of non-compliance penalties for maritime fuels provide stronger guidance than the penalties indexed to fuel price gaps used in aviation, especially in light of the uncertainty regarding the cost of hydrogen as aviation fuel.

Should California also continue to apply regulatory requirements reducing carbon intensity post-2030, its policy framework would also be more likely to secure long-lasting supplies of low-carbon energy than in the case of the IRA, however the LCFS' broad scope means that progress in the marine or aviation sectors may be delayed, as compared to policies that require immediate action in these specific sectors.

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[96] SAF allowances are likely difficult to justify on the grounds of equity, with respect to other allocations of public resources, but could be supported by considerations related with the strategic relevance of the aviation sector.

5. Policy Implications

5.1 Insights from the Analysis of the Existing Policy Framework

The considerations developed in earlier sections flag important limitations and imbalances of the existing policy frameworks of the US and the EU regarding the energy transition and the decarbonization of aviation and maritime transportation.

5.1.1 United States

At the federal level, The US lacks firm and convincing regulatory requirements to stimulate an increase in the demand for low-carbon shipping and aviation fuels. While the SAF Grand Challenge roadmap does provide a vision of the transition of aviation to 2050, its nature is non-binding, and it is not paired with a non-compliance penalty. Existing policy measures with a binding nature, limited to the RFS, even in combination with the package of subsidies passed in the IRA and BIL, are unlikely to be adequate to achieve these goals. The RFS is primarily focused on on-road transportation and exclusively on biofuels. This limits its applicability to meet long run demand for marine and aviation fuels.

The IRA and BIL subsidies, especially the IRA Clean Fuel Production Tax Credit 45Z for aviation fuel, are complemented by state-specific incentives such as the Illinois SAF credit. The Clean Hydrogen Production Tax Credit 45V also provides significant support through incentives. However, hydrogen's role in aviation appears to be primarily as an input to liquid fuel production and the 45Z and Illinois credits may be hampered by feedstock availability challenges due to their focus on crop-based biofuels made with current technology.[97] While promising technologies, like e-fuels, cellulosic fuels, or PBtL may be able to bring relevant volumes of truly low-carbon aviation fuels to market in the long run, they may struggle to compete against more mature current options that are subsidized by existing programs.

On maritime fuels, the US National Blueprint for Transportation Decarbonization touches on the topic of sustainable liquid and gaseous fuels, but the sector lacks binding requirements for ocean going vessels. Vision documents like the Zero-Emission Shipping Mission (ZESM) and its goals are also limited to enabling developments by 2030. Limitations on the generation of demand for low-carbon fuels in aviation and maritime transportation in the US are also paired with a lack of carbon pricing or alternative fuel blending requirements at the federal level.

Existing limitations in federal policy are partly compensated by regulatory action undertaken at the State level. The Illinois credit for SAF and the LCFS in California are the most relevant policy tools in this context. The LCFS combines regulations and pricing mechanisms to stimulate innovation in a way that is unprecedented in energy and transportation policy. It has a longer time horizon than federal regulatory policies and a firm requirement for GHG emission reductions going to 2030. These would be extended to 2045 under a recently

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[97] Preliminary guidance about specifics of the 45Z tax credits (IRS, 2024, US Department of the Treasury, 2024, US DOE, 2024) generally follows the example of previous US biofuel policies like the RFS and Blenders Tax Credit. These were primarily utilized by producers of crop-based biofuels produced with existing technology. The provisions relating to CCS and regenerative agriculture, which were not part of previous US biofuel policy, may offer existing crop-based biofuel producers opportunities to reduce their GHG emissions and retain access to federal incentives.

proposed rulemaking (CARB, 2024a). However, the LCFS presently lacks meaningful incentives and/or penalties for aviation and shipping fuels. Aviation is currently handled an opt-in solution, exempt from any regulatory requirement and from non-compliance penalties. Proposed amendments to the program would bring intra-state aviation fuel into the program, however, this encompasses only a small fraction of total aviation fuel used in the state and there is no guarantee that airlines will use SAF to comply.

The coverage of maritime transportation in the LCFS is limited to smaller vessels. Many of these are more likely to be cost effectively decarbonized through direct electrification than fuel switches and less likely to require more forward-looking investments on synthetic fuels. Simply adding aviation and marine fuels into the LCFS may not be a sufficient measure to address this weakness because obligated marine and aviation fuel providers could possibly achieve cheaper near-term compliance by purchasing credits from on-road fuels rather than investing in lower carbon options for their own sector.[98]

The IRA, the BIL, and the LCFS include mechanisms clearly aiming to incentivize the low-carbon fuels and low-emission technologies that still face research, development, and deployment/commercialization barriers. The mechanisms that they use include: (1) tax credits (i.e., the IRA), (2) funding of infrastructure deployment to remove barriers related with some types of investment risks (i.e., via the BIL and the IRA), and (3) market-based mechanisms favoring technologies that have the capacity to deliver long-lasting GHG emission savings (i.e., via the LCFS).

All of these tools have the advantage of being relatively simple and easy to access for investors and producers, and therefore capable of reducing some of the administrative non-cost barriers to technology deployment. They also tend to minimize net cost impacts to the consumers of transportation fuels. IRA and BIL incentives are funded out of the US budget, which disperses their cost impact among the broader tax base but does not come with a dedicated long-term source of revenue. Tax credits like the IRA and infrastructure-related investments (as in the case of the BIL) can re-shape price signals to consumers in some cases and help support desired decision-making.

However, several conditions may limit their effectiveness in this regard: producer/investor retention of tax credit value, inelastic demand for the requisite good, existence of a prevailing market price, or market failures such as principal-agent problems. Additional challenges can arise from policy stability risks. Most fuel production capacity projects are extremely capital-intensive and require a decade or more of operation to approach the break-even point. Without assurance that policy support will last that long, it can be difficult to access capital for project construction.

The RFS and the LCFS transfer the costs from fuel switching onto consumers of conventional petroleum fuels via the obligated purchase of RINs under the RFS or the requirement to obtain credits to offset deficits generated from fossil fuel consumption in the LCFS. Both rely on market-based instruments and result in increased costs for conventional fuels, primarily to consumers of petroleum gasoline (particularly in the case of the LCFS). This may have positive or negative implications. Broadening the source of revenue to the entire transportation fuel pool minimizes the chance of disruptive cost impacts concentrated in

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[98] In this case, however, the lost emissions benefits from the lack of low-carbon aviation and marine fuels would be made up by over-compliance in decarbonizing on-road transportation.

one sector, however, it may increase the risk of regressive impacts given that lower-income people typically spend a larger share of their personal or household budgets on petroleum than more affluent ones.

Broader conceptual issues are reflected in these decisions in addition to the immediate impacts of revenue flow and stability. For many years, a core principle of environmental policy has been that the industries or stakeholders responsible for environmental pollution should bear the brunt of the cost for mitigating and remediating their pollution; this is often described as the “polluter pays” principle. While some or all of the costs of pollution mitigation and remediation are ultimately passed on to consumers, many environmental policies implicitly seek to hold polluting industries accountable. Policies like tax credits take revenue from the entire tax base of a jurisdiction, whereas carbon pricing, fuel blending mandates, LCFS policies, etc., draw revenue primarily from the industries responsible for pollution in the first place. Even though petroleum producers can, and typically do, pass the full cost of these policies on to consumers, the higher prices that this entails may reduce total sales. Policymakers must balance the value of spreading the cost burden across multiple sectors, which may reduce impacts on critical industries or consumer groups, against the desire to have those that benefitted from historical pollution-intensive business practices bear the primary responsibility for supporting the transition to more sustainable ones.

5.1.2 European Union

The stringent regulatory requirements in place in the EU give very clear signals on the presence of future market demand for low-carbon fuels in aviation and maritime transportation. This is not only the case for sustainable biofuels made from feedstocks in the low ILUC risk category, but also for advanced options such as RFNBOs. Regulatory requirements are especially relevant in aviation, where synthetic fuels are discussed with specific language. Maritime transport is also clearly taken into consideration.

The strong focus of the EU policy on the creation of market demand through ambitious regulatory signals is a clear difference with respect to the US. A second important difference between the EU and the US lies in the use of carbon pricing. This is seen primarily via the EU ETS, as both aviation and maritime transportation are subject to it. Notably, carbon pricing for maritime applies not only to intra-EU waterborne transport, but also to half of international maritime voyages.

Carbon pricing comes with the advantages of (1) providing price signals to energy consumers that align with long-term GHG reduction goals and (2) generating public revenues. Price signals enable important investments in energy efficiency, as they are more cost effective than in the absence of a carbon price. Carbon price revenues can be reinvested to stimulate GHG reductions or technological progress. Amongst other possible uses, they can reduce public debt, mitigate regressive impacts, or address emissions sources for which regulatory or incentive measures are ineffective due to market failures or unusual circumstances.[99]

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[99] For example, with principal-agent problems, as in energy efficiency improvements in rental properties. Natural landscape improvements to enhance ecosystem resilience and maximize carbon uptake are another situation where carbon pricing revenue can be uniquely useful, especially where no clear agent or constituency exists who would normally be able to make such improvements, such as in conservation easements or conservancies.

The availability of revenue to support or de-risk capital investments is especially important in sectors like aviation and shipping. These sectors are highly exposed to asset stranding risks in a transition towards carbon neutrality in the absence of progress regarding low-carbon fuel availability at lower cost.[100]

The EU policy includes provisions to manage near-term impacts of SAF deployment on consumer prices via SAF allowances and to reinvest revenues from carbon pricing to stimulate progress on innovative, low-carbon alternatives to the fossil fuel benchmark. This takes place via the Innovation Fund through project-based funding mechanisms and, as detailed earlier, needs complementary regulations and related non-compliance penalties to mobilize private investments, as it cannot close the investment gap alone.

5.1.2 Combined effects of United States and European Union policies

The combined action of pricing, regulatory requirements, and incentive policies in place in the EU can stimulate domestic production in ways similar to the IRA or the LCFS in the US. However, incentives to mobilize near-term investments, including for exports, may be weaker in the EU than in the US. Reasons include a larger low-cost renewable energy potential in the US and greater simplicity with which producers can access value from the IRA (tax credits) and LCFS (market-based mechanism), as compared to the EU Innovation Fund.

Headwinds for low-carbon aviation and shipping fuel deployment in the US are largely related to far lower stimulation of demand, even in California and other states with Low Carbon Fuel Standards, as all have a far greater focus on road transportation. The lack of predictable long-run demand combined with challenges regarding policy stability make it difficult for producers to justify investing in capital-intensive production capacity projects with long payback periods.

More extensive project reviews associated with the EU funding mechanisms by CINEA and the EIB enable greater steering capacity, in the EU, for investments directed towards GHG reductions and energy diversification. [101] This is in line with the legally binding net-zero emission requirements of the EU Climate Law.

The need for more careful planning and coordinated execution of investments to reduce GHGs could be well-suited if large-scale access to cost-competitive EU solar and wind energy resources is constrained. Interest to bridge the risk of constraints was confirmed by maritime fuels and SAF being included in the EU Global Gateway. With possible limitations in access to a low-cost renewable energy generation potential with respect to other global regions, it is especially important that the EU maximize the value of the resources it has.[102] More extensive review and planning may, however, slow down the overall pace of project

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[100] These risks are higher if clean energy carriers remain expensive than fossil energy (as shown in sections 3 and 4). With firm constraints in terms of the carbon budget available to meet decarbonization goals, and in the absence of significant energy efficiency improvements, this carries the risk to constrain transport activity growth, in these sectors.

[101] Energy diversification and, through it, increased energy security has relevance from a defense perspective. Paired with lower domestic availability of fossil energy, energy security considerations may also underpin the greater opening to the use of nuclear as a primary energy source for aviation fuels, in the EU.

[102] Even if there are areas with high wind potential in the North Sea and solar potential in Southern Europe (Global Solar Atlas, n.d. and Global Wind Atlas, n.d.).

development. This could limit growth of domestic supplies, domestic value generation, and job creation from low-carbon technologies.

The EU legislation does not preclude, in principle, the possibility of relying on imports to comply with regulatory requirements. However, it requires compliance with sustainability criteria[103] and additionality, temporal correlation, and deliverability in the case of hydrogen from electrolysis.

US policies can support low-carbon energy exports to the EU. However, specific provisions in EU legislation exclude fuels produced from installations that received support in the form of operating or investment aid, such as that provided by the US IRA, unless this support is fully repaid from those that can qualify to meet the RefuelEU Aviation and FuelEU Maritime (as well as other Renewable Energy Directive) mandates (European Union, 2023). This choice helps level the playing field for investments targeting the EU market, irrespective of where the investments are made. It also underscores a desire to reduce risks of supply disruptions and price increases due to changes in policy decisions beyond EU jurisdiction. For example, if future US administrations sought to repeal incentives enacted by the IRA or if other countries adopted similar choices. Better control on supplies, however, can slow the pace of investment in global supplies of low-carbon maritime fuels and SAF vs. a counterfactual without this clause.

Both US and EU policies remain largely agnostic about which energy carriers might be most readily traded across borders. Which energy carrier dominates international trade flows will depend on product physical characteristics (i.e., energy density and state at ambient pressure and temperature), production costs, transportation costs (most relevant for hydrogen and other gaseous fuels), infrastructure-related developments (e.g., for storage and handling), and transatlantic coordination (affecting infrastructure usage rates).

Due to major challenges for hydrogen in this respect, and because pipeline transportation is not an option for transatlantic deliveries, the most likely options are either biofuels or hydrogen derivatives. These include ammonia, if safety challenges can be effectively handled, or synthetic fuels such as methane, methanol, or other synthetic hydrocarbons.

Taken together, these considerations highlight the importance for the EU and the US to strengthen their dialogue regarding low-carbon fuels for aviation and shipping. Such a dialogue can offer important opportunities to balance domestic and diversified supplies and produce larger amounts of lower cost, low-carbon options, at scale.

The EU has begun to build a diverse set of international partnerships to achieve this goal. These are in line with developments already started in the context of the Global Gateway. These partnerships can be supported by trade agreements that integrate conditions related to climate action and the effective implementation of the Paris Agreement (European Commission, n.d.o) and, thanks to cost reductions enabled by scale, can also support a global transition towards GHG emission reductions.

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[103] These are discussed in Section 2. Criteria limit the use of fuels made from high-risk food, feed, and other selected forms of biomass from eligibility to satisfy EU fuel policy requirements. They include minimum life-cycle GHG emission abatement thresholds vs. a fossil fuel benchmark of 65% for biofuels and 70% for hydrogen and hydrogen derivatives (European Union, 2018, European Union, 2023).

5.2 Key Policy Decisions

Ensuring that policies effectively lead to increased availability of cost-effective clean energy carriers for aviation and shipping requires a combination of regulatory requirements, incentives, and penalties both in the near- and in the long-term. These are necessary to support compelling emissions reduction and sustainability requirements.

This report has explored several areas where current research and policy discussions have identified clear, actionable guidance or emerging consensus. Several other areas of high relevance to future policy making are still unsettled. These may require additional research to better inform current understanding and support alignment facilitated by international negotiation.

Key trade-offs to be determined include:

- diversity in the fuel portfolio vs. focus on a single fuel,
- maximization of near-term GHG benefits vs. optimization of the trajectory towards carbon neutrality,
- relative importance of regulatory requirements, pricing mechanisms, incentives, and other policy measures.

Below, each decision item will be discussed, and broader considerations will be translated into specific insights for the aviation and shipping sectors.

5.2.1 Diversity in the fuel portfolio vs. focus on a single fuel

Long-distance travel by aircraft or ship are cases where battery-electric technologies will most struggle to cost-effectively satisfy transportation needs.[104] At the same time, there are still open questions about the most appropriate low-carbon alternatives to a fossil fuel benchmark. Several fuels have demonstrated the technical capacity to replace petroleum in marine applications. These include conventional and advanced biofuels, hydrogen and its derivatives, and non-biological synthetic hydrocarbons. Some technologies fit more than one of these categories (e.g., PBtL hydrocarbon fuels). Policymakers, vehicle builders and operators, and infrastructure developers will be faced with a choice in coming decades: embrace a diverse portfolio of multiple fuels, which can maximize local efficiencies and leverage the unique benefits of each, or focus on one, or a small subset of fuels, that maximizes interoperability.

Safety and operational requirements of commercial aviation likely warrant a limited number of options in the fuel space. These include direct substitutes of aviation fuels of fossil origin (namely, jet kerosene) with SAF of biogenic origin or synthetic aviation fuels of non-biological origin. They can also include, despite several challenges and applications likely limited to short-distance flights, the use of hydrogen as an energy carrier.

Flexibility to accept a broad slate of fuels may exist in the marine space, where multiple candidate fuels have emerged including ammonia, methanol, methane, hydrogen, and other gaseous or liquid hydrocarbons. All these options may plausibly be produced in ways that

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[104] Battery swapping technologies or novel battery chemistries with unprecedented energy and power density may eventually shift this balance. These are still speculative in aviation and shipping.

yield very low life-cycle GHG emissions, several of which were evaluated in Section 4 of this report.

Shipbuilders are deploying marine engines that have the flexibility to use multiple forms of fuel, allowing flexibility to switch between these. It remains to be seen how widely such engines will be deployed in practice. If multi-fuel engines become common, then local jurisdictions would have the flexibility to support the fuel production system that best matches their local needs and resources. Areas with high biomass availability could focus on biofuels or PBtL, while those with ample renewable electricity generation could focus on e-fuels or synthetic ammonia. Absent broad deployment of multi-fuel engines, however, the emergence of multiple marine fuels may force ports and bunkering terminals to maintain stocks of each fuel used by ships servicing that port, potentially expanding infrastructure requirements and creating a risk of damage to vessels if the wrong fuel were provided.

Emphasizing or mandating a limited subset of fuels, like the limited number of jet fuel and marine bunker specifications used today, would reduce these infrastructure demands and help ensure that, no matter where a vessel called, it would be able to refuel. It would maximize the possible economies of scale in production of a limited number of fuel specifications. The downside to limiting fuel types is foregoing the opportunity for jurisdictions to adopt preferred fuels and/or production technologies.

Given the relative immaturity of most low-carbon alternatives to petroleum marine and aviation fuels, there is insufficient evidence at the time of writing to provide robust endorsement of either the flexible or focused approach. Several salient points have found significant support in research to date that can help inform policymakers’ thinking on this topic.

5.2.1.1 The role of hydrogen in decarbonizing aviation and marine transport

Uncertainties on hydrogen’s ultimate role in the transportation fuel portfolio are significant. Low-carbon hydrogen production will likely require large-scale facilities to achieve cost-competitiveness, but transporting hydrogen at the scales required for aviation or shipping hubs would require either pipelines, which are costly and time consuming to build, or liquefaction, which imposes a large energy penalty and significant other infrastructure costs. Low-carbon hydrogen could serve as a feedstock for other energy carriers that offer better energy density, more manageable handling and storage, and less-costly infrastructure requirements. Alternatively, low-carbon hydrogen could be directly used as a vehicle fuel, with simpler production processes than hydrocarbon synthesis. Technological development on the vehicle side, for both on-board storage and propulsion systems, are also subject to greater technical challenges and higher costs for hydrogen than for its derivatives. Fuel cells still face cost, performance, durability, and scalability challenges. Hydrogen internal combustion engines may be burdened by low thermodynamic efficiencies also found in hydrocarbon fuel engines. The decarbonization of shipping and aviation could, therefore, be more affordable with a transition that focuses on derivatives (rather than hydrogen) as energy carriers, despite lower energy efficiency of fuel production and combustion.

Uncertainties also exist for critical near-term decisions regarding the scale and prioritization of investments on hydrogen infrastructure. This sector faces competition for access to renewable electricity supply and transmission capacity. While hydrogen has been proposed as an alternative to natural gas or other fossil fuel combustion, heat pumps or other direct electrification technologies could heavily limit the overall scale of hydrogen demand for low- and medium-temperature heat.

Where hydrogen is part of a broader industrial supply chain, such as e-fuel synthesis, development will have to consider other geographically limited aspects of the production system, such as access to CO_2 or CCS reservoirs, or low-grade heat to support carbon capture. This, as well as the option to keep transporting gas if CCS is possible, calls for the careful consideration of investments on hydrogen transportation, storage and distribution infrastructure, leaving different options open (Patonia et al., 2023; ETC, 2021). Despite remaining uncertainties, there is growing consensus that hydrogen and/or its derivatives can play a significant role in decarbonizing long-distance applications in shipping and aviation, either as a complement or as an alternative to biofuels. Hydrogen is an input to existing hydrotreating processes that produce most of the SAF on the market today and will likely continue to be an input to many, perhaps most, forms of liquid fuel production for the foreseeable future. Hydrogen can have a critical role supporting long-duration energy storage to stabilize supply on grids that depend on wind and solar generation for a large fraction of total capacity. Hydrogen can also function as an industrial chemical in a variety of applications. It remains to be seen whether demand from these applications will help lead to a broader utilization of hydrogen, including as a vehicle fuel.

At a minimum, factoring hydrogen and hydrogen-based options into policies dealing with the decarbonization of aviation and shipping can reduce risks of overdependence on specific pathways. This would likely also reduce related energy-security risks. In more optimistic scenarios, hydrogen and hydrogen-based fuels can enable access to a wider, low-cost and low-carbon alternative fuel base, essential for modes of transportation that will continue to rely on liquid fuels.

As long as life-cycle energy efficiency and cost minimization remain in focus, it is appropriate for policies to integrate ambitious signals that support hydrogen-related investments while remaining open to different possibilities regarding whether hydrogen is used directly or as a feedstock.

5.2.1.2 Flexibility in primary energy and production systems

Jurisdictions may rely on a broad range of primary energy options while maintaining a clear focus on reducing life-cycle GHG emissions and reducing costs to consumers. Each jurisdiction will have a unique portfolio of low-carbon primary energy resources such as wind, solar, geothermal, nuclear, biomass, tidal energy. Making sure that policies remain open to diverse pathways for low-carbon fossil energy and are coupled with firm and ambitious sustainability requirements[105] can maximize opportunities to reduce GHG emissions, although not always at scale. Production of solid carbon from methane pyrolysis, for example, would quickly outweigh current demand for carbon black, if the technology were scaled, due to the carbon-to-hydrogen weight ratio of methane.

Care must be taken to ensure any incentives that support lower-carbon fossil options do not encourage lock-in of fossil options that impose worse environmental incentives than readily available renewable alternatives.

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[105] The ambition is essential to reduce asset stranding exposure to climate and other policy choices aiming to meet the UN Sustainable Development Goals.

While jurisdictions may seek to emphasize locally abundant resources, a diversified portfolio of primary energy sources can reduce risks arising from geographical concentration (e.g., weather, public health, or geopolitical disruptions) and reduce exposure to the risk of availability limitations of specific resources.[106]

Current policies integrate features to handle the risk of an over-reliance on specific low-carbon fuel production pathways, as they are conceived in a way that leaves different options open and enable additional energy security benefits from competition between different forms of energy.

This is the case for:

- The modulation of incentives based on GHG emissions and other social policy goals in the US, with greater incentives going to those associated with better outcomes.
- The wide scope of coverage of IRA incentives, which include biofuels, hydrogen, and its derivatives from renewables including for carbon sourcing from DAC and from natural gas with carbon capture.
- The technology agnostic, market- and performance-based approach used in the LCFS.
- The use of minimum life-cycle carbon intensity reduction requirements in the EU aviation policy, that, while being ambitious on life-cycle GHG emission abatement thresholds, leaves open the option to rely on a range of non-emitting resources, including nuclear electricity, to produce SAF.
- The establishment of specific, simplified entities in aviation to remove barriers for the certification of new fuels, as shown by the examples of the EU and the United Kingdom (UK) SAF clearing houses (EU SAF Clearing House, n.d. and SAF clearing house, n.d.).

Flexibility is relevant downstream, as well. Flexibility can be enabled by the opening to the use of different energy carriers for ammonia, methanol, possibly hydrogen, and other synthetic and biogenic hydrocarbons. With multiple energy carriers possible, policies need to consider challenges related with new infrastructures. These include technical complexity, physical constraints, toxicity-related risks,[107] investment costs, and anticipated usage rates as well as risks that may arise from market fragmentation (e.g., lower infrastructure use tends to result in higher per-unit costs).

Finally, while openness to different technological options is important, flexibility should not come at the cost of not spotting clear opportunities to make specific technologies more effective or resilient. Technology-specific investments for electrification are a key example, as direct electrification is clearly well-positioned to meet specific sector needs for targeted applications in shipping and aviation. These include cost-effective emission cuts via onshore power supplies for ships stationed, moored, or anchored in ports (cold ironing) and for aircraft stationed or taxiing in airports. They further include specific applications likely to benefit from direct electrification, such as vessels operating over short distances in maritime

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[106] One example arises from the high reliance on specific natural gas supplies in the EU, as shown on the occasion of the Russia/Ukraine conflict, in the case of natural gas.

[107] Toxicity-related risks can be especially relevant for ammonia. Specific challenges exist for spill behavior (Kass et al., 2021) and ammonia gas dispersion (EMSA, 2023). These can extend to security-related vulnerabilities, especially for storage facilities located in urban ports.

transport and short-haul light craft (including but not limited to electric vertical take-off and landing aircraft) in aviation. Technology-agnosticism offers value at some points in the transition to carbon-neutral transportation, particularly when no technology has demonstrated a clear, obvious, and cost-effective capacity to meet the needs of a given application. When one technology has demonstrated such capacity, however (as battery electrification has in light-duty on-road vehicles) there may be less value in maintaining technology agnosticism or neutrality for that application.

5.2.2. Maximizing near-term greenhouse gas benefits vs. optimizing the trajectory to carbon neutrality

Due to high prices and limited alternatives to decarbonize long-distance aviation and shipping, it is crucial to mobilize low-carbon fuel supplies for these transportation modes. At the same time, it is also crucial to ensure that these same policies do not lead to adverse, unintended consequences, such as the lock-in of technologies that have no plausible pathway to zero- or near-zero carbon operation by mid-century. Misleading policy signals could come with very significant risks, especially if they lead to investments made in response to policy signals becoming stranded assets.

If the transition to a sustainable climate is going to be predominantly financed through private capital leveraged by policy, it is important that policy signals are clearly interpretable by the finance community, and that policies are stable enough to allow a reasonable return on investment. Establishing, then quickly withdrawing an incentive can destabilize investments made in good faith and massively increase the perceived risk of climate-friendly investments. This would ultimately harm both the economy and the long-term development of low-carbon alternatives. Strict sustainability requirements, and robust GHG assessment based on conservative, risk-aware assumptions of future behavior help ensure that incentives are issued only where actual GHG reductions justify them. Conversely, lax sustainability requirements or GHG assessment methodology increase the risk that incentives will flow to activities that do not yield the desired emissions benefits. In that case, policymakers either must accept the misallocation of incentives in order to support policy stability or withdraw or alter the program leading to loss of confidence in policy signals. Basing incentives on robust, risk-aware science, evidence, and modelling enhances the likelihood that they will not need to be changed and can contribute to a predictable policy environment.

Within this framework, a clear dilemma for policymakers comes into focus. There are technologies and approaches that offer the opportunity for near-term GHG reductions when used to displace fossil fuels in the marine and aviation sectors, such as crop-based biofuels like hydrotreated lipid fuels or alcohol-to-hydrocarbon synthesis of conventional ethanol. They offer the potential for modest GHG benefits in the near term but lack a clearly viable pathway to zero- or near-zero life-cycle GHG emissions over the long term. Nascent technologies that have a stronger likelihood of zero- or near-zero GHG fuel production are likely to be a decade or more from being ready to achieve large-scale production at reasonable cost. Incentives that emphasize near-term GHG reductions may, therefore, tend to result in the deployment of the former category of fuels, which can drive down emissions now but risk becoming stranded assets when deep decarbonization is needed. Incentives that focus on developing the most efficient trajectory to mid-century carbon neutrality may focus on the latter category of technologies. This could potentially bring them to market slightly sooner but would forego the opportunity to reduce emissions in the short term.[108]

Biofuels are a clear example of where sustainability challenges and poor assessment of indirect and time-dependent GHG effects led to a lack of policy stability and poor GHG outcomes. Policies initially promoted biofuels supply technologies with little coherent prioritization of sustainability and lackluster GHG reduction benefits. Early assessments of GHG benefits indicated potential value as a climate policy tool due to their biogenic carbon component, but these assessments overlooked land use change (especially ILUC) emissions, time-dependent shifts in ecosystem carbon balances, and market-mediated indirect impacts. With growing recognition of these impacts, policies evolved to cap production of biofuels with adverse sustainability impacts and limited GHG abatement potential. They also placed greater attention on other environmental concerns, including risks of biodiversity losses (ECA, 2023). In the US, in particular, the decision to waive the advanced and cellulosic requirements of the RFS, called into question US policy commitment to advanced low-carbon fuel technologies and may have contributed to the lack of progress in this area through most of the 2010s.

Key issues that underpinned these policy changes are still relevant in recent legislative choices. They include the risk of limited GHG emission reductions on a life-cycle basis and the limited effectiveness of existing policy tools to effectively mitigate risk from indirect or market-mediated effects of biofuel use, such as ILUC. Even where current research provides high-confidence assessments that GHG reductions from biofuels are real and robust to a variety of conditions, the inability of scalable current biofuel technology to achieve zero- or near-zero carbon technologies creates tension in efforts to decarbonize transportation. The biofuel industry's capacity to scale up – as evidenced by the nearly five-fold increase in biomass-based diesel substitute production in the US since 2019 – allows for near-term GHG reductions. Questions remain about whether this growth competes for resources or market share that would otherwise go to electrification or other near-zero fuel options and, at the international level, with resources that would otherwise be destined to other sectors, including agriculture and industries using oils and fats as their feedstocks, also having impacts on resource costs.

Solutions that have been adopted for biofuels combine a shift in policy focus towards options with greater GHG emission reductions, the introduction of sustainability criteria (clearly integrated in EU policies), and/or the choice to take a precautionary (or risk-aware[109]) approach on aspects that are difficult to assess, in particular land-use change. A positive example of international cooperation in this area is provided by the agreement reached at ICAO regarding the LCA accounting for SAF recognized under CORSIA. The agreement was reached despite different starting positions across countries, especially on ILUC. This likely sped up work on life-cycle emission accounting for maritime transport fuels at the IMO, as indicated by substantial advancements in 2023 and 2024 (IMO, n.d.).

Hydrogen and hydrogen-based fuels embody the tension between maximizing near-term vs. long-term benefits. Electrolytic hydrogen production can yield near-zero life-cycle GHG

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[108] This is particularly problematic due to the well-demonstrated time dependence of GHG emissions related to warming effects (Kendall 2012).

[109] See Murphy, 2023 on this topic.

emissions when powered by zero-carbon electricity. Achieving this is a challenge, as several global power grids are still largely dependent on fossil fuels. Even where renewable sources are used to supply electrolysis, electrolytic hydrogen production (as well as e-fuel synthesis, DAC, or other large sources of electricity demand) can indirectly increase in emissions by consuming renewable electricity that could otherwise be used to displace and retire fossil generation. Given the efficiency losses entailed with electrolysis (i.e., loss of energy as waste heat or unwanted byproducts) the carbon benefits of electrolytic hydrogen are modest in the near term, at best, but will likely be quite large once the grid has more fully decarbonized. Preventing these emissions underpins the choice to adopt strict additionality, temporal matching, and geographical correlation (or deliverability) requirements.[110] This is the direction currently taken for those already in place in the EU (European Union, 2023h) and recently proposed in the US (US Department of the Treasury, 2023b).

The efficiency of electrolytic hydrogen production, as well as its cost, would likely improve if it were deployed and allowed to mature at a large scale. This would improve its long-term value as a GHG reduction tool, but possibly at the cost of poor near-term GHG outcomes.

Policymakers will resolve this tension through policy in coming years. It may be possible to strike a balanced approach in which there is enough large-scale deployment to support technological maturation but not so much that the life of existing fossil generation is significantly extended as a result. Any policy in this space needs to be paired with transparent and sound methodologies to account for life-cycle emissions[111] and must enable long-term resilience and certainty, despite adding initial barriers, ultimately delivering net benefits for all stakeholders, as it reduces chances of asset stranding.

5.2.3 Relative importance of regulatory requirements, pricing mechanisms, incentives, and other policy measures

Major policy choices like those taken into consideration in this review are a clear example of an organic approach to policy making. They provide clear signals to stakeholders and are capable of bridging uncertainties. They are, therefore, well-suited to mobilize investments. These signals arise from a combination of regulatory requirements, carbon pricing tools and incentive mechanisms or a selection of these. The portfolio of climate policies adopted by any jurisdiction reflect a wide range of political, social, economic, and technological factors. In most cases, there are multiple policy tools that can yield a desired outcome and

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[110] Different choices on additionality, temporal and geographical correlation could induce, indirectly, emission increases in the electricity generation sector, negating the climate and energy security benefits sought by the policy instruments in the first place.

[111] A specific delegated act covers this subject, including both hydrogen and hydrogen-derivatives, in the EU (European Union, 2023f). This allows CO_2 sourced from carbon capture as a viable option, up to 2036 (for combustion in electricity generation) or 2041 (in other sectors). This is grounded on the idea that the origin of carbon used for the production of renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels is not relevant for determining emission savings of such fuels in the short term as many current carbon sources are available and can be captured while making progress on decarbonization. However, this is no longer the case in an economy on a trajectory towards climate neutrality by 2050. In the US, emissions up to the point of production related with IRA credits are assessed based on the Argonne National Laboratory Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model (US DOE, 2023e). Internationally, the ISO also launched recently its methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate (Hydrogen Council, 2023, ISO, 2023).

policymakers have a degree of flexibility to choose which tools best match the needs of their time and place.

This report has identified some consistent trends in the types of policy mechanisms chosen in the US and EU. There is a preference for incentives and state-level performance standards in the US, as compared to carbon pricing and regulatory requirements in the EU. Both policy approaches have significantly improved the economics of alternative aviation and shipping fuels. However, this assessment flagged important aspects that could be improved, including the incomplete adoption of carbon pricing and the importance of long-term predictability in policy instruments. These signals are particularly important to reduce investment risks and, as such, crucial to create a clear case to mobilize investments.

Carbon pricing has been widely regarded as a foundational element of an effective climate policy portfolio. The analysis presented in Section 4 supports this conclusion. Carbon pricing yields a twofold effect, first by directly improving the economics of renewable energy, as compared to fossil fuels, and second by generating revenue that can be used in a variety of ways, including to support further decarbonization. Despite this, carbon pricing generates political opposition in many jurisdictions, especially in the US, and so it may not be feasible in many cases.

Policy choices limited to regulations and incentives are insufficient to ensure that energy end-users can benefit from the cost reduction opportunities enabled by the mobilization of these same investments. The reason is that, in the absence of specific provisions, policy-related benefits (in particular if they come in the form of production incentives) may not be passed on to energy end-users if they can instead be retained by producers of low-carbon fuels (and, indirectly, their shareholders). Evidence from analysis of the pass-through of biodiesel subsidies in the US suggests that, while policy costs affecting transportation fuels are completely passed to the consumer via higher prices, policy incentives for low carbon fuels are only partially passed through via lower prices for these substitutes (Mazzone et al. 2022).

This problem is shared by many incentive-based policies. This is because business stakeholders tend to be more focused on maximizing the amount of incentive they receive and minimizing the costs needed to receive it than they are on achieving the real-world outcomes the incentive hopes to support. There are many examples of perverse behavior resulting from poorly designed incentives, such as companies producing high-GWP refrigerants solely to destroy them and claim offset credits for the destruction (Schapiro, 2010). Incentives for clean energy also fail to ensure that fossil fuel emissions fall because simply having a cleaner alternative does not mean that fossil plants will be decommissioned.

Structural price signals must be passed on to end users to support long-term change in behavior and investments consistent with achieving carbon neutrality without perpetual and ever-increasing subsidies. This is especially applicable to price differences between low-carbon options and the fossil benchmark, which are likely to remain in place in the long-term.

Achieving an affordable decarbonization pathway requires a balance between allowing end-users to access lower-cost, low-carbon energy supplies while still ensuring that low-carbon energy producers can be effectively remunerated. Policymakers implicitly bet that, as a robust market for a clean energy product emerges, economies of scale, technological maturity, and sheer volume can help a previously cost-prohibitive clean energy alternative achieve cost-competitiveness with incumbent fossil fuels and eventually allow a phase down of incentives. Producers, however, may be more focused on maintaining margins or returns to capital. These motivations are seldom helped by a reduction in policy incentives. Policymakers can couple multiple types of policy to help reach desired GHG or other social and economic outcomes.

One way to address the challenge of credit value not being passed to end-users is to integrate instruments that can support innovation while also enabling a distribution of the benefits that they bring across different stakeholders, through competition.

In the specific case of the IRA, the guidance released by the IRS on transferability and elective (or direct) pay (US Department of the Treasury, 2023c) can contribute effectively to enhance competition. Transferability exposes fuel producers entitled to the tax credits (including for 45Z, on SAF, and 45V on hydrogen) to risks of losing market access by not transferring tax credits with respect to competitors that do so. Direct pay also enables access to a broader set of clients for clean energy tax credits. This expands the scope to tax-exempt and governmental entities that were previously unable to access them.

The SAF credit introduced in Illinois, targeted to airlines rather than fuel producers, as well as the SAF allowances in the EU, may enable cost reductions for airlines, who ultimately hold significant decision-making power around which fuels are used in their aircraft, though cost savings may still not be passed on to consumers. The sufficiently long duration of the Illinois credits, from 2023 through 2032, is important to mobilize investments while costs are higher than the benchmark. In contrast, the EU SAF allowances, available on a yearly and proportional basis to SAF volumes produced, do not create as much certainty. Clear sunset clauses are also relevant to avoid hiding price signals in the aviation fuel market. The risk of doing this lies in exposing the sector to shocks in the longer term, when increased shares of low-carbon fuels make subsides and incentives not economically viable.

Making sure that energy end-users, not just fuel producers, can seize cost-reduction opportunities could also be enabled by the integration of some of the instruments of the reform the European electricity market in low-carbon fuel policies for long-distance aviation and shipping (European Union, 2024). These instruments include PPAs or low-carbon energy purchase agreements and CfDs (Section 2.1.3). The use of CCfDs in this context could offer an administratively lean, competition-aligned, and cost-effective way to stimulate investments for low-carbon shipping and aviation fuel supplies. This could enable the fund to work in a way that would be similar to the LCFS credit market.

Regulatory requirements, such as the volumetric requirements created by the ReFuelEU Aviation and FuelEU Maritime packages, offer a comparatively simple approach with a high degree of certainty regarding GHG benefits. The downside is that such requirements can result in significant costs passed on to consumers by regulated parties.

GHG performance standards, like California’s LCFS, blend elements of regulatory requirements and carbon pricing. By setting targets for the efficiency with which energy is produced and delivered to market, rather than for absolute amounts of specified types of energy, producers are granted the flexibility to achieve compliance in the lowest cost fashion.

All of these tools can help support an efficient transition to low-carbon aviation and shipping fuels. Policymakers must ultimately navigate the complexities of their own jurisdiction. Political realities often conflict with the desire to select the most effective measures to achieve their GHG reduction goals. The optimal, or even feasible options will vary greatly.

5.3 Recommendations

This concluding section builds on the technology analysis and policy characterization of Section 3, the policy analysis of Section 4, and the indications on key policy requirements developed above. We elaborate a set of recommendations that aim to improve the current policy setting. As in the case of the rest of the analysis, the focus is on EU and US policy frameworks regarding the promotion of low-carbon fuels in aviation and shipping.

5.3.1 Better integrate carbon pricing in the United States policy framework

While politically difficult to implement, carbon pricing is widely recognized as a key pillar of any decarbonization policy framework. On this basis, it is clear that the US federal policy lacks systemic instruments (similar to the EU ETS) that effectively put a price on GHG emissions. This type of mechanism is only in place in California. Twelve other states accounting for over a quarter of the US population and a third of the US gross domestic product also have active carbon-pricing programs (C2ES, 2024). Nevertheless, as these mechanisms apply to specific sectors, they result in less than 10% of the US emissions being subject to a carbon price and less than 40% being subject to a net effective carbon rate (excluding aviation and shipping) (OECD, 2022 and OECD, 2023). This is even more relevant in shipping and aviation, as the fuels they use are taxed at rates well below road transport (OECD, 2022).

Carbon pricing can also help raise revenues to fund innovation and incentives for the deployment of low-carbon fuels, as already shown by California's LCFS. Current US policy actions, including subsides and public funding for infrastructure, have partially closed the cost gap between petroleum and alternative fuels. Carbon pricing could help fully close the cost gap with unabated fossil options, especially in the longer term, creating favorable and structurally stable conditions for commercial viability for low-carbon fuels.

Carbon pricing is also important to provide price signals to energy end-users, favoring direct investments in energy and indirect– investments in other resource-efficient technologies. This is relevant in shipping and aviation, as both sectors are highly exposed to energy costs.

Economy-wide carbon pricing can help ensure that no sector or application lags too far behind in the process of decarbonization. It also serves as an important backstop to targeted, sector-specific regulatory requirements by applying broad pressure to decarbonize across virtually all economic sectors.

Crucially, carbon pricing enables governments to generate revenues that can be reinvested to promote innovation and address equity challenges. The revenue from carbon pricing can also be used to offset other sources of governmental revenues, such as those that might decline as the economy decarbonizes.

5.3.2 Introduce long-term regulatory signals for United States low-carbon aviation and shipping fuel demand

Existing regulatory requirements on transportation fuels in the US stem from the RFS for fuels of biogenic origin and, in states applying it, the LCFS. The timeframe of these regulations is limited to 2025 at the federal level via the RFS and varying dates in states, mostly 2030 with few beyond this date (mainly in states applying the LCFS).

It is crucial that both federal and state policies integrate long-term signals, with requirements that extend beyond 2025 or 2030. Low-carbon fuel mandates and carbon intensity reduction also need to become more stringent. Ramping up supplies of affordable low-carbon fuels is essential in the presence of an ambitious climate policy, given the necessity to delay and reverse impacts from climate change. The technology transition is also necessary to avoid risks to lose economic opportunities, in this framework.

While significant uncertainty exists about the specifics of vehicles, fuel technologies, resources, and markets in the 2030s, there is also awareness of the potential gains available from a range of different technological solutions. Policy makers can—and should—set targets compatible with climate stabilization scenarios. Ideally, targets will be complemented by measures capable of accelerating technological progress and cutting low-carbon fuel costs.

The increased availability of low-carbon fuels at lower cost points has relevance for sectors that are crucial enablers of mobility and trade, and which will remain strategic in a world progressing toward net-zero GHG emissions. In a policy environment where GHG emissions need to be brought to net-zero, securing the availability of low-carbon affordable fuels for aviation and shipping is, therefore, essential to fostering greater resilience and enhancing economic, industrial, social, and political stability.

5.3.3 Adopt sector-specific regulatory requirements to enhance the effectiveness of United States policies

The current policy framework in the US has a much stronger focus on road transportation than on aviation and shipping. Aviation fuels can opt-in to credit generation under the LCFS and RFS, but this provides only limited support. Marine fuels are largely overlooked by US fuel policies. This results in the absence of regulatory requirements addressing the decarbonization of maritime transport.

Sector-specific requirements, paired with compelling non-compliance penalties, are necessary to avoid the risk of seeking compliance strategies in other sectors of the economy. Full integration of aviation and maritime fuels to LCFS and RFS regulations would help incentivize the deployment of lower-carbon fuels in these sectors. Separate compliance pools are important to ensure that critical investments in production capacity for these fuels are made today, rather than waiting until cheaper on-road compliance options are exhausted.

Subsector- or mode-specific policies typically come with the drawback of increasing near-term abatement costs across the transport sector overall, but also with the advantage of enabling lower long-term compliance costs to achieve carbon neutrality or other deep decarbonization goals. Since the transition for any sub-sector or transport mode from current practice to carbon neutrality is likely to require decades to fully execute, and global net GHG emissions must approach zero by mid-century, no significant part of the global economy can afford to delay the beginning of its transition because of incremental increases in marginal abatement costs.

Requiring aviation and marine fuels to begin their transition to carbon neutrality as soon as possible will likely lead to net benefits for the economy in the long term. This is because decarbonization requirements are bound to become more stringent over time and lower compliance costs for shipping and aviation bring about greater prospects for socio-economic growth.

5.3.4 Integrate hydrogen and its derivatives in sector-specific regulations in the United States

Hydrogen and hydrogen derivatives like ammonia, e-methanol or other synthetic fuels have the potential to deliver deep emission cuts in sectors that will remain dependent on energy-dense liquid fuels, like aviation and shipping.

Hydrogen and hydrogen derivatives are not directly addressed by the current regulatory frameworks developed in the US, though they do receive incentives such as tax credits under the IRA. The RFS omits hydrogen because it is solely focused on fuels of biogenic origin. The LCFS has the advantage of being technology-neutral, setting requirements that are related to carbon intensity, and is capable of stimulating interest in options that achieve very low levels of emissions, including hydrogen and synfuels.

Biofuels face constraints with respect to land use availability despite some potential margins for growth from other sources of biogenic carbon. This will be especially relevant if competition for biomass resources with other sectors increases, which could further exacerbate lignocellulosic biofuels' struggle to enter the market.

The very significant potential for low-cost, low-carbon electricity production available in the US, can reduce demand for biomass, easing pressure that could otherwise lead to converting natural land into cultivation and allowing growers to focus on higher-value and/or lower environmental impact crops.

Large-scale deployment of electrolytic hydrogen and e-fuel production capacity will require policy steering to produce desired GHG benefits while the grid is not decarbonized. This need is incorporated in existing IRA-related guidance. Near-term deployment of these technologies—even if initially expensive—is critical in sectors likely to provide resilient demand (and hence including aviation and shipping fuels). Near-term availability will enable sectors to advance along their maturation trajectory in advance of full-scale deployment.

Policies should, therefore, introduce specific demand requirements for hydrogen-based fuels in aviation and shipping in a way that is similar to the EU's RefuelEU Aviation regulation.

5.3.5 Introduce minimum thresholds for noncompliance penalties for sustainable aviation fuels in the European Union

Minimum thresholds for non-compliance penalties in the EU's RefuelEU Aviation regulation prevent risks of delayed investments in supplies. The current approach in RefuelEU Aviation sets minimum non-compliance penalties at twice the price gap between SAF and the fossil fuel benchmark.

The prices of SAF and fossil jet fuel are set by producers and are influenced by a variety of technological, economic, and market conditions. SAF is a relatively new technology with comparatively immature markets.

Several plausible scenarios exist in which the gap between SAF and fossil jet fuel may be small enough that airlines would rather pay the penalty than make the investments required to fully comply with Refuel EU Aviation. For example, an obligated airline that had a dominant market position and a controlling interest in a SAF producer could price its SAF low to reduce the gap between SAF and fossil jet fuel, thereby reducing the noncompliance penalties it may be subject to. More concretely, hydrotreated SAF made from waste oils have already established themselves on the market, at relatively low cost, in the EU and elsewhere. This includes several countries in Asia. A near-term focus on these technologies, with supplies sufficient to cover the limited volumes initially required by RefuelEU Aviation, could lead to the establishment of low non-compliance penalties. These, in turn, may lead to a preference by aviation stakeholders to pay low non-compliance penalties as regulated volumes increase. This could result in delayed investments in SAF supplies.

An effective non-compliance penalty for SAF is crucial to support supplies of alternative sustainably produced biofuel technologies like oleochemical pathways based on sustainably produced oils or biochemical or thermochemical pathways reliant on waste products as feedstocks (Section 4.2). Near-term investment in these technologies is critical to allow the technologies and associated supply chains to mature and achieve more efficient, lower-cost production over the long term.

Linking non-compliance penalties to the price gap between fossil jet fuel and SAF may support a perverse outcome because it could cause under-investment in technologies enabling deeper decarbonization and with larger scale-up potential.

Setting a price floor for non-compliance penalties for SAF, while also tightening controls on fraudulent practices regarding imported oleochemical SAF and their feedstocks, could help support the development of low-carbon alternative fuel production in Europe, and ensure that policies like ReFuel EU Aviation have their intended effect.

5.3.6 Reduce uncertainties on regulatory requirements for hydrogen-based fuels for shipping in the European Union

While the FuelEU Maritime regulation contains strong non-compliance penalties technically capable of stimulating increased availability of hydrogen and hydrogen-based fuels and a dedicated incentive for RFNBOs. However, there are aspects that can be improved. In particular, the conditionality of a 2034 RFNBO 2% sub-target upon specified volumes of RFNBOs made available on the market in 2031 may result in delayed investments, generating compliance difficulties.

To reduce the scope for uncertainties on the role of RFNBOs towards decarbonization of maritime transport, already relevant due to multiple options still openly competing, revisions of the FuelEU Maritime regulation could remove the conditionality for RFNBO requirements. With the same objective, the FuelEU Maritime regulation could offer better visibility on the post-2034 framework for RFNBO requirements, similar to what RefuelEU Aviation does with synfuels.

Greater clarity on the role of specific RFNBOs in the future maritime fuel portfolio could also greatly improve the ability of policy makers to support an efficient transition–in particular, ammonia, methanol, and synthetic diesel. At present, however, all candidate fuels have unique sets of advantages and drawbacks, and no single alternative fuel has clearly seized an advantage in the race to supplant petroleum bunker fuels.

Policy makers have been—correctly—prioritizing the development of technical standards and life-cycle assessment methodologies for alternatives to existing fuels, particularly ammonia and methanol. They will need to consider how best to balance the operational flexibility of having one or two ubiquitous shipping fuels in the global marketplace vs. the economic and political efficiency of allowing a wider portfolio of fuels.

To some extent, the pace at which these candidate fuels mature, reduce costs, and enter the market may ultimately determine which prevail for long-distance maritime fuel portfolios. Until that time, technology-neutral incentives and performance standards will likely be best suited to supporting progress in this space. The funding of targeted, fuel-specific projects aiming to develop early demonstrations are also important to acquire greater information on cost and technical feasibility. This information will support policymakers and stakeholders in the shipping sector in decision making.

If a fuel demonstrates that the combination of technical characteristics and successful market penetration enables it to secure a place in the long-term fuel portfolio safely and cost-effectively, and if there is a clear pathway for significant scale-up, regulatory requirements with greater specificity (e.g., regarding ammonia and/or methanol) can help ensure rapid and efficient deployment.

5.3.7 Expand access to European Union innovation funds for hydrogen-based aviation and shipping fuels

The existing mechanisms in place in the EU to support innovation regarding low-carbon fuels are based on Innovation Fund and Hydrogen Bank auctions and are financed by carbon pricing. These mechanisms help cover the cost gap between clean options and the benchmark. Funding is distributed via specific calls for proposals it is administered through grants agreement by CINEA (Box 3). This comes with the advantage of greater scrutiny and stronger steering capacity to align investments with policy choices, but it also runs the risk of placing administrative barriers on the mobilization of investments.

Thanks to open competition for the access to funds, the auction-based approach used for the Innovation Fund and the Hydrogen Bank also comes with the advantage of reducing risks that savings are not passed on to energy end-users. A similar effect is achieved by targeting airlines for the availability of SAF allowances.

Disbursements from the Innovation Fund could leverage the steering potential of the auction-based EU framework to prioritize low-carbon hydrogen supplies for aviation and shipping fuels, given the likely resilience of future demand. This could be achieved by introducing restrictions in auction eligibility criteria, in line with recommendations also made by the European Parliament (European Parliament, 2023).

Going forward, disbursements could also benefit from a progressive transition from the current project-based approach to a leaner and less administratively heavy market-based approach. This could be similar to the credit trading mechanism used in the low-carbon fuel standard while maintaining sector-specific requirements for aviation and shipping fuels to ensure progress within those sectors. Lower administrative barriers are more likely to be suitable for the scale-up required by the RefuelEU Aviation and FuelEU Maritime regulations.

While the SAF allowances nominally present some of these characteristics, their availability on a yearly basis—and in a way that is proportional to produced SAF volumes—creates potential drawbacks for investments in SAF production. Modifying mechanisms to enable longer term certainty and lower exposure to risks could help strengthen the capacity of investments to scale up SAF supplies.

5.3.8 Leverage offtake agreements, public procurement, and flexibility mechanisms like book and claim to mobilize investments, increasing affordable supply

Lessons from the EU electricity market reform could be used to facilitate the adoption of offtake agreements for the supply of low-carbon fuels, in conjunction with the use of book and claim flexibility instruments. These are particularly interesting as:

- They could grow the low-carbon hydrogen-based fuel availability, while allowing energy end-users to finance investments on fuel supplies and, indirectly, on renewable electricity, while respecting additionality/incrementality, temporal matching and deliverability/geographical correlation requirements that are already integrated in existing policies.
- They are well suited to help avoid (thanks to very low operational costs of renewable electricity) risks of price volatility.
- They allow end users of low-carbon fuels to reap these benefits directly, bridging risks of resistance from energy suppliers that see greater returns from continued investments in fossil energy supplies.

To be effective, they need to be multi-year (10 or more) to match the long payback periods of fuel production capacity, with take-or-pay conditions and a pricing formula that at least partially reflects the input costs, and they work best if paired with other de-risking measures, such as loan guarantees, debt service reserves[112] or government-held subordinated debt.[113]

Fuel supplies available from offtake agreements are also important to ensure downward pressure on the price of low-carbon fuels entering the market, helping to strike the balance between the joint needs of affordability and profitability for low-carbon aviation and shipping fuel options.

A similar role can be played by the public sector through public procurement. For example, to provide SAF to power government purchased air travel or low-carbon energy with significant scalability and cost reduction potential on shipping routes supported by public service contracts.

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[112] Where governments keep cash deposits to make interest and principal payments in case a private borrower fails to make scheduled payments.

[113] Where a public agency agrees to take on a lower priority position for debt repayment than senior debt holders, allowing senior debt holders to be repaid fully before other debt holders.

CfDs, CCfDs or similar auction-based instruments enable a progressive transition across the remaining part of the market. These, combined with platforms (including market-based mechanisms) enabling access to lower-cost, low-carbon fuels to multiple stakeholders, can help bridge potential inequalities in terms of capacity to access low-carbon fuels at more affordable costs, while leaving freedom to take voluntary action to businesses that are willing to be early adopters.

5.3.9 Set and/or maintain strict sustainability requirements to avoid misleading policy signals

Credible and stringent sustainability criteria and associated assessment methods are essential to ensure an effective alignment with sustainability and GHG reduction goals. They also support stable policy signals and consistent progress toward decarbonization, by ensuring that incentivized actions actually reduce GHGs, so policy makers are not required to revise requirements for low-carbon technologies to correct errors or avoid unwanted outcomes. While revising policy to align with evidence-based best practices is necessary at times, each revision risks stranding assets, reducing public and institutional confidence in policy signals as a guide for investment, and delaying decarbonization as stakeholders and markets adapt to new policy landscapes. Strict sustainability requirements, including additionality criteria, transparency and data sharing agreements, verification, and enforcement help ensure that any actions taken as a result of policy are likely to have their intended effect, thereby reducing the need for future corrective policy action.

The lack of these stringent criteria or the choice to adopt specific waivers, even if temporary, could increase the near-term availability of alternative fuels, but also risks of hampering or delaying the development of zero- and near-zero-carbon alternatives, and ultimately may backfire by postponing or preventing deep decarbonization.

In the case of aviation and shipping fuels, key requirements helping to guarantee long-term policy stability and technology viability include:

- Stringent sustainability criteria for fuels reliant on biogenic feedstocks, in line with the provisions already included in the Renewable Energy Directive of the EU[114], as they are necessary to guarantee the avoidance of undesired effects related with direct and/or ILUC, as demonstrated by the history of biofuel policies to date.
- Stringent additionality/incrementality, temporal matching and deliverability/geographical correlation requirements for electricity used in the production of hydrogen and e-fuels are essential to guarantee that investments in hydrogen and hydrogen-based fuel supplies do not induce increased reliance on unabated fossil fuel use in other parts of the economy.
- Transparent and coherent GHG emission accounting methodologies. These should not be limited to effects occurring at the margin (i.e., referring to the relative change

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[114] EU requirements are more stringent than in the case of the US, especially on feedstocks also needed for food and feed. These need to be capped or limited accounting for yield growth, net of the evolution of agricultural demand, to avoid price impacts that risk to be disproportionately impacting low-income countries and risk to induce deforestation (Murphy & Sperling, 2024). Caution also needs to be paid regarding waste oils and fats (whose use is capped in the EU), as their demand is already close to full exploitation of the available potential and its increase for aviation and shipping fuels can trigger unwanted indirect feedstock substitution dynamics in other industries (Malins & Sandford, 2022, IEA, 2022b, Malins, 2023).

in emissions of carbon with respect to the current conditions) but also integrating structural aspects (i.e., related with the absolute emissions of fossil carbon of the processes), as in the case of recycled carbon fuels in the post 2041 framework, in the EU.

Additional requirements are applicable to complementary technologies, including batteries, given their relevance to enhance energy efficiency of vessels and aircraft and their access to electricity when stationing in ports and airports.

5.3.10 Support the global alignment and mutual recognition of life-cycle greenhouse gas emission accounting and criteria for aviation and shipping fuels

Aviation and shipping fuel markets are international and current policies, in general, remain open to international sourcing options for low-carbon fuels destined to these end-uses. However, differences in life cycle GHG emission accounting and criteria defining sustainability alignment for technologies that could contribute to the decarbonization of aviation and shipping remain. These differences could act as undesirable barriers for the international mobilization of investments to scale up supplies.

The work started years ago at ICAO, on bio-based SAF has been offering opportunities to develop and strengthen international cooperation in this field. While it built on EU- and US-specific approaches developed with life cycle GHG accounting methods for their respective domestic biofuel policies, this effort also integrated effectively inputs from other global economies, including but not limited to Brazil, Japan and Indonesia. This work has also opened up opportunities to consider differentiated capacities to deliver GHG emission reductions for fossil-based fuels, depending on the way they are produced.[115] This same effort is now providing the basis of an expansion in scope, integrating e-fuels/RFNBOs. As discussed earlier, this is also offering the possibility to achieve significant progress at the IMO, following the recent decision to take a life cycle GHG emission accounting approach for the decarbonization of international shipping (similar to earlier decisions for international aviation). These examples also offer a strong basis for future coordination.

Enhanced coordination can be facilitated by international standards around GHG assessment via life-cycle assessment, better international alignment on the definition of sustainability criteria, and international cooperation to obtain and make public critical data needed to inform models used for regulatory purposes, especially LCA and ILUC assessment.

There are multiple approaches to life-cycle assessments and sustainability criteria that have been accepted as valid by the scientific community, which means that different methodologies of any given fuel or system may arrive at several equally valid outcomes based on defensible methodological choices. In absence of a common, empirically defined and shared methodology, consensus among experts and stakeholders is the primary approach to standardizing life-cycle assessment methods and sustainability criteria. This can be either by specification of methodological choices, or certification of a single model for a given regulatory purpose. International scientific consensus-building efforts can help identify

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[115] One example is the case of low-carbon aviation fuels (LCAF), even if—to date—this is still paired with limited GHG emission abatement levels. Other examples can emerge for different types of hydrogen derivatives.

where areas of agreement exist and codify these in law or standards at various jurisdictional levels.

Fully expanding international policy bodies' coverage to non-biogenic fuels and aligning their assessment methods with those used for biofuels can also help support effective decision-making and ensure policy incentives achieve their desired outcome. Participating in scientific consensus-building exercises maintains the strength that is already available from an inclusive process, globally, ensuring broad buy-in regarding the approach taken. This participation is ultimately necessary to ensure that these activities can effectively support the emergence of low-carbon fuel supplies. While there will be circumstances where deep divisions between stakeholders may prevent a consensus on a given topic from emerging, the time, effort, and resources spent engaging with the process can deliver a wide range of benefits towards implementing effective policy.[116]

A key advantage of the achievement of a multilateral consensus lies in the replicability and enhanced scalability of the market response, at the global scale, for the mobilization of sustainable, low-carbon aviation and shipping fuel supplies. This is particularly important in these sectors, given their international relevance. Aligning assessment methods can also help to leverage capital in developed economies to stimulate the development of low-carbon fuel supplies, at scale and in line with sustainability needs.

At the same time, national action is needed to move forward the global policymaking process. Specific efforts initially developed in the EU and the US were instrumental to achieve global progress, and so were inputs reflecting region-specific considerations by other countries. Early, region- or country-specific efforts on e-fuels/RFNBO accounting, will likely do the same for other pathways. Alignment of life-cycle GHG emission accounting and criteria defining sustainability alignment across fuels and regions can facilitate investments, but the urgency of addressing the climate crisis and challenges of reaching ambitious global agreements (paired with potential delays) also suggest that global alignment shall not be reached at all costs (ITF, 2021). This should therefore not exclude EU and US specific progress. Bilateral and multilateral action with like-minded countries can also be effective interim steps, supplementing country- or region-specific actions to accelerate progress.

5.3.11 Further explore power- and biomass-to-liquid fuel production systems and their integration in low-carbon fuel policies

PBtL fuels could help reap benefits available from low-carbon hydrogen and concentrated sources of biogenic carbon to yield greater amounts of fuels from the same amount of biogenic resources. PBtL processes can be designed to leverage biogenic carbon as an alternative to the capture of CO_2 and its reduction to CO, which is an energy-intensive part

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[116] For example, seminal papers on the topic of ILUC estimates for biofuels, especially corn ethanol, were published in the mind-to-late 2000s. In the decade following, the topic received a substantial amount of government and philanthropic funding for research and engagement. There were multiple scientific conferences on the topic, and dozens of peer-reviewed articles published. While true consensus is still elusive, the uncertainty range around corn ILUC estimates have narrowed over time and remain notably smaller than those on other feedstocks that have received less attention. In this case, the existence of multiple conferences, and the formation of various workgroups on the topic (e.g., CRC, n.d., NAP, 2022 and EPA, 2023b, in the US) created an opportunity for researchers and policy makers to share information and exchange ideas, improving both scientific understanding and the effectiveness of policy in this space, even though divisions remain around the topic.

of the e-fuel production process and risks being complex and expensive. By using biomass as the source of carbon, PBtL fuels leverages plants' photosynthetic capacity to perform this work, essentially outsourcing this difficult step to them. Many biofuel processes can achieve significantly higher yields at very low carbon intensity when low-carbon hydrogen (e.g., made by hydrolysis of water using electricity with near-zero life-cycle emissions, respecting additionality, temporal and geographical matching conditions) is integrated into the production process and other energy demands are also met with technologies with near-zero emissions.

Current policies integrate PBtL only implicitly into the mix of options suitable to supply low-carbon fuels to aviation and shipping and rely on frameworks that separate the accounting approaches for the biofuel and hydrogen-related shares (European Commission, 2024a). This may lead to proposed PBtL projects being deemed ineligible for incentive support because they don't match parameters intended for biofuel or hydrogen projects, and/or cause delays in deployment due to limitations in the way the regulatory framework accommodate PBtL pathways.

If they can live up to their potential, PBtL fuels can help provide demand for low-carbon hydrogen, as a feedstock for low-carbon aviation and shipping fuels. This could be especially promising in terms of GHG emission abatement in the cases where electrolytic hydrogen inputs can reduce emissions of biogenic CO_2. Processes based on the recovery of concentrated streams of CO_2 and their conversion into fuels (as RFNBOs) are also relevant here. PBtL fuels can also help ensure that low-carbon hydrogen production capacity has a near-term viable market, in absence of opportunities for its direct use as energy carrier.

The development of explicit guidance enabling a scale up of PBtL fuels could enable a more resource efficient use of biogenic carbon, especially in cases where the scope for carbon capture (which is an alternative to the use of concentrated streams of CO_2 for fuel synthesis) is limited. Due to the complexity of the pathways and related certification of PBtLs, dedicated clearinghouses for data and expertise—such as those already established in the EU and the UK—can be instrumental to enable progress on the way PBtL can become part of the aviation and shipping fuel mix.

To avoid risks of policy instability, care should be placed for PBtL-specific requirements to ensure consistency with strict sustainability requirements, both for biogenic and (in case of combined CO_2 sourcing, e.g., from waste) for non-biogenic feedstocks (leading to RCFs).

Additional support for both PBtL fuel research, commercial-scale technology demonstration projects, and improved tools for modeling and assessment would also help maximize their potential to reduce GHG emissions.

Annex 1 – Data Sources

Table A1.1. Data sources used for the assessment of life-cycle GHG emissions and energy ratios

Fuel group	Sources of information used
Fossil fuels	Values based on GREET (ANL, 2024 – GREET – and ANL, 2019 – GREET-ICAO) and slightly lower, for life-cycle GHG emissions, than the benchmark of 94 gCO_2/MJ used in European legislation (European Union, 2018).
Biofuels	Values are based on GREET (ANL, 2024 – GREET – and ANL, 2019 – GREET-ICAO) and consistent with ranges available in Sarisky-Reed, 2022 for direct GHG emissions from biochemical conversion of cereals, complemented by Pavlenko & Searle (2021) for emissions from indirect land use change, based on ICAO default values. ANL, 2024 and ANL, 2019 also inform energy ratios. Pavlenko & Searle (2021), based on ICAO default values, is the source of information used for biochemical conversion of sugar cane, and both biochemical and thermochemical conversion of advanced feedstocks (biomass residues), in combination with ANL, 2024 and ANL, 2019, also used to inform energy ratios. Chiaramonti & Testa (2024) and Hannon et al. (2019) are used for assumptions on the incremental energy losses for alcohol-to-jet (ATJ) pathways with respect to ethanol, considering a progressive transition towards a 10% energy penalty from the ATJ conversion. Oleochemical pathways are assumed to meet the 65% minimum GHG emission abatement on a life-cycle basis required by the EU Renewable Energy Directive. Based on Pavlenko & Searle (2021), this requires to avoid the displacement of waste oils and fats from existing uses. Resulting estimates are also aligned with indications available in Prussi et al. 2021, Prussi et al., 2020, Bakker et al., 2022, Malina et al., 2022 and Cai et al., 2022. They also benefit from information from Sarisky-Reed, 2022, Searchinger et al., 2022, Panoutsou & Maniatis, 2021, Panoutsou et al. 2022, IRENA, 2019, Giuntoli & Searle, 2019, van Dyk et al, 2019, IEA, 2020, Valin et al. 2015, OECD/FAO, 2021, OECD/FAO, 2022, OECD/FAO, 2023, IEA, 2021, IEA, 2022c, Malins, 2017, Malins et al., 2020, Taheripur et al, 2020 and Malins & Sandford, 2022.
Hydrogen and e-fuels	Values are based on NREL (2021) and Soler et al. (2022) for low-carbon hydrogen. Data reported reflect an average value for different low-carbon pathways, from renewable and nuclear primary electricity, excluding indirect effects (and therefore additionality, temporal and geographical correlation considerations). Life-cycle energy use and GHG emissions are based on Liu et al. (2020), IRENA (2022) and Bicer at al. (2016) for ammonia, ANL, n.d. , Howarth & Jacobson (2021), Romano et al. (2022) and Howarth and Jacobson (2022) for hydrogen from natural gas, with CCS and Diab et al. (2022) for hydrogen from methane pyrolysis. In 2030 and beyond, hydrogen from fossil resources is assumed to meet the EU 70% life-cycle emission reduction requirement. This is feasible, based on Romano et al. (2022), but only with the integration of renewable

	energy in the process and the use of specific technologies, allowing to maximize abatement opportunities, for the hydrogen synthesis. As in the case of hydrogen, indirect effects (and therefore additionality, temporal and geographical correlation considerations) are excluded. Ocko and Hamburg (2022), Derwent et al. (2020), Kobayashi et al. (2019), Wolfram et al. (2022) and European Union (2023) also informed the assessment.
Recycled carbon fuels	Values are based on a 40% life cycle GHG emission reduction with respect to the benchmark due to the need to share emission savings with industrial users and a 1.5 MJ/MJ energy ratio, based on indications from DfT (2022).

Note: this assessment draws extensively from information contained in the Annex of Trinomics (2023). Processes are assumed to be optimized, leading to gains from improved energy efficiency and technology learning as they are scaled up. This is reflected by limited reduction in energy ratios and life-cycle GHG emissions over time.

Table A1.2. Data sources used for the assessment of costs

Fuel group	Sources of information used
Fossil fuels	Production costs of petroleum-based fuels (assuming no change in oil prices, values centered on an oil price of 95 USD/barrel oil paired with a 20% markup from refining and distribution for aviation fuels, and a 25% lower benchmark for shipping fuel. This is in line with estimates used by IEA (2023b).
Biofuels	Production costs for biochemical biofuels are the result of a balance between feedstock costs and conversion costs of feedstock into fuel (including capital and operating costs). Feedstock costs are lower for lignocellulosic biomass and higher for food and feed products, like cereals (IEA, 2013, IRENA, 2013, ICAO, 2018 and Detsios et al., 2023). Conversion costs (i.e., the cost of processing feedstocks to obtain fuels) are higher for lignocellulosic pathways, in comparison with corn, cereals and sugar cane conversion (enzymatic hydrolysis is more complex than conventional fermentation). Production costs (excluding cases of biomass production on marginal land, for which costs are higher due to low productivity, unless there are other revenue streams) were in the range of 15-18 USD/GJ for both US corn and Brazilian sugarcane ethanol before the surge in commodity prices seen between 2021 and 2023 (IEA, 2019b, Irwin, 2021 and 2024 and prices from US Grains Council, 2019 and 2024). Accounting for a 70% increase in corn prices and 40% increase in sugar prices vs historical (pre-Covid) values and for a feedstock cost share of 60% for corn in the final production cost (before the price increase) for both corn and sugar cane-based pathways (in line with the information available in IEA, 2013), suggests that biofuel production costs were close to 21-26 USD/GJ for corn-based ethanol and to 18-22 USD/GJ for sugar cane-based pathways in 2022. Similar biofuel costs are also at the lower end of the range reported in IEA (2024). This is also consistent with indications from ethanol prices (US Grains Council, 2022). Due to the maturity of the conversion technologies, future costs are likely to depend in a way that is far more significant on the evolution of commodity prices rather than technological developments Costs of biochemical ethanol from advanced feedstocks have been assessed in a range between 33 and 55 USD/GJ, and even as low as 30 USD/GJ with technology improvements and scale increases (IEA, 2013, Witcover & Williams,

2020), as long as feedstock prices remain at a level comparable with those observed before Covid. Due to slow progress against similar expectations in the early 2000s (IEA, 2004), costs at the lower end of the ranges retained are considered here as optimistic. Accounting for a 25% increase in feedstock price (reflecting lower impacts on lignocellulosic feedstock prices of the commodity price increase, in line with historical trends) and a feedstock cost share of 20%, in line with IEA (2013) and Detsios et al. (2023), costs for ethanol from advanced feedstocks fall between 37 and 58 USD/GJ range in the base year and decline to values between 30 and 45 USD/GJ in the long term, attempting to factor in (possibly too optimistically) a cost reduction potential from technology progress.

Cost estimates for ATJ are well above those of conventional ethanol, and estimated at 45 to 55 USD/GJ (ICAO, 2018, Pavlenko et al., 2019, Malina et al., 2022 and Detsios et al., 2023). This assessment uses cost gaps between ethanol and ATJ reflecting lower energy penalties from improved ATJ from ethanol conversion processes in comparison with these assessments. These are informed by data available in Chiaramonti & Testa (2024) and reported in Hannon et al. (2019). This results in cost ranges between 24 and 35 USD/GJ in the near term, for ATJ from ethanol from cereals and cane, and 20 to 26 USD/GJ in the long term. Values for biochemical pathways from advanced feedstocks are higher, owing to higher alcohol costs. They range between 47 and 79 USD/GJ in the near term, declining in the range between 36 and 59 USD/GJ in the long term. Lower values reflect more optimistic assumptions on capital investment cost reductions and energy efficiency improvements.

Oleochemical biofuel production costs are also largely dependent on feedstock costs. Estimates pre-dating the price surges observed after the Russia/Ukraine war are in the range of 25-35 USD/GJ for pathways based on virgin vegetable oils – based on IEA (2013), IRENA (2013), IEA (2018) , Pavlenko et al. (2019) and ICAO (2018). Technological developments are unlikely to have significant impacts on cost reductions, as conversion technologies for oleochemical feedstock are mature. For the same reason, feedstock cost variations have significant impacts on the cost of production of oleochemical biofuels. Considering an 80% share of feedstock cost before the commodity price increase of 2022 – in line with IEA (2013) and Detsios et al. (2023) – which show that production costs of fuels from oleochemical pathway largely depend on the cost of the feedstock), along with a 45% increase of vegetable oil prices, indicates that near term production costs for oleochemical pathways reliant on vegetable oil as feedstock are closer to 34-48 USD/GJ. Limited reductions arise from energy efficiency improvements going forward. Costs of oleochemical biofuels from low ILUC risk feedstocks also integrate an incremental factor (about 10%) to reflect the cost gap between virgin oil and used cooking oil (or methyl esters derived from them) observed in market data (e.g., Argus, 2023 and Kosenkow, 2024).

Thermochemical biofuels, and in particular fuels produced through a gasification/Fischer-Tropsch process, are subject to large upfront capital investments. Overall cost estimates (developed before the recent commodity price increase) are likely to range between 45 and 55 USD/GJ (Pavlenko et al., 2019 and ICAO, 2018). These, corrected to factor in a 25% increase in feedstock price and a feedstock cost share of 20% (similar to advanced biogenic pathways) are the values retained in this assessment for near term costs. More optimistic cost assessments, as low as 30 USD/GJ, have also been reported (IEA, 2013,

	IRENA, 2013, Pavlenko et al., 2019, Hannula, 2016 and ICAO, 2018). A 30 to 45 USD/GJ is what has been used here in the long term, to factor in (possibly too optimistically) a cost reduction potential from technology progress. The costs of all biofuel feedstocks are not assumed to evolve (in real terms) over time, with respect to the ranges observed in the recent past.
Hydrogen and e-fuels	Production costs of renewable hydrogen largely depend on the costs of renewable electricity production. For hydrogen obtained from electrolysis (in gaseous form), production costs are estimated between 25 and 50 USD/GJ (3 and 6 USD/kg) if electricity costs are between 0.025 and 0.07 USD/kWh (IEA, 2019a). Costs could also be as low as 8 to 16 USD/GJ (1 to 2 USD/kg) if production takes place in very favorable conditions (i.e., with high capacity factors and therefore low capital costs – in the 0.01 to 0.02 USD/kWh range, and low electricity costs – in the 0.01 to 0.025 USD/kWh range) (IRENA, 2022b). Liquid hydrogen costs are higher, even in regions where electricity costs may be very low, due to the need for additional processing steps. According to Breitschopf et al. (2022), this leads to production costs for liquid hydrogen that are between 27 and 55 USD/GJ, depending on the renewable electricity production costs that are possible in different global regions. The costs of transporting hydrogen by road (on-board trucks) are estimated in a range between 12 and 20 USD/GJ (1.5 and 2.5 USD/kg) (carrying liquid or pressurized gaseous hydrogen, considering transport volumes greater than 5 t/day). The costs of transporting hydrogen by dedicated pipelines (which require tens of tons in terms of volumes transported) are between 8 and 12 USD/GJ (1 and 1.5 USD/kg) (IEA, 2019). Additional costs, estimated between 20 and 40 USD/GJ (2.5 and 5 USD/kg), also apply to cases where hydrogen is imported by sea (IRENA, 2022b, Breitschopf et al., 2022) The distribution of hydrogen is also necessary to bring hydrogen to end users, possibly combining with the need in industrial facilities. Similar to transport, distribution can take place in two ways: by road, on-board of trucks, and by pipelines. The latter are much less relevant for small volumes of demand in widespread distribution sites, such as in the case of use in transport vehicles, due to high investment costs per unit of fuel delivered. Estimates of distribution costs are close to 12-15 USD/GJ (1.5-1.8 USD/kg) for hydrogen trucks (Yang and Ogden, 2008 and IEA, 2019a). Hydrogen refueling stations at 700 bar have investment cost estimates of around USD 1-1.5 million for a capacity of 500 kg/day (equivalent to 2,000-3,000 USD per kg/day of distribution capacity) (IEA, 2019a). The unit cost per kg of hydrogen also depends on the capacity utilization rate of the filling station. Considering a value for capacity utilization of 20% adds about 3 USD/GJ. Costs of renewable hydrogen as a fuel delivered to aviation and shipping may be lower (where it may be possible to avoid distribution costs and to leverage synergies with industrial clusters and the so-called hydrogen valleys), but it is estimated to be likely above 50-66 USD/GJ (6-8 USD/kg) at least for a decade. Since the unit cost per kg of hydrogen also depends on the capacity utilization of infrastructure, costs risk being significantly higher of low infrastructure utilization. This is reflected in the high end of the cost estimates, in this work. On the contrary, low-cost estimates reflect both low production and infrastructure costs, based on the data outlined above.

Optimistic assumptions reflect cases where costs for hydrogen deliveries fall below USD 35/GJ (USD 4/kg). This is only possible if hydrogen is produced from abundant primary renewable energy resources available at very low costs (e.g., in cases where they would otherwise be stranded, due to high costs of access to demand markets) and if it is widely used in other sectors (as this is crucial to share transport and storage costs). It is clearly an optimistic assumption.

Centralized renewable hydrogen production (e.g., in large-scale renewable electricity & electrolyzer plants) is subject to lower unit costs thanks to economies of scale, but it loses competitiveness vs. decentralized production due to the need for a hydrogen transport and distribution network.

Based on IEA (2019), capital costs for fossil-based hydrogen production from methane reforming have been estimated at 2.5 USD/GJ without CCS and 4.2 USD/GJ with CCS. Operational costs have been estimated at 1.75 USD/GJ without CCS and 3.3 USD/GJ with CCS. Ratios of energy inputs to hydrogen outputs have been assumed in the 1.5 to 1.7 range, for these processes based on ANL, 2023, Romano et al. (2022) and Howarth and Jacobson (2022). Related methane to hydrogen ratios are assumed 0.5 units lower. Production costs for hydrogen from methane are based on these data, combined with a range of methane prices that span from current values in the US market in the low-end (2.1 USD/MMBtu, or 8 USD/MWh, or USD 2.2/GJ) to sustained price increases for natural gas, reaching 120 USD/MWh, or USD 33/GJ, as discussed in the main text. These values are well below the peaks observed in 2022 and 2023 in the EU, which exceeded USD 50/GJ in 2022 and reached USD 100/GJ before the winter of 2023 (IEA, 2022a, Trading economics, n.d.). A 10% energy penalty is also factored in, for CCS. This is consistent with indications from Romano et al. (2022).

Production from methane pyrolysis is assumed to have the same CAPEX and OPEX as SMR without CCS. Methane and electricity consumption costs are added to this, taking into account of methane-to-hydrogen and electricity-to-hydrogen needs based on Diab et al (2022), including significant potential for improvement for long term estimates, with primary energy ratios falling from 3.2 to 2.6 MJ/MJ, overall. This is also paired with a range of methane prices that span from current values in the US market in the low-end to sustained price increases for natural gas, reaching 120 USD/MWh, or USD 33/GJ, as discussed in the main text.

In cost estimates retained for the analysis, different estimates of centralized production from pathways based on fossil energy are also combined with the same ranges of infrastructure cost assumptions used for centralized renewable hydrogen production. The combined ranges of methane prices and infrastructure costs explain the wide variability of possible cost estimates for fossil-based hydrogen.

IRENA (2021) gives near-term cost estimates for renewable e-methanol in a range of 60 to 120 USD/GJ. An assessment developed in Breitschopf et al. (2022) suggests cost estimates in a similar range (between 55 and 100 USD/GJ) for imported e-methanol (delivery at the border of Europe). For renewable e-methane, the cost suggested by Breitschopf et al. (2022) is roughly 4-5 USD/GJ lower than for e-methanol, and, for renewable e-diesel production, up to 4-5 USD/GJ higher than for e-methanol. IEA (2019) also points to a similar gap (roughly 7 USD/GJ) between renewable e-methane and e-diesel. Near-term cost

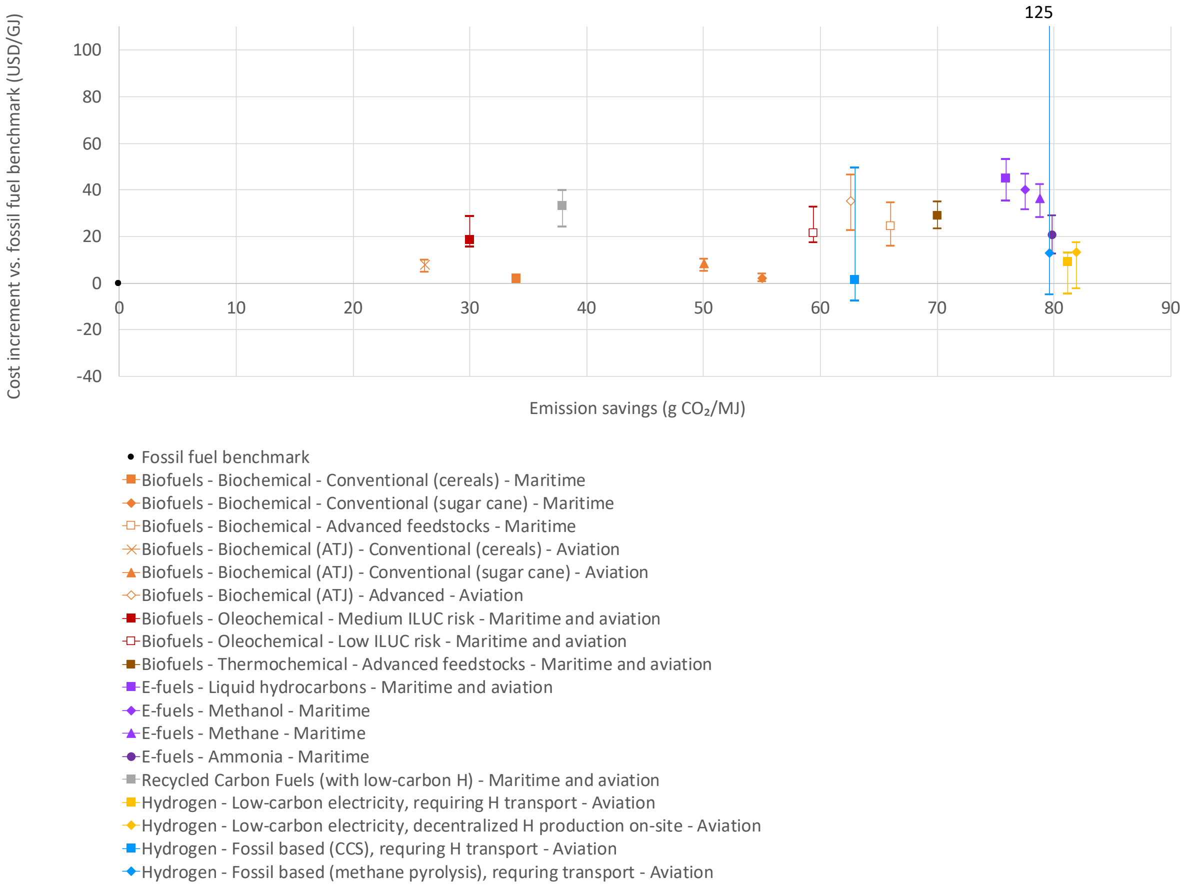
	values estimated for renewable e-diesel by Breitschopf et al. (2022) and IRENA (2021) are also similar to those of renewable e-kerosene assessed in Zhou et al., (2022) (70 to 100 USD/GJ). The values in this range are compatible with costs between 600 and 1,000 USD/t for DAC and 3 to 6 USD/kg for hydrogen production from renewable electricity and electrolysis. Long term values by Zhou et al., (2022) and IEA (2019) range between 30 to 60 USD/GJ. Similar ranges (47 to 64 USD/GJ in 2030 and 25 to 35 USD/GJ in 2050) are also projected for renewable methanol form DAC by the Mærsk Mc-Kinney Møller Center, focusing on shipping (Mærsk Mc-Kinney Møller Center, 2021). This is paired with a gap between DAC and point source that adds 5 to 10 USD/GJ in 2030 and about half in 2050. Soler et al. (2022) also point at a cost penalty of 5 USD/GJ in the long term, for DAC. In addition, Breitschopf et al. (2022) estimates that approximately 2.7 USD/GJ should be added to renewable e-methane and USD 2.2/GJ for e-methanol costs, if they are traded (at scale) across global regions, compared with 1.6 USD/GJ for e-diesel. Renewable e-ammonia is the cheapest RFNBO to produce, except for renewable hydrogen (Mærsk Mc-Kinney Møller Center, 2021). As in the case of other e-liquids, the cost of renewable e-ammonia depends largely on the cost of hydrogen production through electrolysis (IRENA, 2022a and IEA, 2019a). The other steps of e-ammonia production (nitrogen purification and the Haber-Bosch process) are only a small fraction of the total cost. Estimates by Concawe range between 45 and 65 USD/GJ for European production, in a 2030 timeframe (Soler et al., 2022). IRENA's near-term cost estimates for renewable e-ammonia range between 40 and 75 USD/GJ. Potential cost reductions largely depend on decreases in the price of renewable electricity. Additional savings can result from reductions in the cost of electrolyzers. These could come from technology learning with large-scale deployment. Efficiency gains and the optimization of storage and operational hours can also contribute to reducing production costs (IRENA, 2022a). Projected values integrating such improvements are in the range of 30 to 50 USD/GJ by 2030 and even 15 to 30 USD/GJ by 2050 (IRENA, 2022a). Concawe indicates a range between 35 and 55 USD/GJ for ammonia, in 2050, considering production in Europe and/or the Middle East and North Africa (Soler et al., 2022). Infrastructure costs for e-methanol are assumed to be half of those of methane (LNG) as a shipping fuel. Methane infrastructure costs are assumed to be a sixth of the transport cost with respect to hydrogen (as part of the CAPEX for transport infrastructure already amortized), adding to half of the distribution and refueling costs for hydrogen. Infrastructure costs for e-ammonia are assumed to be half of those considered for hydrogen as an energy carrier, to reflect handling complexities due to its toxicity. The cost assessment is also informed by Breitschopf et al. (2022), ACER (2021), Houssin et al. (2021) and H2FCP (n.d.) for hydrogen, by IEA (2023b), Breitschopf et al. (2022), Global Maritime Forum (2021) for e-hydrocarbons, by IEA (2023), Breitschopf et al. (2022) and Global Maritime Forum (2021) for e-ammonia.
Recycled carbon fuels	Cost estimates are informed by the assessment of the Mærsk Mc-Kinney Møller Center for methanol from point source CO2, ranging between 41 and 55 USD/GJ in 2030 and 22 to 32 in USD/GJ 2050 (Mærsk Mc-Kinney Møller Center, 2021),

	paired with a gap between DAC and point source that adds 5 to 10 USD/GJ in 2030 and about half in 2050. Soler et al. (2022) also point at a cost penalty of 5 USD/GJ in the long term, for DAC. The cost assessment for recycled carbon fuels is also informed by DfT (2022).

Note: this assessment draws extensively from information contained in the Annex of Trinomics (2023), adding targeted updates – namely on ATJ, based on Hannon et al. (2019), from IEA (2023) and from IEA (2024). Processes are assumed to be optimized, leading to gains from improved energy efficiency and technology learning as they are scaled up. This is reflected by limited reduction in energy ratios and life-cycle GHG emissions over time. Variability comes from differences in CAPEX, OPEX, feedstock and infrastructure costs, as discussed in the main text. This is why costs are considered in the analysis as ranges. Mid-point estimates reflect considerations outlined in the main analysis, generally focusing on mid-point assessment of production costs detailed here (except for pathways based on natural gas, for which central estimates exclude the price spikes seen in the EU and in Asia between 2021 and 2023, as outlined in the main analysis), adding to mid-point values for infrastructure costs.

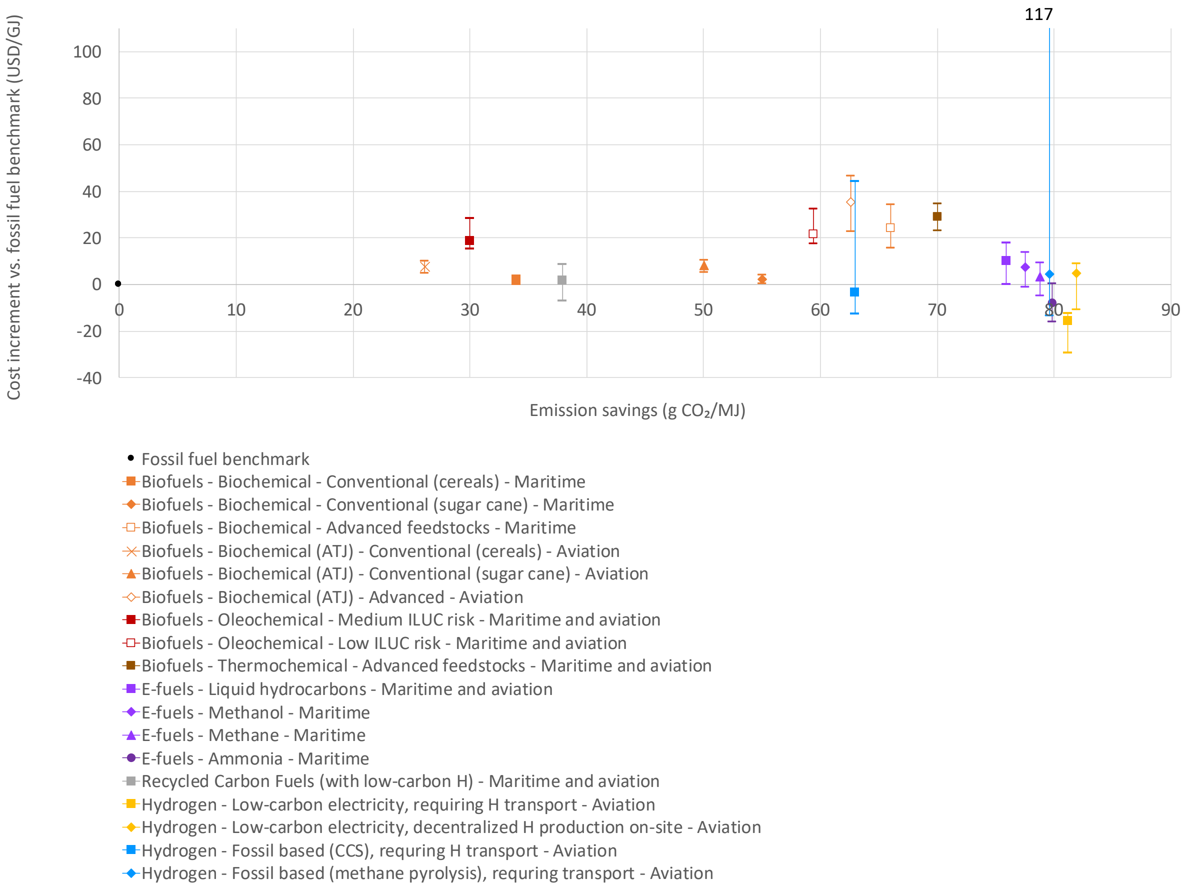
Annex 2 – Complementary Results

Figure A2.1. Savings of GHG emissions/MJ and production cost differentials for a selection of shipping and aviation fuel, no policy case, near-term (2030)



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 7 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Costs only reflect production, excluding infrastructure. For the fossil fuel benchmarks, the cost considered is an arithmetic average of the values applied for aviation and maritime.
Source: this assessment.

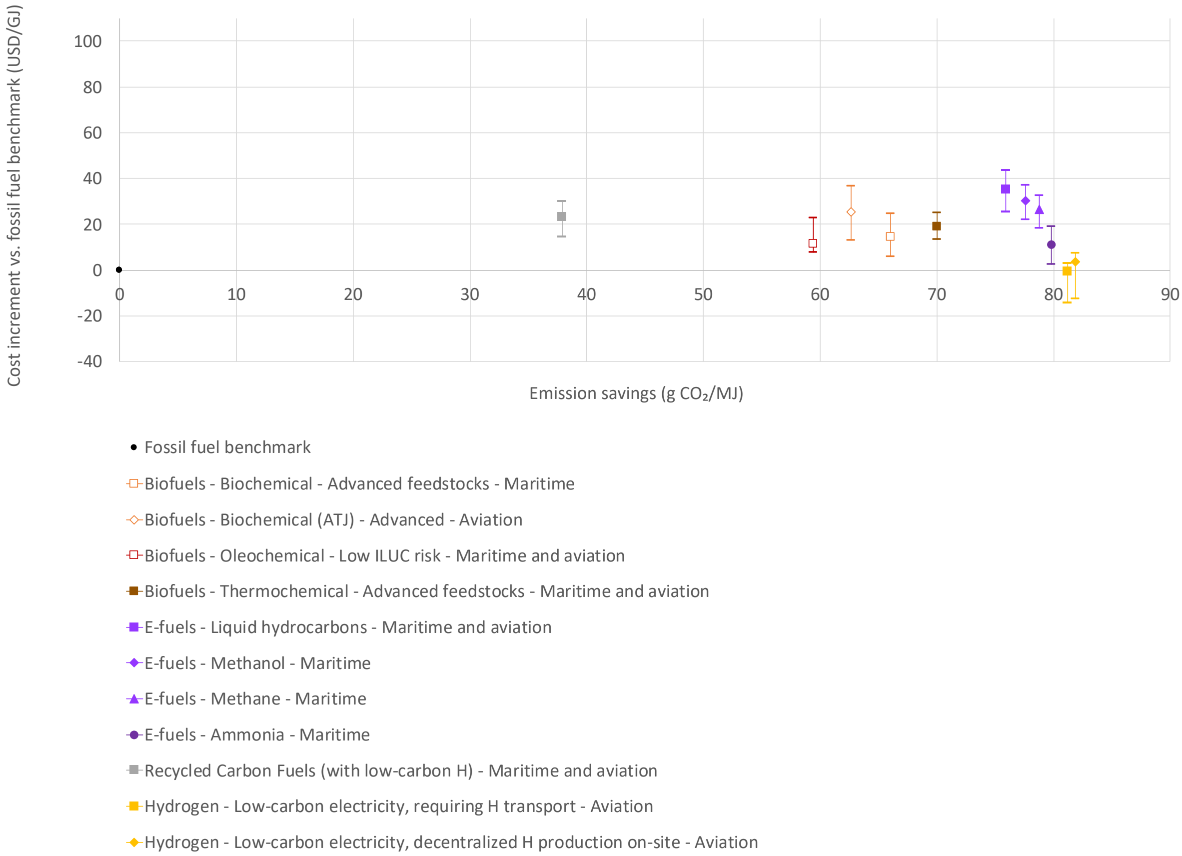
Figure A2.2. Savings of GHG emissions/MJ and production cost differentials for a selection of shipping and aviation fuels, showing the impact of production credits available from the IRA, near-term (2030)



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 7 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Costs only reflect production, excluding infrastructure. For the fossil fuel benchmarks, the cost considered is an arithmetic average of the values applied for aviation and maritime.

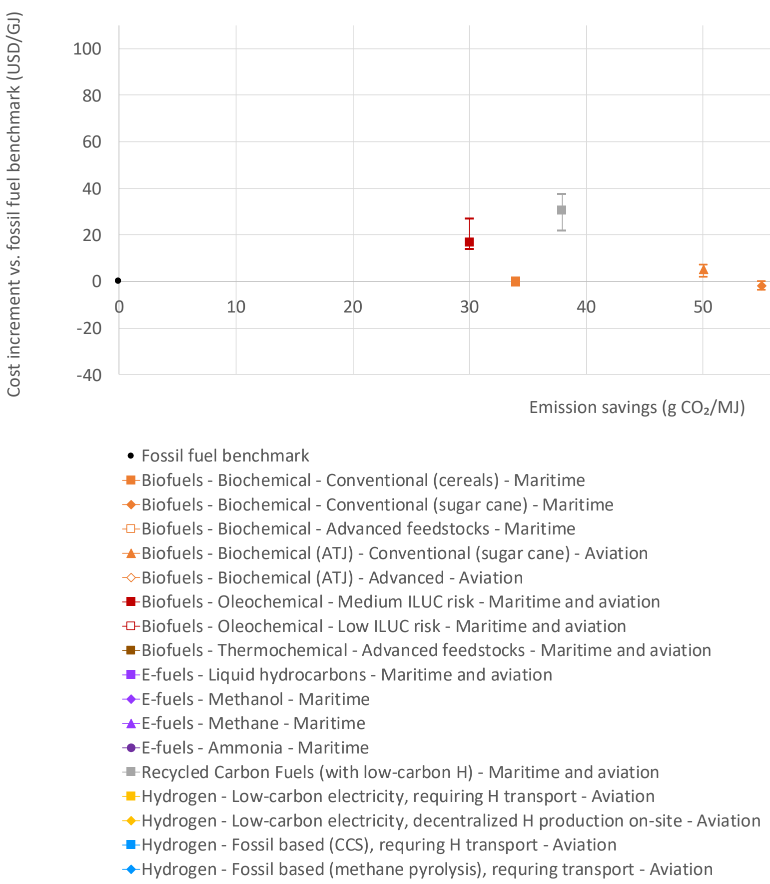
Source: this assessment.

Figure A2.3. Savings of GHG emissions/MJ and production cost differentials for a selection of shipping and aviation fuels, showing the impact of the EU ETS, near-term (2030)



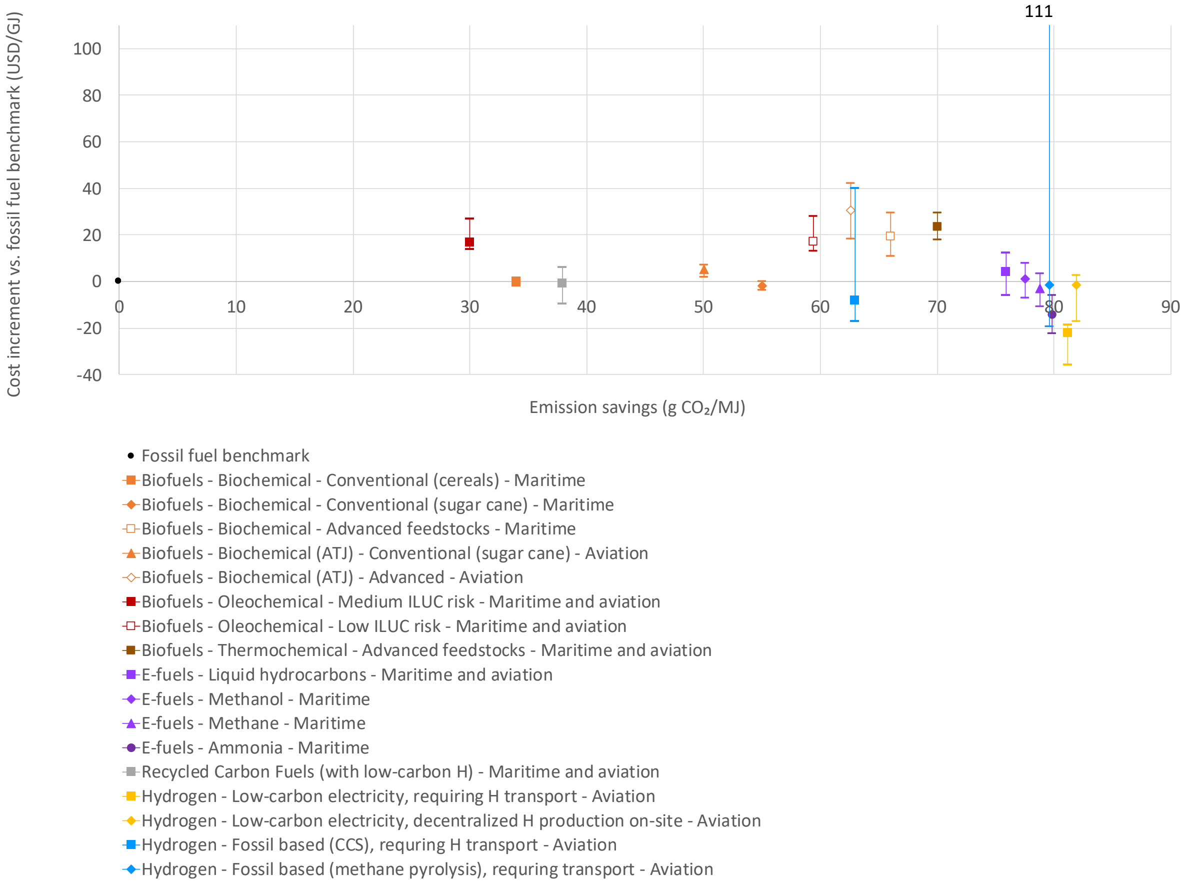
Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 7 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Options not qualifying for the sustainability requirements under the Renewable Energy Directive or the RefuelEU Aviation (which excludes food and feed crops) are not shown. Costs only reflect production, excluding infrastructure. For the fossil fuel benchmarks, the cost considered is an arithmetic average of the values applied for aviation and maritime.
Source: this assessment.

Figure A2.4. Savings of GHG emissions/MJ and production cost differentials for a selection of shipping and aviation fuels, showing the impact of California's carbon pricing policies, near-term (2030)



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 7 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Costs only reflect production, excluding infrastructure.
Source: this assessment.

Figure A2.5. Savings of GHG emissions/MJ and production cost differentials for a selection of shipping and aviation fuels, showing the impact of California's carbon pricing policies and the IRA, near-term (2030)



Notes: each alternative energy option is represented by a range of values, reflecting the lower bound, the central estimate and the upper bound of the cost assessments included in Table 7 combined with the policy effects. Lower and upper bound are represented at the top and bottom of the whiskers, for each fuel. The central estimate is shown by the central marker. Costs only reflect production, excluding infrastructure.
Source: this assessment.

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