Title

Analysis of Clean Fuel for Aviation and Maritime Transport in US and EU

Author

Kang, Laedon

Publication Date

2024

Analysis of Clean Fuel for Aviation and Maritime Transport in US and EU

By

LAEDON KANG
THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Transportation Technology and Policy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Daniel Sperling, Chair

Alan Jenn

Jesus M. Barajas

Committee in Charge

2024

Abstract

Aviation and Marine transport are small but critical elements of the global transportation ecosystem. This study compares each jurisdiction's policy strategies (i.e., aims, enforcement type, and policy level) and policy influence on the production costs of low carbon fuels for maritime and aviation in the US and EU. In the US, two policies, the Renewable Fuel Standard (RFS) and Inflation Reduction Act (IRA), provide a foundation for alternative fuel deployment in these sectors. The EU has an extensive legislative package, Fit for 55, for aviation and maritime. The two regions also have carbon credit trading systems: Low Carbon Fuel Standard (LCFS), Cap and Trade (CAT) in California (CA), and Emission Trading System (ETS) in the EU. As CA provides additional benefits to federal policies, it would represent the highest level of US clean fuel policies. We analyze the policy impact on production costs of clean fuels. After applying policy influence to production costs, we calculate the Total Actual Cost (TAC) of fourteen different fuels in three categories (i.e., biofuel, hydrogen, and electrofuel (Efuel)). In phase I, we estimate production costs through subsidies, penalties, and carbon trading prices in the CA and EU. In phase II, we predict the value of input parameters of TAC using Vector Autoregression (VAR) with macroeconomic variables (i.e., Consumer Production Index (CPI) and Natural Gas (NG)). Monte Carlo Simulation (MCS) is implemented to consider the uncertainties of TAC in the future. In phase III, Marginal Abatement Cost (MAC) is generated for maritime and aviation in each region, as it is widely used for climate change policies. The result in phase I shows that the price of clean fuel in CA is lower than in the EU, but the cost of penalized fossil fuel in the EU in maritime is 78.5 \$/GJ, while it is only 45 \$/GJ in CA. The predicted distribution of TAC in phase II reveals that clean fuels would be more competitive with continued policy. In phase III, the projected Marginal Abatement Cost (MAC) suggests that a combination of sources would be used for both aviation and maritime. In all phases, the EU has higher costs than CA, and the shipping sector has continuously higher expenses compared to aviation. In the future, hydrogen and biofuels tend to have lower abatement costs than Efuel.

Acknowledgments

I would like to thank Incheon International Airport Corporation for supporting me in the Transportation Technology and Policy master program. I would like to thank Colin Murphy, Pierpaolo Cazzola, Jin Wook Ro, and Julie Witcover for sharing research experience and knowledge on regulations in CA and EU. I would like to thank my wife and children for their patience and encouragement.

Contents

List of Tables

List of Figures

List of Acronyms

ACI Airport Council International

AFIR Alternative Fuels Infrastructure

CAPEX Capital Expenditure

CAGR Compound Annual Growth Rate

CO2e Carbon Dioxide Equivalent

CPI Consumer Price Index

ETS Emissions Trading System

Efuel Electrofuel

GHG Greenhouse Gas

GWP Global Warming Potential

IATA International Air Transport

ICAO International Civil Aviation Organization

IMO International Maritime Organization

IRA Inflation Reduction Act

LCFS Low Carbon Trading System

LCA Life Cycle Assessment

LNG Liquefied Natural Gas

MAC Marginal Abatement Cost

MCS Monte Carlo Simulation

NG Natural Gas

NPV Net Present Value

OPEX Operational Expenditure

RFS Renewable Fuel Standard

RED Renewable Energy Directive

RINs Renewable Identification Numbers

SAF Sustainable Aviation Fuel

VAR Vector Autoregressive

CAT Cap and Trade

Introduction

Emissions from maritime account for about 3%, and aviation contributes approximately 2% to total GHG emissions worldwide. This is expected to increase with the increasing demand for shipment and international business (Bjerkan, 2019; ICAO, 2024). Road transportation has been electrified at a fast pace and is expected to account for over 60% of vehicles sold globally (IEA, 2022). Aviation and Maritime are heavy oil demand industries. Still, given the importance of the weight and space of vessels and aircraft, they are hard to electrify due to the difference in energy density. The energy density of a lithium battery is around 3MJ/kg at best, while heavy fuel for maritime and jet fuel in aviation are over 40 MJ/kg (DOE, 2020). Three alternative fuels are being investigated as primary resources in aviation and shipping. Firstly, biofuel is a ‘drop-in' fuel, which means they can be easily integrated into existing infrastructure and engines. (EMSA, 2023). Secondly, hydrogen is chosen because it is the most common element in the world (IATA, 2020). Lastly, producing Efuel from renewable sources is a more cost-effective alternative to electrification in the aviation and maritime sectors (ITF, 2022). Given the challenges of electrification, pilot projects are already launched with these project. For example, hydrogen-powered commercial ships have been operating in Norway since 2023, and the European Economic Area (EEA) launched 45 Efuel projects for aviation in 2024[1]. Additionally, Airbus Corporation launched a hydrogen project with academic partners in three EU airports[2]. Thus, we consider these three types of fuels (i.e., biofuel, hydrogen, and Efuel) in the study.

---

[1] (EU Federation, 2023), (Holtze, 2023)

[2] (EN Airbus, 2024)

This study seeks to answer the research question: what are the most economically viable and sustainable alternative fuels for the aviation and maritime sectors in the context of current U.S. and EU policies, and how would these policies influence the future fuel mix in these industries? This study also aims to provide policymakers with insights about the expected impact on the aviation and maritime fuel markets. The US and EU have different approaches to encouraging alternative fuels. The US is a supply-driven strategy, offering incentives to clean fuel producer and refiners, but the EU is demand-driven, requiring operators to reduce GHG emissions. Analyzing current policies is critical, but incorporating uncertainty into the forecast would also be necessary. This paper presents an economic analysis of the existing clean fuel policy for alternative energy, using methodologies to address uncertainty. Policymakers would be able to identify the most viable fuels for each industry with the aid of this analysis.

1. Background

US and the EU have unique regulation environments. These two jurisdictions have two tiers of legislation, in contrast to other countries. Federal law and state regulation coexist in the US. The EU has a directive that establishes a legal objective and regulations, and each member developed their own policy to achieve the goal from directives.

1.1 policy in the US

In the US, key policies recently enacted include the Infrastructure Investment and Jobs Act, known as the Bipartisan Infrastructure Law of 2021 (US Congress, 2021), and the Inflation Reduction Act of 2022 (US Congress, 2022). The Bipartisan Infrastructure Law (BIL) is a massive once-in-a-generation infrastructure investment aiming to ensure a durable and equitable economic recovery post-Covid. It provides billions of dollars to modernize the electricity grid, expand public transit and passenger rail, and invest in new clean energy and emissions reduction technologies. (White House, 2023).

IRA focuses on monetary incentives, providing tax credits for alternative fuels and a comprehensive benefits package that supports technology development and infrastructure. The IRA includes provisions specifically promoting the production and use of Sustainable Aviation Fuel (SAF) through tax credits. Producers of SAF who meet specific criteria are eligible to claim tax credits.

The IRA introduces SAF credits (40B) conditional to levels of GHG emission reduction and only available for SAF cutting GHG emissions by more than 50% (White House, 2022, US Government, 2022). The IRA Clean Fuel Credits (45Z) apply to SAFs and other bio-based fuels for maritime fleets. Hydrogen producers can also receive production credits (45V) under the IRA. These credits range from 0.6 to 3 \$/kg for facilities that meet registered apprenticeship requirements, depending on the life-cycle GHG emission intensity of hydrogen production. Direct air capture (DAC) is also eligible for different levels of credits (45Q) (White House, 2022, US Government, 2022). Different IRA credits apply to aviation and maritime, as shown in Table 1.

Table 1. IRA policy framework

Fuel	Credits	Unit	Details
Biofuels	1	\$/gallon	Dependent on lifecycle GHG emission cuts from 2025
SAF	1.25	\$/gallon	50% lifecycle GHG emission reduction
	1.75		75% lifecycle GHG emission reduction
Clean hydrogen	0.6	\$/kg hydrogen	Between 2.5 and 4 kgCO_2e/kg hydrogen
	0.75		Between 1.5 and 2.5 kgCO_2e/kg hydrogen
	1		Between 0.45 and 1.5 kgCO_2e/kg hydrogen
	3		Below 0.45 kgCO_2e/kg hydrogen

Source: White House, 2022

RFS is a key federal policy that supports the development, production, and use of low-carbon, domestically produced renewable biofuels destined for the transportation sector (EPA, 2023). It is currently the only regulatory requirement at the federal level to establish requirements on applicable volumes and percentages of renewable fuels. It is focused on biofuels, including cellulosic biofuels, biomass-based diesel, other advanced biofuels, and conventional renewable fuels. They qualify for different subcategories based on their GHG emission profile, assessed from a life-cycle perspective. Environmental Protection Agency (EPA) set a target of renewable volume obligations (RVOs) annually. When the required RVOs are fulfilled, Renewable Identification Numbers (RINs) will be issued[3]. Obligated parties and non-clean fuel producers, including refiners and importers, can purchase RINs from clean fuel producers for compliance (EPA, 2024). When Obligated parties buy clean fuels, RINs come with a batch of renewable fuel. As shown in Table 2, there are four different RINs based on the type of feedstock, and the market will determine the price.

Table 2. RINs credits from RFS

Category	GHG reduction rate	RINs Credits Price[4] ($/gallon)	Feedstocks
D3	60%	3.00	cellulosic feedstocks
D4 / D5	50%	0.70	non-cellulosic feedstocks
D6	20%	0.86	corn ethanol

Source: S&P Global, 2023, EIA, 2023

LCFS, a state law first implemented in CA, is intended to reduce the life cycle carbon intensity (CI) of transportation fuels based on life-cycle assessment. Fuel producers generate credits or deficits depending on whether their reported CI is below or above a mandatory threshold. The target CI for the overall fuel consumed gradually decrease every year, up to a 20% reduction by 2030 based relative to the baseline year CI level of 2010 (CARB, 2023). Failing to meet these requirements leads to penalties.

---

[3] RINs are credits used under RFS

[4] Rins price in 2023

In addition, alternative fuel suppliers are eligible for the credits from CAT in CA. The credits, often called allowance, are generated based on the permitted total amount of emissions. Around 50% of allowances are attributed to utility corporations, and natural gas companies are followed. Each year, the permitted allowance decreases to expedite the use of green energy (CARB, 2024). If a company reduces its emissions, it can sell its excess allowances to other companies that might fail to meet emission cap. This creates a financial incentive for companies to produce low carbon fuels.

1.2 Policy in the EU

The clean fuel policies in the EU are outlined in the Renewable Energy Directive (RED), which was introduced in 2001 (EU Commission, 2023). In 2018, the EU introduced the 'Clean Energy for All Europeans' package, requiring at least 32% of total energy to be renewable energy and reducing GHG emissions by 20% from the 1990 baseline (EU Commission, 2023). EU proposed the 'Fit for 55' package in July 2021, which requires a more aggressive GHG reduction goal of 55% by 2030 compared to the 1990 baseline (EU Commission, 2019). The directive establishes a goal based on an agreement among EU members, and each nation may implement alternative measures to achieve the goal (EU Commission, 2023). Regulation is a legally binding act that must be implemented across all EU members. The Fit for 55 package set includes a comprehensive plan for renewable energy adoption in various sectors, ranging from taxation benefits to a social climate fund (EU Commission, 2023).

Under the Fit 55 directive, RefuelEU Aviation and FuelEU Maritime regulations, integrated in the context of the Renewable Energy Directive, set new regulatory requirements. Unlike the US, the EU primarily targets the operators rather than fuel suppliers[5]. There would be an indirect impact as the demand is connected to the requirements of operators. RefuelEU Aviation obliges fuel suppliers to deliver an increasing share of sustainable aviation fuels (SAF) as part of the fuel supplied at EU airports. SAF provided to operators in EU airports needs to grow from 2% by 2025 to 6% by 2030, following other steps, up to 70% by 2050. A sub-obligation for Efuels, synthetic aviation fuels requires shares of 1.2% in 2030, 2% in 2032, 5% in 2035, and then up to 35% in 2050 (European Union, 2023). FuelEU maritime focuses its requirements on the GHG intensity of energy used on board ships larger than 5000 gross tons, which are currently responsible for 90% of the GHG emissions from maritime transportation (European Union, 2023). GHG intensity of energy used on board shall decline by 2% in 2025 compared to the 2020 baseline, then by 6% in 2030, and, progressively, it will reach an 80% reduction by 2050.

The EU Emission Trading System is the largest carbon credit trading market (EU Commission, 2024). ETS was launched in 2005, and phase 4 revisions of ETS were made in July 2021. The free allocation for non-Extractive Industries Transparency Initiative (EITI) sectors, such as heat sectors and aviation, will be phased out by 2030 (EITI, 2024). Based on ETS annual reporting, it is estimated that 75% of total revenues (€56.5 billion) was used for climate and energy purposes in 2019 (EU Commission, 2022).

Aside from ETS, the Alternative Fuels Infrastructure Regulation (AFIR) requires a minimum of one charging hub every 60 to 100 km in the TEN-T network[6]. It stands for the first law of its sort ever established. This regulation proposal includes road, shipping, and aircraft (EU Commission, 2023). The TEN-T policy develops coherent transport (i.e., railways,

---

[5] New regulation on the FuelEU, Norton Rose Fulbright, 2023

[6] Trans-European Transport Network (TEN-T) : transport network designed for the efficient transportation for people and goods in EU. Trans-European Transport Network (TEN-T) - European Commission (europa.eu)

inland waterways airports, and terminals) to strengthen territorial cohesion across borders (EUROPA, 2013)

1.3 Non-governmental policy

There are three major international organizations for aviation: International Air Transport Association (IATA), Airport Council International (ACI), and International Civil Aviation Organization (ICAO). IATA represents airlines, and ACI represents airports' interests. ICAO is a specialized agency under the United Nations (UN) that establishes international regulations. IATA and ACI are advisory and representative organizations providing guidelines and supporting members. ICAO's standards and recommended practices are legally enforceable. In 2021, IATA set a goal of Net zero emissions by 2050 with the increased use of SAF (IATA, 2023). ACI set net zero emissions by 2050, as well, and conducts an SAF study to support SAF infrastructure development (ACI, 2022). ICAO developed standards for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016, and members of the ICAO are obligated to offset carbon by either purchasing credits or using renewable energy (ICAO, 2023). CORSIA aims to reduce GHG emissions by 20% in 2027 compared to the 2019 baseline, and it will be compulsory after 2027. CORSIA applies only to international flights (FAA, 2023). While international flights account for roughly 77% of all flights in the EU, they only account for 14% in the US (Eurostat, 2022).

International Maritime Organization (IMO) is the equivalent in maritime to what ICAO is in aviation. IMO established its emission reduction targets in the marine sector of at least 20% reduction by 2030, 70% by 2040, and 100% by 2050 compared to the 2008 baseline. The decarbonization goal is estimated at approximately 1.4 trillion US dollars (Krantz, 2020). In addition, the IMO also announced regulations that may promote biofuels, such as waiving NOx emission assessment for B30 (blended with 30% biodiesel), strengthening efficiencies, and regulating CI values of fuels used for international shipping. (Sydner, 2022). In the meeting of IMO CCC9 in 2023, the guidelines for ammonia and hydrogen are discussed, including fundamental principles such as safety (IMO, 2023).

In summary, government primarily executes three distinct policies as shown in Table 3: (1) A mandate requiring the use of specific volumes of renewable fuel in gasoline or reduction of GHG, (2) Tax credits incentives, and (3) Carbon markets. Tax credits will directly benefit the reduction of production costs to the clean fuel producers and suppliers. In the Carbon markets (i.e., LCFS, CAT, and ETS), companies are allowed to trade the credits. Carbon trading platforms set a carbon intensity target called benchmark CI every year. If a business emits a higher level of target CI than the benchmark, it needs to purchase credits to comply with the regulation, while clean fuel producers can make an additional budget by selling credits.

Table 3. Legislative landscape of aviation and maritime in US and EU

	Mandate (use of clean fuel)	Mandate (Reduction GHG)	Direct Incentives	Carbon Credits	Penalties
US	RFS	-	IRA	RFS	LCFS (CA)
				LCFS (CA)	
				CAT (CA)	
EU	RefuelEU Aviation	RED	-	ETS	RefuelEU Aviation
	FuelEU Maritime				FuelEU Aviation
International Organization	-	IMO ICAO (Corsia)	-	-	-

Source: DOT, 2022, EPA, 2024, LCFS, 20204, CARB, 2024, EU Commissions, 2023, EU Commissions, 2022, EU Commissions, 2024

1.4 Literature review

With the growing attention to alternative fuel in hard-to-be-electrified areas, many literatures analyzed abatement costs and emissions for the clean fuel transition in aviation and maritime.

For the shipping industry, Lagouvardou (2023) has analyzed clean fuel costs in maritime using a marginal abatement approach in the EU. The study finds that biofuels have a great potential for alternative fuel compared to Efuel and the adoption of hydrogen requires policy incentives to be considered.

Kanchiralla et al. (2022) has used a lifecycle assessment (LCA) approach for decarbonization in the shipping industry and analyzed carbon abatement costs. The study finds that policy incentives are required for the adoption of clean fuels in maritime. Also, he finds that there is a trade-off between environmental impact and renewable fuel infrastructure.

Harahap et al. (2023) analyzed Sweden’s opportunities and limitations of the use of renewable marine fuels focusing on pathways, legislation, and transition dynamics. The analysis considers pathways of biofuel, Efuel, and hydrogen for the evaluation of economic competitiveness. The study finds that the cost of green electricity is crucial in the decarbonization of the shipping industry.

For the aviation industry, Prussia, Lee, and Wang (2021) reviewed GHG emissions of sustainable aviation biofuels (SAF) using LCA-based methodology from Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the first internationally adopted approach.

De Jong and Antonisseen (2017) have also analyzed emissions of SAF with the focus on approved pathways. Noh et al. (2016) analyzed the policy role in the biofuels of aviation in the EU and found that the current economic conditions of biofuel production require policy incentives. Wang et al. (2019) analyzed the challenges of biofuels for aviation with a focus on technology, policy, and environmental impact. The study also presents the potential integration of research with the industrial chain in aviation.

Martin, Dimanchev, and Neumann (2023) have analyzed the levelized cost of carbon abatement (LCOE) of renewable fuels in aviation and maritime in Norway. Although this study considered direct incentives, carbon credits in the carbon trading platforms are not included.

A comparative analysis and forecast of renewable fuels between the US and the EU is missing. Also, comparisons of different methodologies under the same conditions were not made. This is where this paper adds value, providing a comprehensive analysis of different renewable fuels in two different regions.

2. Methodology

2.1 Data

The study's goal is to identify the best cost-effective and environmentally friendly alternative fuel for the shipping and aviation sectors, both now and in the future. The main variables used with quantitative policy analysis are production costs ($/GJ) and emissions ($tCO_2e$/GJ). We referred to central estimates from literature reviews, as a range of data is often given. The energy contents of each fuel are used to convert units as production costs in literature were often given as $/kg.

Five types of biofuels, four types of hydrogen, and four different Efuels are studied, as these fuels are subject to the existing policy and are being discussed options as clean fuels in shipping and aviation. Conventional biofuel, commonly known as ethanol, and advanced biofuels, including SAF, are already being used. Thermochemical and Oleochemical technology is another representative biomass conversion process, and the market of oleochemicals is growing fast, with a CAGR of over 9% (Wood, 2022). The limited resources, production costs, and deforestation are the primary concerns with biofuels (J.Zhou, 2016; Canabarro, 2013).

Hydrogen requires electricity, so the energy source can be either fossil fuel or renewable energy. Also, hydrogen can be produced either on-site or transported. Carbon Capture, Utilization and Storage (CUCC) could reduce emissions levels when hydrogen uses fossil fuel as an electricity resource. (K.Machaj, 2022). Synthetic hydrocarbon, often called an Efuel, can produce high energy-density fuel (Revankar, 2019).

This paper uses thirteen different alternative fuels and fossil fuels from literature reviews, as shown in Table 4. Corn grain and sugar cane are the most commonly used for biofuel. This study also included oleochemical and thermochemical biofuels, as they represent distinct technological pathways. We considered different energy resources to generate electricity and transportation to deliver hydrogen. We also included four different Efuels (ammonia, methane, methanol, and liquid hydrogen) with potential benefits in long-distance transportation, such as a drop-in fuel and, compatibility with existing fuel infrastructures.

Table 4. Data of emissions and production costs across fuel types

All fuels	Category	Description	Emission (gCO2e/MJ)	Production Cost ($ / GJ)
Fossil fuels	Fossil	Fossil	89	20
Biochemical biofuels(C-C)	Biofuel[7]	Conventional (Corn grain)	59.8	23.5
Biochemical biofuels (C-S)	Biofuel	Conventional (Sugar cane)	35	20
Biochemical biofuels (A)	Biofuel	Advanced[8]	25	44.8
Oleochemical	Biofuel	parm oil (HEFA)	60	30
Thermochemical	Biofuel	gasoline	25	50
Hydrogen (R-T)	Hydrogen	Renewable E requiring transport	4.7	53.7
Hydrogen (R-O)	Hydrogen	Renewable E, production on-site	4	50
Hydrogen (F-T)	Hydrogen	Fossil-based, requiring transport	129.6	38.75
Hydrogen (F-T-C)	Hydrogen	Fossil-based (CCUS), requiring transport	36	59.7
Efuels (LH-R)	Efuels	LH (Liquid hydrogen), Renewable E	9	88.1
Efuels (methanol-R)	Efuels	Renewable electricity	7	87.1
Efuels (methane-R)	Efuels	Renewable electricity,	9	46.6
Efuels (ammonia-R)	Efuels	Renewable electricity	5.3	40.7

Source: Production costs based on EIA, 2022, IPOL, 2023, IRENA, 2020, IEA, 2019, IEA, 2021, Jachin, 2019, Valerie, 2022, ICCT, 2021 and Emissions based on Prussia, 2021, ANL, 2023, Howarth , 2021, Howarth, 2022, ICCT, 2021, Argonne, 2023

2.2 Model

We assessed TAC in three phases. As shown in Figure 1, phase I presents the TAC value in 2024. We collected four key input variables (i.e., production costs, emissions level, direct incentives, and carbon credit value) from literature and government-issued documents. Then, we quantified the policy influence on each fuel, calculating TAC. Through this phase, we can see which alternative fuels are most competitive and which jurisdictions developed more economically viable places for clean fuel producers.

In Phase II, we obtained target CI from different policies to measure the financial benefits of carbon credits. The price of carbon credits is forecasted through the VAR model. To account for the uncertainty in the future, we used the Montecarlo simulation, generating the probability distribution of TAC. We can find which clean fuel might be cost-effective in each region in the short and long term.

---

[7] Induced land use change(ILUC) has not been included in the CI levels of biofuels.

[8] According to RFS, advanced fuels refer to pathways that save emissions of at least 50% of fossil jet fuel (EPA, 2023). The average CI of fuels that reduce over 50% of emissions is calculated from the study from Prussia.

In Phase III, we adopted another economic feasibility model, MAC. We calculated net present value using capital expense (CAPEX) and operational expense (OPEX). The learning rate of technology is applied to production costs. The calculated MAC TAC reveals the cost of avoiding emissions for each clean fuel. We can rank the options to reduce emissions in terms of abatement costs, helping policymakers make decisions.

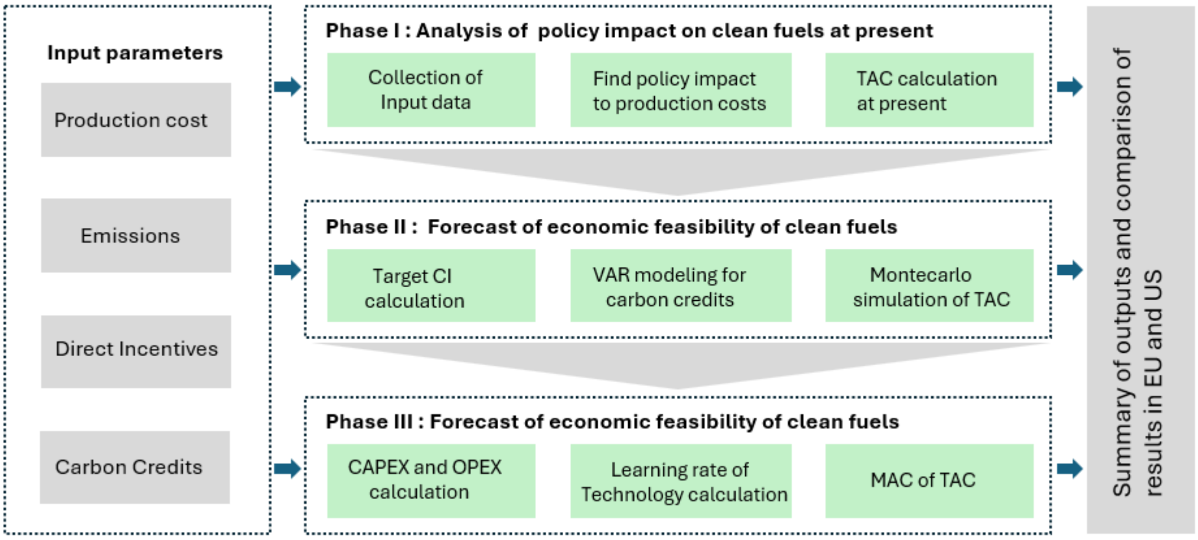


Figure 1. Overview of the methodology of the analysis. Phase I gives present value of TAC and phases II and III show future value of TAC with uncertainty analysis

2.2.1 Phase I model

Among many policies, we considered quantifiable policy instruments. In the US, two federal policies (i.e., IRA and RFS) are applied. RFS issues RINs credits for only biofuel suppliers. Also, as discussed in the background, IRA provides direct subsidies for biofuel and hydrogen producers. The rate of credit varies based on operational conditions. Therefore, we forecast it by considering relevant economic variables such as NG and the CPI.

Clean fuel producers in CA would receive federal subsidy from IRA and credits from IRA. Also, they generate credits from states' carbon trading systems (i.e., LCFS and cap &

Trade). As the EU focuses on the demand side, not the supplier side, only ETS would have a direct monetary policy.

For the TAC in CA, we included credits from LCFS and CAT and the Penalty from LCFS. In the EU, credits are derived from the ETS, whereas penalties are imposed through two regulations (i.e., FuelEU marine and RefuelEU aviation). The credit price fluctuates daily, similar to the cost of trading stocks. Therefore, the credit price of the trading platform is assumed to be 74 $ / t CO2e for LCFS and 87.2 $ / t CO2e, the highest price in the fourth quarter of 2023.

The penalty is calculated based on the statement of each regulation. Section 95485 of LCFS states that the penalty can be up to 1000 $ per deficit. Thus, considering the CI of jet fuel for aviation and heavy fuel in maritime, we could convert it into 25 $ / GJ. In the EU, FuelEU Maritime states that the non-compliance parties can be charged 2400 €/t VLSFO. According to the equation given by the EU council, we could convert 59 $/GJ. RefuelEU Aviation says that the fine can be up to twice as high as the different amounts of SAF and conventional jet fuel. The difference between most advanced biofuel (D3) and fossil fuel is 11 $, and the total amount is 22 $ /GJ[9]. Higher penalties between maritime and aviation are applied to each nation for phase I. Table 5 displays the summary of the carbon trading policy.

---

[9] D3 requires 60% reduction requirement and made from cellulose (Celingnis, 2023)

Table 5. Representative carbon trading policy of EU and US

LCFS credit price	Assumed 74 \$/ t CO_2e; highest price in 4th quarter in 2023	
Non-compliance penalty of LCFS	Assumed 25 \$ / GJ ; calculated by using energy density ; assumed t CO_2e / ton for fossil (regulation) 1000 \$/t CO_2e could technically be the penalty in the market.	
ETS credit price	Assumed 87.2 \$/t CO_2e ; highest price in 4th quarter in 2023	
Non-compliance penalty of ETS	Aviation	Assumed 22 \$/ GJ; calculated within the data for this study (regulation) At least twice as high as the difference between alternative and conventional fuel, with differentiated values for SAF or Efuels.
	Maritime	Assumed 59 \$ / GJ; calculated according to the equation in EU council of maritime[10] (regulation) 2400 €/t VLSFO of very low sulfur fuel oil

Source: European Union, 2023, European Union, 2023, Safety4Sea, Huson, 2020, CARB, 2023, CARB, 2023, CARB, 2023, CARB, 2020, EU Commission, 2023, Transport & Environment, 2022

TAC represents Total Production Cost, which is calculated as

$$TAC = Production\ costs - Subsidy - \left[\left(CI_{base} * (1 - \ Target\ Rate)\right) - CI_A/EER\right] * EER\ * Carbon\ Price \qquad (1)$$

The Energy Efficiency Rate (EER) for biofuel and Efuel are the same, as those fuels would not require entirely different maritime and aviation systems. The thrust-specific energy consumption (TSEC) of a hydrogen engine is actually the same as that of conventional kerosene engines. Thus, the EER of hydrogen(2.69) is calculated using the different energy densities of kerosene (44.59MJ/kg) and hydrogen (120MJ/kg) (Eytan K, 2023).

$$Relative\ EER\ = EER\ of\ Alternative\ fuels \div \frac{EER\ of\ Alternative\ fuels}{EER\ of\ conventional\ Jet\ fuels} \qquad (2)$$

CI_A is carbon intensity of alternative fuels and CI_{base} is the baseline carbon intensity in emission trading systems (i.e., LCFS and ETS). TAC is reduced by the amount of direct incentives, mainly from IRA and RGS and then, the value of carbon credits is derived by multiplying the saved emissions level by the carbon price. CA and EU have different target rates with different baselines, as shown in Table 6. The baseline Target CI of LCFS is emissions in 2010, which is 100.05 gCO2e/MJ. CARB announced that the emissions level was lowered by 6.25% in 2019 relative to the benchmark in 2010 (CARB, 2024). In 2025, a 13.5%

---

[10] FuelEU penalty with respect to compliance balance for greenhouse gas intensity.

reduction will be achieved. The target in 2030 is set at 80.36 gCO2e/MJ. The target for 2050 has not been specified yet. Thus, we applied the same yearly reduction rate to 2050. Over the last five years, a decrease of 6.25% has been accomplished with an annual reduction of 1.5%.

Table 6. Target CI for each policy

	CAT	LCFS	EU ETS	
			Maritime	Aviation
Baseline	year: 1990	year: 2010	year: 2020	year: 2020
	(92.92)	(100.05)	(91.16)	(91.16)
2024	92.92	87.89	89.33	89.33
2030	55.75	80.04	85.69	85.69
2050	18.58	55.03	18.23	27.34

CAT in CA announced that the target to meet the emission level of 1990 has been achieved in 2020(CARB, 2021), which is the benchmark year. The emission level in 2020 is 92.92 gCO2e/MJ. The goal of CAT is a 40% decrease in 2030 and an 80% reduction in 2050, based on CI in 2020. CI in 2024 is interpolated between 2020 to 2025.

The Target CI of ETS is controlled separately in each sector. FuelEU maritime set the requirement of CI relative to the 2020 CI of the fleet in maritime. Within the EU, 100% of the energy will be used for this calculation and 50% for the voyage outside the EU[11]. EU ETS set a SAF mandate target, specifically aviation, 6% in 2030 and 70% in aviation. SAF has the potential to reduce greenhouse gas emissions by up to 94% (DOE, 2024). For the model's simplicity, we applied a 100% GHG reduction compared to conventional jet fuel and applied it to the base year for future target CI in aviation.

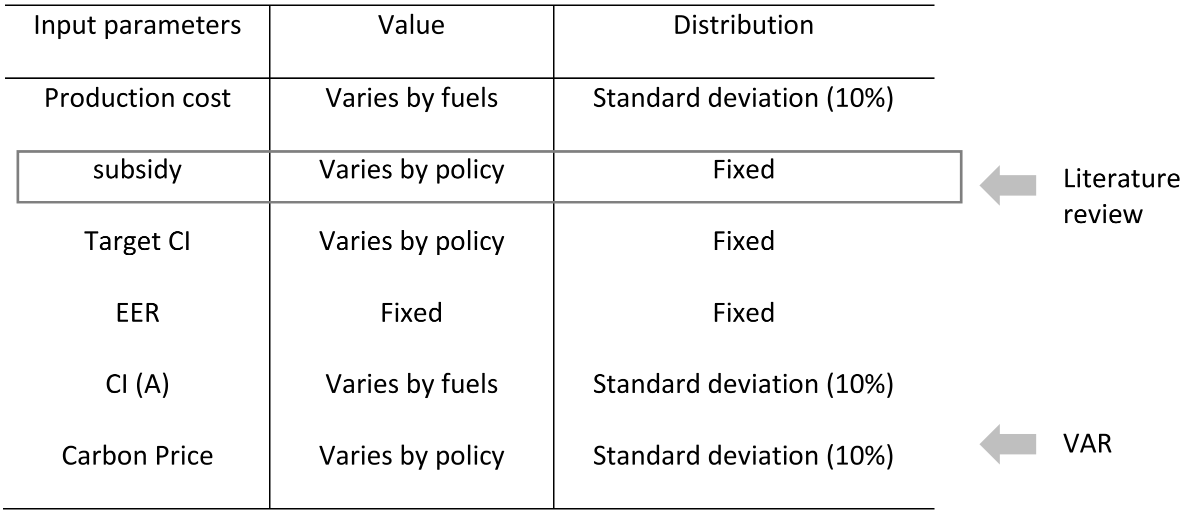
---

[11] FuelEU Maritime (dnv.com)

2.2.2 Phase II model

Phase II applies MCS to reflect cost uncertainty by showing the possible value of each type of low-carbon fuel.

Figure 2 gives the structure of the input parameter of TAC in phase II. Present value solely defines the distribution and is simulated to see the distribution of costs. However, for prediction purposes, the multivariate autoregressive model (VAR) is employed to forecast products and carbon prices. Macroeconomic variables (i.e., NG and CPI) are used for both techniques. VAR models used 91 monthly observations (from April 2016 to November 2023) for carbon price, NG, and CPI (IEA, 2023; FRED, 2023; UC Davis, 2023 ;CARB, 2023).



Input parameters	Value	Distribution
Production cost	Varies by fuels	Standard deviation (10%)
subsidy	Varies by policy	Fixed
Target CI	Varies by policy	Fixed
EER	Fixed	Fixed
CI (A)	Varies by fuels	Standard deviation (10%)
Carbon Price	Varies by policy	Standard deviation (10%)

Figure 2. Economic methodology specification. 10% of standard deviation is applied to production cost, CI and Carbon credits

Here, we briefly describe the VAR model, often used for carbon price forecasts (Julien, 2011). VAR examines the dynamic relationship of multiple time series variables (Kenton, 2024). As shown in equations (3), (4), and (5), the interaction of lagged dependent variables and independent variables for each equation are examined. $x_{t,1}$ represents the carbon price. $x_{t,2}$ refers NG, while $x_{t,3}$ denote CPI. Our VAR model is a second-lagged VAR, which means it lagged twice, having three more variables in each equation. Based on AIC and BIC, each equation's lag number is selected.

$$x_{t,1} = \alpha_1 + \phi_{11}^1 x_{t-1,1} + \phi_{12}^1 x_{t-1,2} + \phi_{13}^1 x_{t-1,3} + \phi_{11}^2 x_{t-2,1} + \phi_{12}^2 x_{t-2,2} + \phi_{13}^2 x_{t-2,3} + w_{t,1} \quad (3)$$

$$x_{t,2} = \alpha_2 + \phi_{21}^1 x_{t-1,1} + \phi_{22}^1 x_{t-1,2} + \phi_{23}^1 x_{t-1,3} + \phi_{21}^2 x_{t-2,1} + \phi_{22}^2 x_{t-2,2} + \phi_{23}^2 x_{t-2,3} + w_{t,2} \quad (4)$$

$$x_{t,3} = \alpha_3 + \phi_{31}^1 x_{t-1,1} + \phi_{32}^1 x_{t-1,2} + \phi_{33}^1 x_{t-1,3} + \phi_{31}^2 x_{t-2,1} + \phi_{32}^2 x_{t-2,2} + \phi_{33}^2 x_{t-2,3} + w_{t,3} \quad (5)$$

The VAR model requires that input parameters be stationary, meaning that a time series has no trend (Korstanje, 2021). LCFS , CAT and ETS all exhibit distinct seasonal patterns; hence, differencing was necessary. ETS is differenced single time, whereas LCFS and CAT are differenced twice, and appropriate tests are conducted to verify the trend.

As shown in Table 7, the Dickey-Fuller test assumes a unit root in the model, which means that the data is non-stationary. We confirm that the data is stationary (Jalil, 2019), as the P value tested is lower than 5%. The null hypothesis of the ARCH test is that there is no conditional heteroscedasticity. We cannot reject the null hypothesis, as p value tested is greater than 5% (Kenton, 2021) Also, we confirm the stability of our VAR model since roots of a polynomial in the model are less than 1 (Ozbun, 2021).

Table 7. VAR model Results

	Test	Model 1	Model 2	Model 3
Serial Correlation	Portmanteau Test	< 2.2e-16	< 2.2e-16	< 2.2e-16
Stationary	Dickey-Fuller Test	0.01	0.01	0.01
Heteroscedasticity	ARCH Test	0.319	0.246	0.545
Stability of models	Roots of the polynomial	<1	<1	<1

[Model 1: NG, CPI, CAT, Model 2 : NG, CPI, LCFS, Model 3 : NG, CPI, ETS]

As shown in Table 8, the Arima model has been compared with VAR. Overall, the VAR model shows better model fitness, so we employed the VAR model for the prediction of TAC.

Table 8. VAR and ARIMA Test Property

	Types of models	MAE	RMSE
ETS	VAR	2.38	3.35
	ARIMA	2.61	4.07
LCFS	VAR	7.72	10.31
	ARIMA	5.91	7.84
CAT	VAR	2.65	3.89
	ARIMA	0.39	0.84

Table 9 shows the forecasted credits price of three carbon trading platforms from VAR model. While all three increase until 2050, prices in ETS rise most significantly. Figure 15 (appendix) displays the forecasts from VAR models.

Table 9. Forecasted Credits Price

	LCFS	CAT	ETS
2024	74	26	87
2030	146	38	114
2050	182	41	319

CAT is predicted to increase the least. Unfortunately, the historical data on the production costs of thirteen different clean fuels was unavailable. Thus, the production costs in 2030 and 2050 are obtained from literature reviews. As shown Figure 3, Production costs are likely to fall in the future, except for biofuels. While Efuel is expected to fall by 20% between 2024 and 2050, biofuel levels stay stable. Green hydrogen would decrease quicker than grey hydrogen.

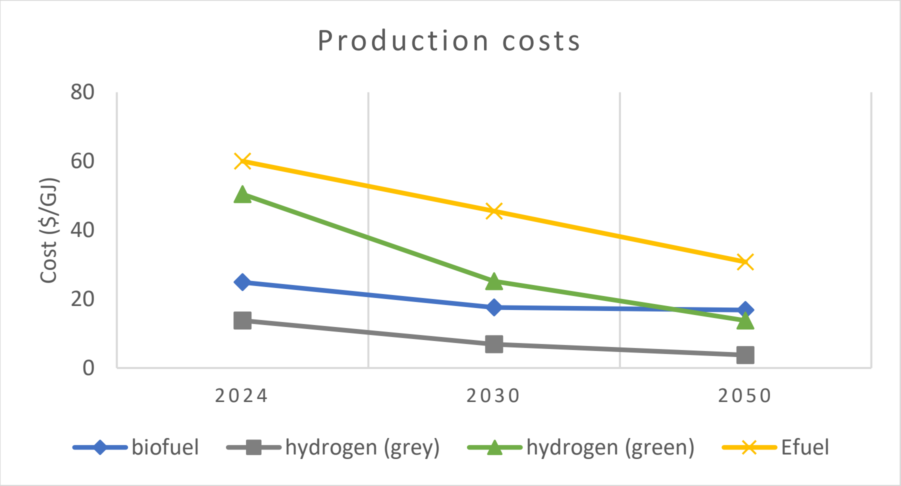


Figure 3. Production costs from literature review (Ralph E.H.2009, Jeroen, 2017, Efuel, 2022)

In summary, TAC is estimated using production costs obtained from a literature study and by forecasting credit prices for each jurisdiction using VAR models. Production costs, credit pricing, and clean fuel CI are allocated evenly at a standard rate of 10% in this scenario.

2.2.3 Phase III model

Table 10 presents the input parameters used for each sector. Specific fleets are chosen to calculate annual consumption and capital investments. In aviation, the price and annual consumption of Boeing 747 are used, as it is one of the best-selling aircraft[12]. For maritime, we chose traditional supramax vessels with a cargo capacity between 58,000–65,000 tons (Largemann, 2022).

Table 10. Parameters for MAC

Industry	Model	Annual Consumption (GJ)	Capital Cost ($)
Aviation	Boeing 747	1,786,457	New aircraft + infrastructure
Maritime	Supramax Vessel	141,121	New Vessel + Infrastructure

Source: Lagouvardou, 2023, Largemann, 2022, Hanson, 2023, AIRBUS, 2020

---

[12] The world's best-selling airplanes (CNN, 2022)

Vessels in maritime need to be modified to use alternative fuels. Various required capital costs, ranging from 800 to 2700 $/kW, are used(Elizabeth, 2021). In aviation, biofuel is assumed to be used with existing engines, so no capital cost is required. Hydrogen-based aircraft require an additional 16% of the total cost of Boeing 747, and various costs are applied for Efuels[13]. In addition, the estimated cost of hydrogen infrastructure is 750 $/kW[14]. Thus, applying annual consumption, we calculated $3.3 million. Hydrogen (renewable-based and onsite) added pipeline costs to the total.

In phase III, MAC offers insights into the estimated costs associated with reducing emissions for each type of clean fuel. The process for preparing MAC data involves specific equations (6), (7), (8) and (9). Here, the change in Net Present Value (delta NPV) is divided by the change in carbon dioxide equivalent emissions (delta CO2e). The NPV is calculated from CAPEX and OPEX, with a discount rate of 3% being applied. This rate is chosen in light of the current inflation rate and is expected to increase by 3% annually. This adjustment ensures that the calculation remains aligned with economic conditions over time, providing a realistic estimate of the costs involved in emission reduction efforts.

$$MAC(A) = \frac{\Delta NPV\ (A)}{\Delta CO_{2e}\ (A)} \tag{6}$$

$$\Delta NPV\ (A) = \Delta CAPEX(A) + \sum_{t=1}^{T} \frac{\Delta OPEX\ (A)}{(1+i\ )^t} \quad ,\ i = discount\ rate \tag{7}$$

$$\Delta OPEX = \left(Production\ cost_{cleanfuel} - Production\ cost_{fossil}\right) * Annual\ Consumption \tag{8}$$

$$\Delta CAPEX = System\ modification + (New\ vehicle) \tag{9}$$

---

[13] $47.3 million for hydrogen, $33.3 million for e-fuel of liquid hydrocarbon, and methanol, and $37.5 million for e-fuel from methane, and $36.8 million for ammonia.

[14] no-318.pdf (princeton.edu)

The technology learning rate is applied in the production costs of clean fuels. Technology learning rate represents a factor of the reduced rate of production costs relative to the accumulated production. (Karka, 2021; Nemet 2006; Trappey et al., 2016). Q_t is the cumulative production at the time of *t* and $C(Q_0)$ denotes the unit cost of production at Q_0. $C(Q_t)$ is expressed as the function of cumulative production and beginning production unit cost, as shown in equation 10. The learning parameter *b* is related to the learning rate and the unit production cost ($Learning\ Rate = 1 - 2^{-b}$).

$$C(Q_t) = C(Q_0) * \left[\frac{Q_t}{Q_o}\right]^{-b}, \qquad Q_t\ is\ cumulative\ production \tag{10}$$

The direct information for cumulative production was not available, so the growth rate of three categories is used to estimate the scale of $\frac{Q_t}{Q_o}$ over the years. Table 11 presents the calculation for the scale of cumulative production. Different learning rates (LR) are applied to biofuels compared to hydrogen and Efuels.

Table 11. Parameters of Learning rate of Technology

	Beginning (A)	CAGR	Prediction (B)	Scale of $\frac{Q_t}{Q_o}$ (B/A)	LR	b
Biofuels	100	27%	416	4.16	5%	-0.074000581
Hydrogen	100	14%	221	2.21	20%	-0.321928095
Efuel	100	23%	338	3.38	20%	-0.321928095

Source: Allied Market Research, 2023, Ananya Sharma, 2024, PR Newswire, 2024

3. Result

3.1 Phase I. Policy Influence Analysis

Figure 4 provides graphs illustrating the emission abatement and costs for different fuel types in the aviation and maritime sectors under two policy scenarios: California (CA) and the European Trading System (ETS). In the aviation sector, biofuels exhibit lower production costs and significant emission reduction potential, ranging from 29 to 62 gCO_2e/MJ. Advanced biofuels, despite their higher costs of around 15-25 \$/GJ compared to fossil fuels, offer a substantial abatement capacity of about 60 gCO_2e/MJ. Hydrogen, particularly with carbon capture, utilization, and storage (CCUS), shows competitive emission savings, though the costs are higher. Efuels, while having the highest emission-saving potential, are also relatively costly. The analysis reveals that the production costs for clean fuels in the CA range from 11 to 91 \$/GJ, whereas in the EU, the costs span from negative 20 to 94 \$/GJ. This higher cost of penalized fossil fuels in the EU makes alternative fuels, especially biofuels, more attractive.

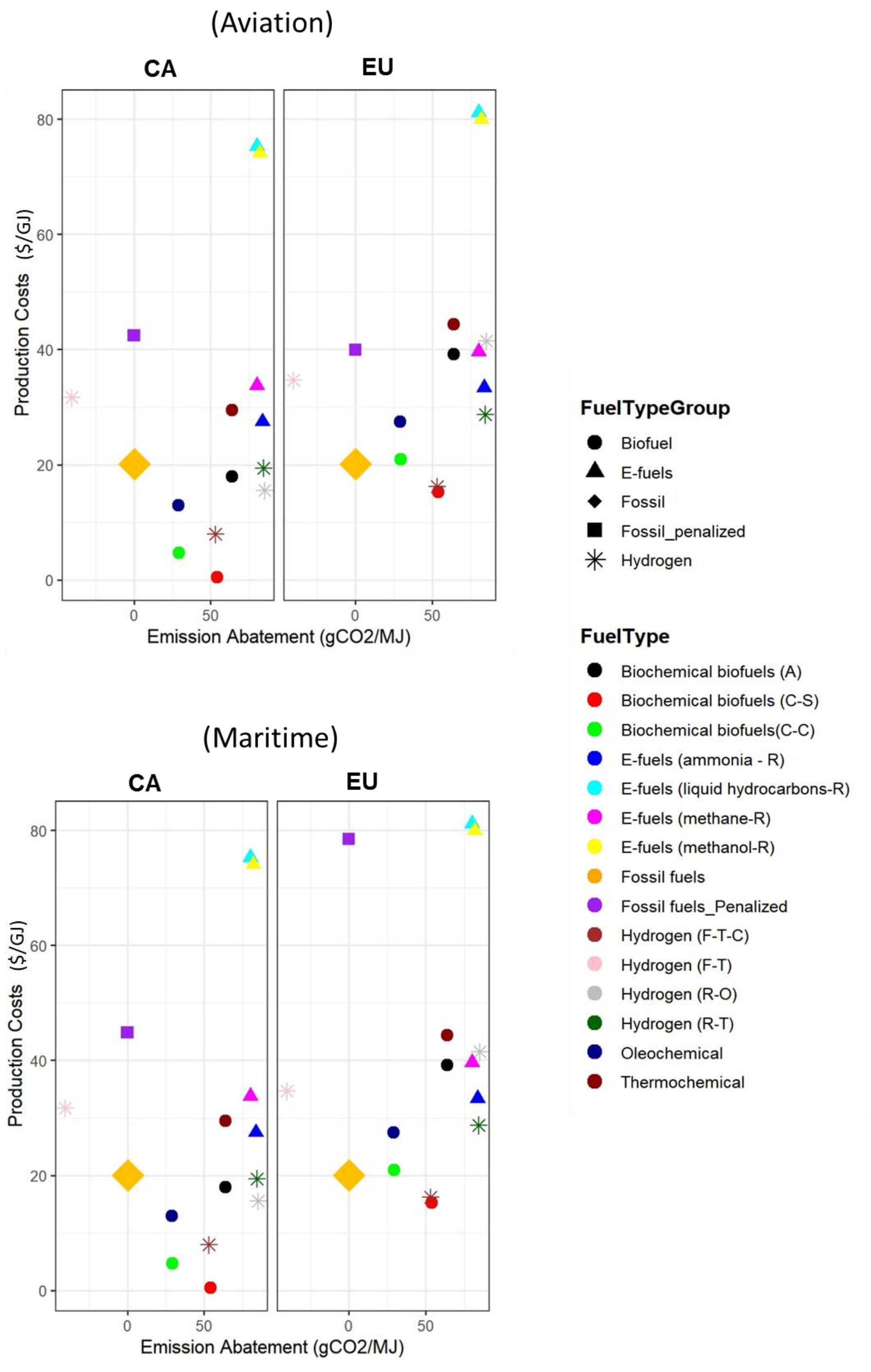


Figure 4. Phase 1 results of TAC in CA and EU in 2024. The figure presents a scatter plot comparing the production costs ($/GJ) on the y-axis with the emission abatement (gCO2/MJ) on the x-axis

In the maritime sector, the trends are similar, with biofuels showing competitive positions due to their lower production costs and significant emission reductions. However, clean fuels in the US are less appealing compared to the EU, where the higher penalized fossil fuel costs (78.54 $/GJ) make clean fuels more competitive. Overall, the higher penalized fossil fuel costs in the EU drive the attractiveness of alternative fuels, emphasizing the importance of aligning incentives and penalties to encourage the adoption of low-carbon fuels.

3.2 Phase II. MCS

Figure 5 presents the TAC distribution of various alternative fuels within the biofuels sector for the US and the EU across different years (2024, 2030, and 2050). The charts illustrate that the US exhibits lower overall costs, ranging from 0-40 $/GJ, with a smaller distribution, suggesting more predictable costs compared to the EU's wider range of 0-60 $/GJ. The preferred fuels in both regions follow a similar order, with advanced biofuels being closer in TAC to oleochemical processes. However, thermochemical processes display a significant level of uncertainty, evidenced by their extensive distribution. Biochemical biofuels dominate the lower range of TAC in both regions. Over time, biochemical fuels (C-S) show reduced uncertainty with higher frequency. In 2050, the TAC has increased, which can be attributed to the low target Carbon Intensity (CI) rate from LCFS, CAT, and ETS, despite rising credit prices, as indicated in Table 8. This increase in TAC reflects the challenges in achieving lower CI targets.

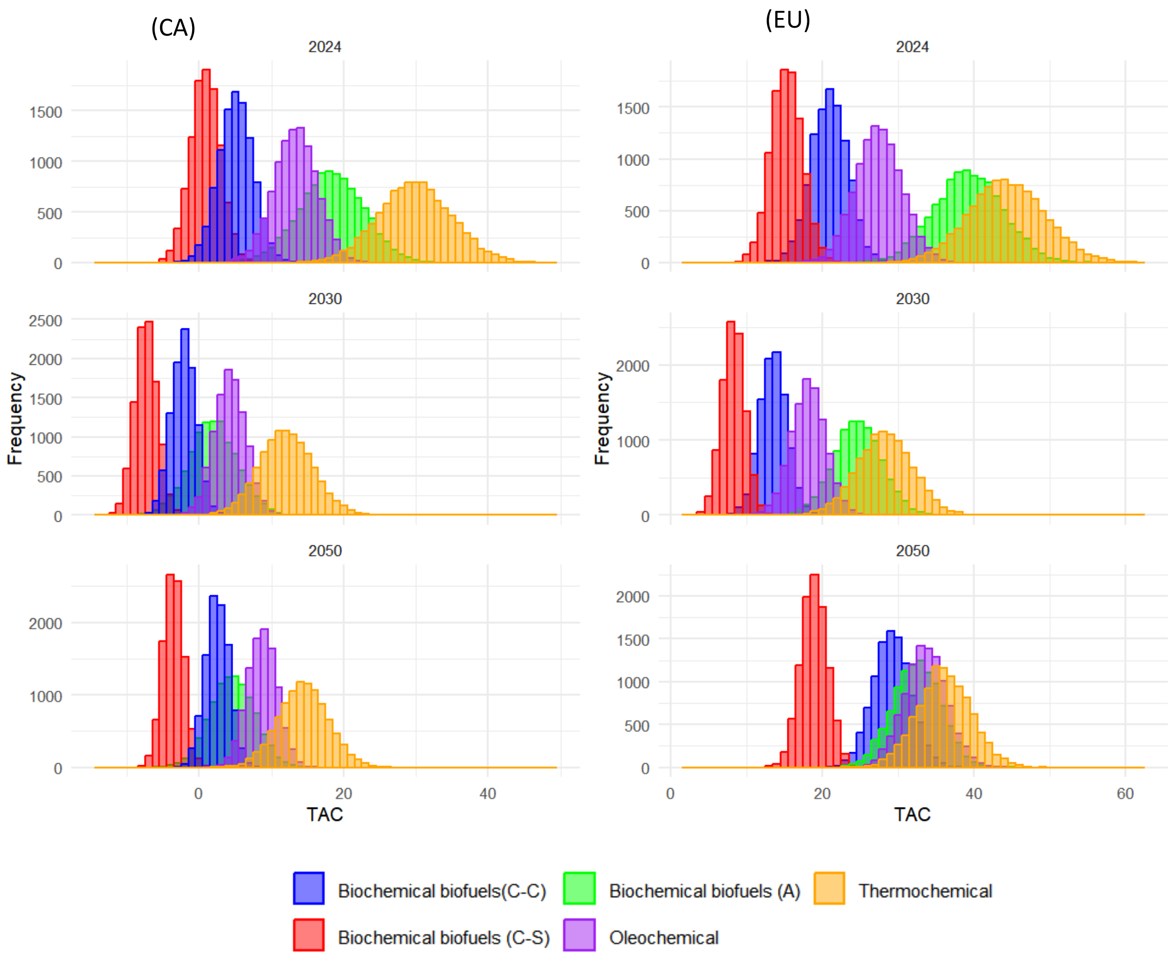


Figure 5. Probability distribution of TAC in the biofuel sector. The x-axis represents TAC values, while the y-axis indicates the frequency of occurrences for each TAC value. The figure compares distributions across three years (2024, 2030, and 2050) for CA and EU

Figure 6 shows the TAC distribution of hydrogen, highlighting significant differences between the US and EU. In the US, the cost of hydrogen (R-T) is more consistent and exhibits less variation, with a lower price range compared to the EU. High incentives from the IRA contribute to lower costs, especially for renewable-based hydrogen (green hydrogen). On-site hydrogen production in the US avoids transportation costs, resulting in relatively lower TAC. While the TAC for fossil fuel-based hydrogen remains similar until 2030 in the US, renewable-based hydrogen becomes more cost-effective with lower target CI levels. Similar to biofuels, the EU displays a wider range of cost distributions, indicating greater uncertainty.

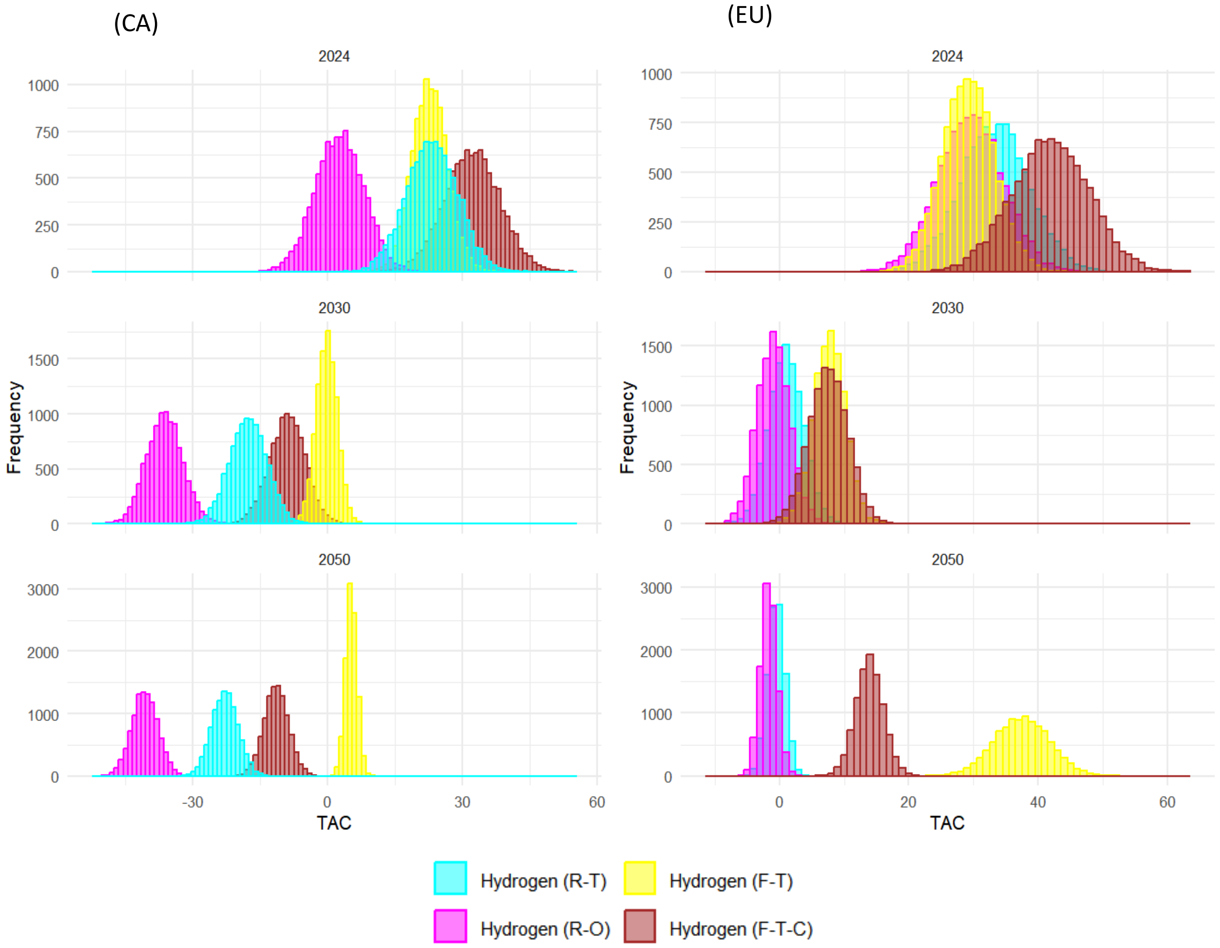


Figure 6. Probability distribution of TAC in hydrogen. The x-axis represents TAC values, while the y-axis indicates the frequency of occurrences for each TAC value. The figure compares distributions across three years (2024, 2030, and 2050) for CA and EU

Figure 7 shows the TAC distribution of Efuels, highlighting ammonia and methane (often referred to as LNG) as favorable options in both the US and EU. Both ammonia and LNG exhibit more consistent and less variable costs compared to liquid hydrocarbons and methanol, which remain more expensive. These distributions suggest that ammonia and LNG are more stable and cost-effective options for Efuels in both regions. However, liquid hydrocarbons and methanol have greater and broader cost ranges, highlighting their economic constraints. Liquid hydrocarbon and methanol distribution patterns indicate unpredictability and more significant abatement costs, underlining the need for sustained innovation and cost reduction in these industries.

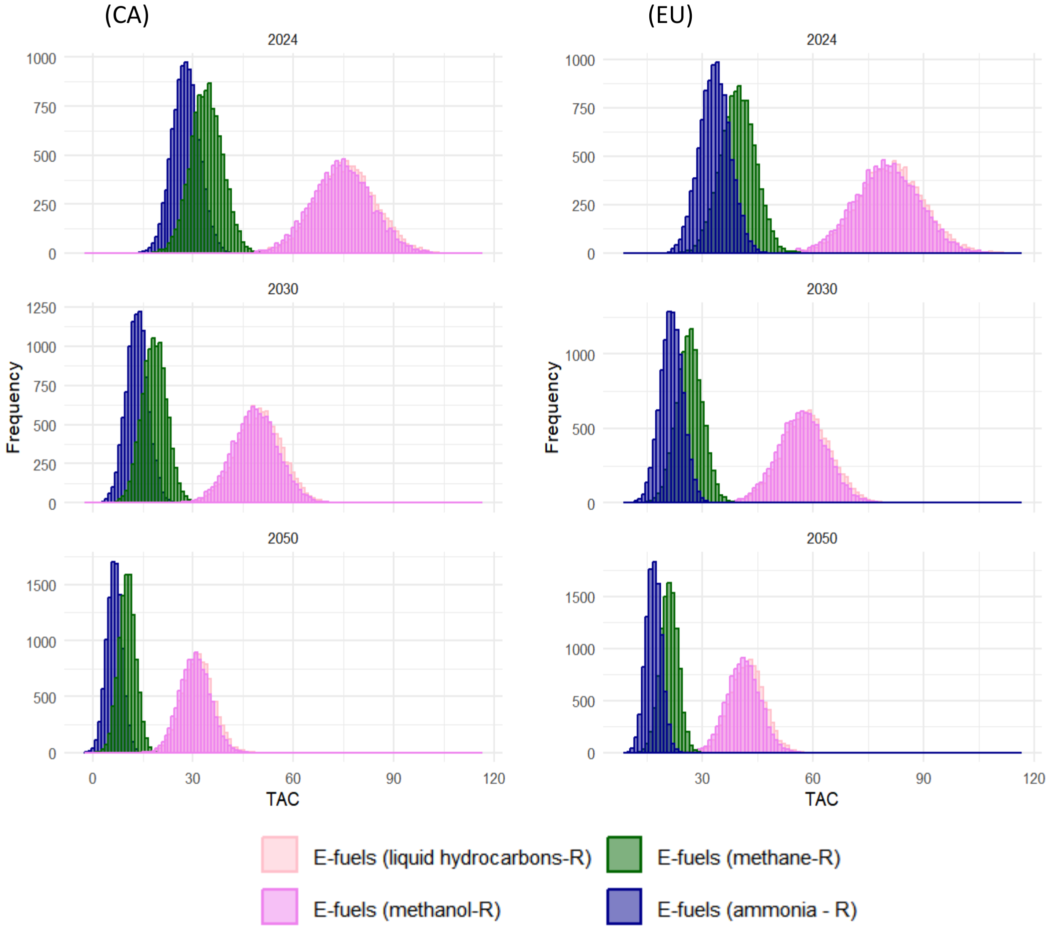


Figure 7. Probability distribution of TAC in Efuel. The x-axis represents TAC values, while the y-axis indicates the frequency of occurrences for each TAC value. The figure compares distributions across three years (2024, 2030, and 2050) for CA and EU

From Figure 8, Biofuels exhibit narrow distributions and low TAC values in CA, implying short-term economic benefits. In 2030, renewable-based hydrogen will become increasingly prevalent when its distribution approaches zero TAC, indicating economic feasibility. In the long term, TAC values for hydrogen are still broad but become increasingly important throughout time.

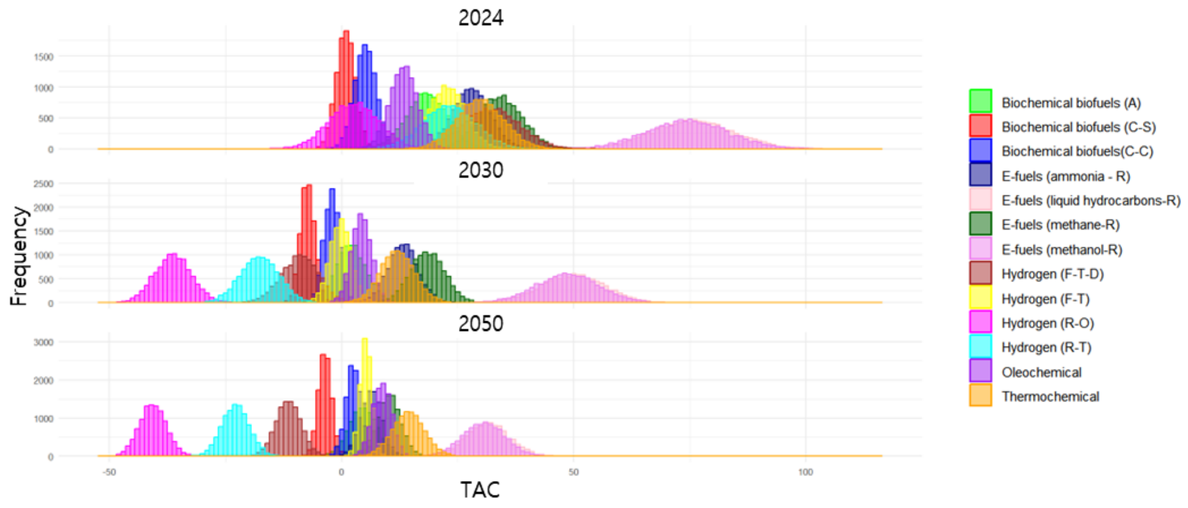


Figure 8. Projected distribution of TAC in CA. This figure compares the cost dynamics of all alternative fuels in three categories

Figure 9 shows that in the EU, hydrogen remains a top choice for 2050, exhibiting concentrated distributions at zero TAC. This consistency shows that hydrogen will remain a promising long-term technology. Efuel will become relatively competitive by 2030 and 2050, making it appealing for long-term adoption. While competitive early on, Biofuels tend to face increased uncertainty and probable cost rises as time goes on, making them less likely to dominate the market.

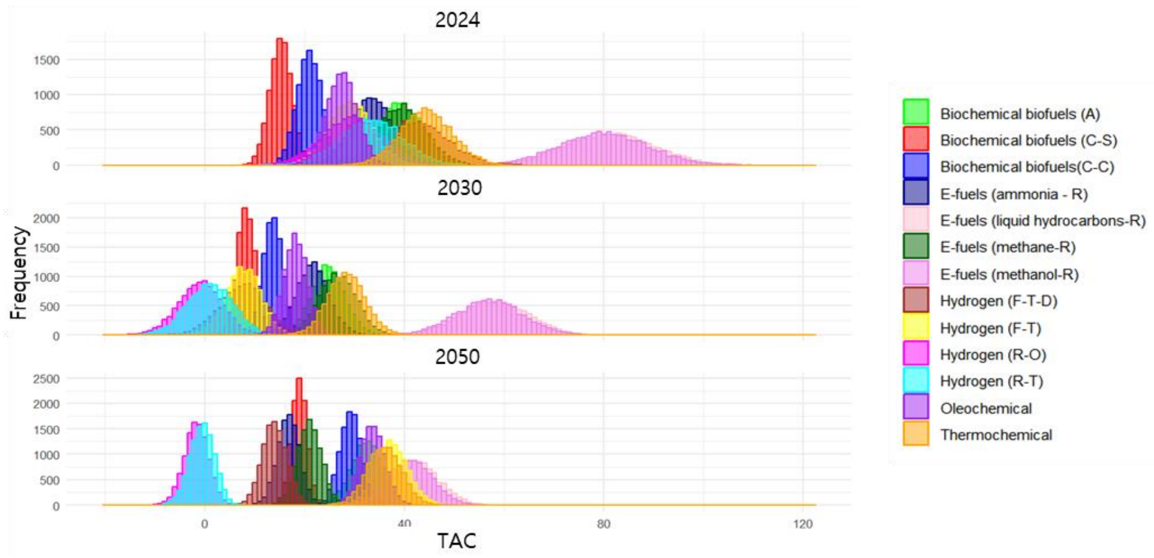


Figure 9. Projected distribution of TAC in EU. This figure compares the cost dynamics of all alternative fuels in three categories

3.3 Phase III. MAC

Table 12 shows the average MAC in maritime and aviation in two nations. The MAC of the EU exceeds that of the US. Also, the value of maritime is greater than that of aviation. The MAC gradually declines with time and at a faster rate in the EU. Although the MAC in the two nations is significantly different from that in 2024, the MAC in 2030 will soon reach a comparable level between the US and the EU. As discussed in 2.2.3, MAC is the function of various factors (i.e., target CI, credit price, capital investment, and so on). The impact of each parameter is explored in sensitivity analysis in the following chapters.

Table 12. Yealy Average of MAC

Year	Maritime - EU	Maritime - US	Aviation - EU	Aviation - US
2024	1,089	892	689	521
2030	556	390	503	337
2050	360	236	343	222

Figure 10 depicts the trajectory of MAC in the futures market. All three sectors see a decline between 2030 and 2050 in the maritime industry. In general, biofuels appear to have a competitive cost advantage in 2024. However, beyond 2030, hydrogen would be more favorably positioned. The marginal abatement cost (MAC) of hydrogen experiences a significant decrease due to the elevated capital expenses. Efuels would continue to be an expensive choice for reducing emissions.

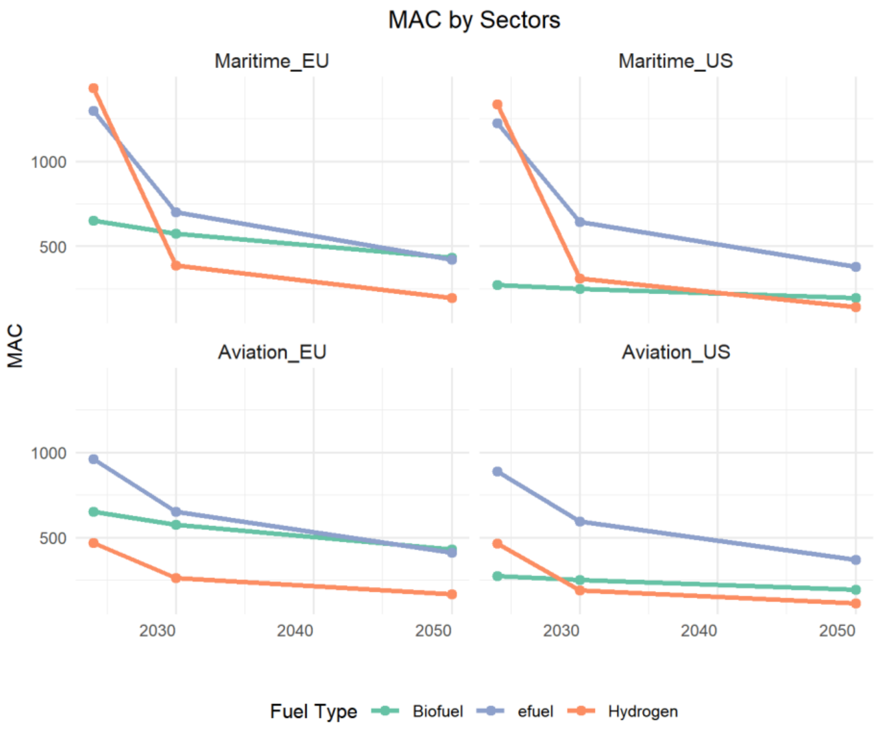


Figure 10. MAC by sectors in the short term (2030) and long term (2050). This figure compares MAC of biofuel, hydrogen and Efuel between EU and US

3.3.1 MAC of Maritime

MAC of phase III measures the cost of reducing one ton of CO2e. As the amount of pollution reduction grows, the expenses associated with using alternate fuels would also increase. Private parties would attempt to utilize low-cost fuels, so the MAC shows a potential order of alternative fuel use in the future. Figure 11 demonstrates that CA has a lower average MAC in the marine sector than the EU. Biofuels will be the dominant energy source in the US in the future, followed by ammonia and LNG. This aligns with the present use of clean fuel in the market. LNG and green ammonia have been used in maritime recently (K. Machaj, 2022). However, CA should prepare a cost spike after using ammonia and LNG. EU appears to prioritize hydrogen over biofuels. In maritime, hydrogen seems to be a promising fuel in the long term. Also, in both the US and EU, oleochemicals and liquid hydrogen are regarded as the most expensive choices.

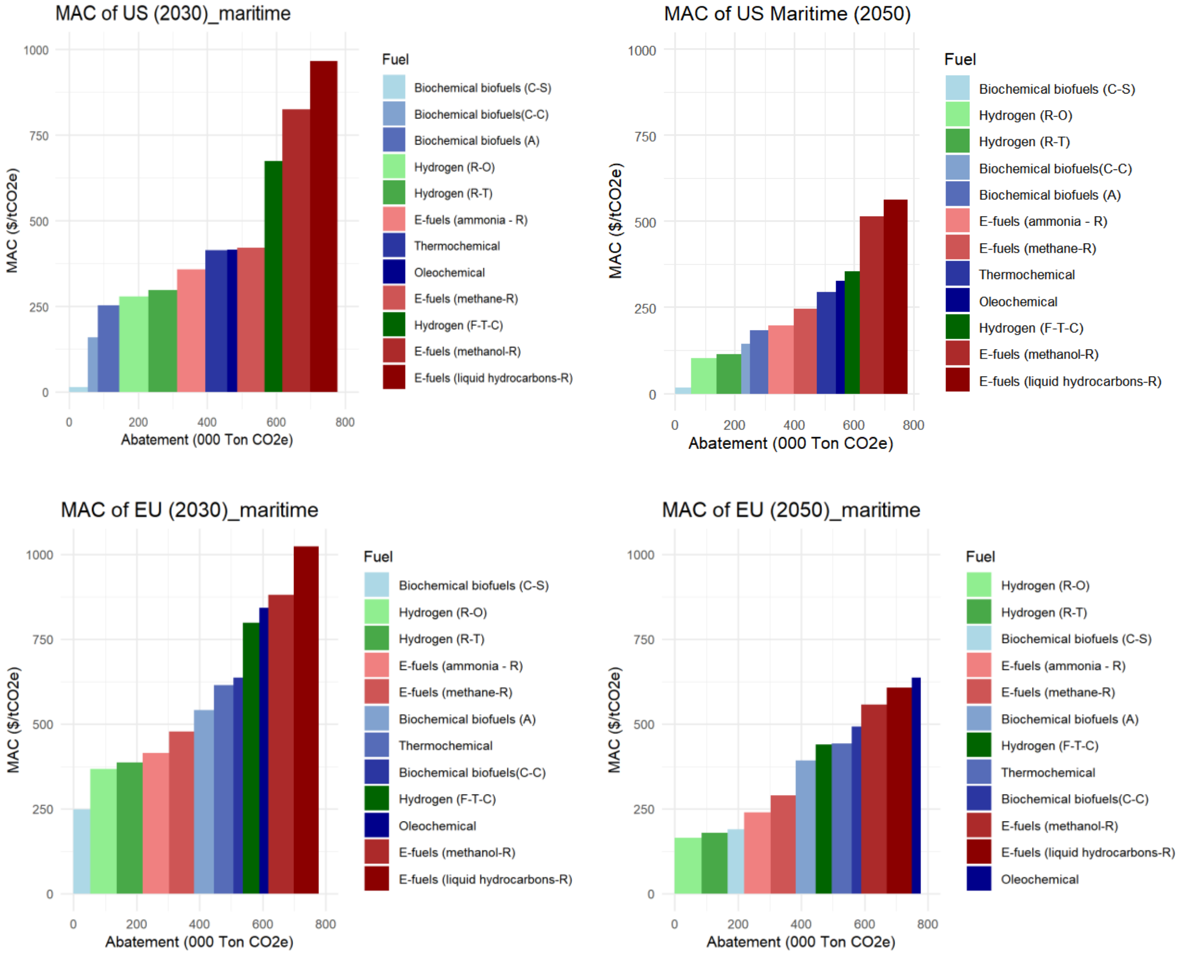


Figure 11. MAC for maritime in CA and EU. The bar chart displays the MAC in $ per ton of CO2e (y-axis) and total CO2e abatement of different alternative fuels in maritime sector for the year 2030 and 2050. Each bar corresponds to a specific fuel type

3.3.2 MAC of Aviation

In aviation, SAF has been discussed as the most promising fuel, as it does not require system modification and infrastructure investment. As expected, sugarcane-based-biofuel is the most cost-competitive fuel in the two nations. An SAF pathway for sugarcane-based biofuel using alcohol-to-jet technology has been approved recently[15]. However, Figure 12 reveals that hydrogen and biofuels are expected to be used alternatively in both the US and EU. The EU has fewer low-cost abatement options under 500 $/tCO2e than the

---

[15] Sugar Valley Energy biorefinery pivots to SAF | Ethanol Producer Magazine

EU. The MAC of fuel increases more rapidly in the EU than in the US as the accumulated abatement increases with fuels. In both countries, oleochemical technology and Efuel come last, suggesting they are the least economical choice.

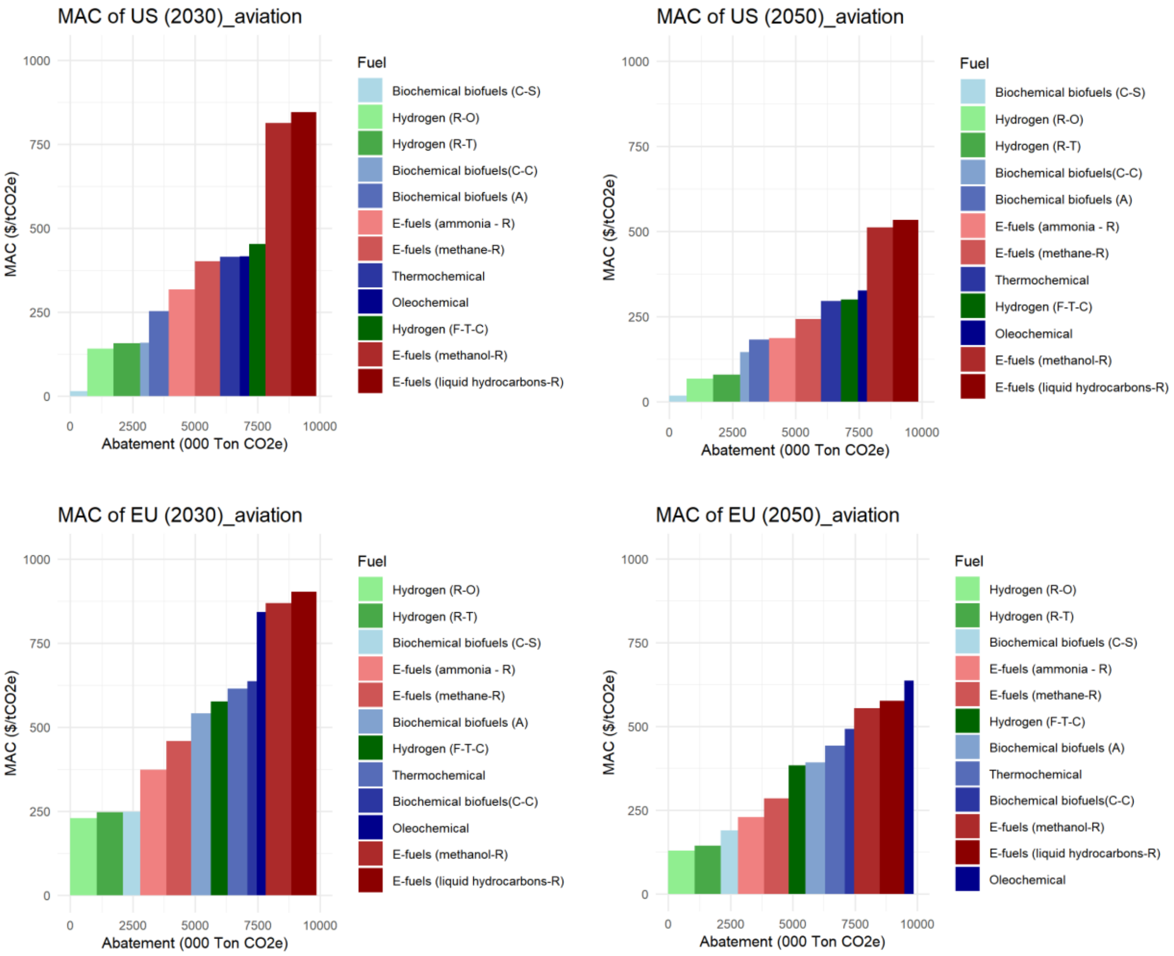


Figure 12. MAC for aviation in CA and EU. The bar chart displays the MAC in $ per ton of CO2e (y-axis) and total CO2e abatement(x-axis) of different alternative fuels in aviation sector for the year 2030 and 2050

3.3.3 MAC Sensitivity Analysis

Sensitivity analysis is only provided in aviation because the results are similar in maritime and aviation. Surprisingly, Figure 13 shows minor change value of MAC. Common parameters (i.e., Target CI and credit price) were not the major drivers of MAC. A 1% change in the discount rate results in a considerable change in MAC for Efuel, although hydrogen is not as sensitive. Biofuel responds most sensitively at the target CI level.

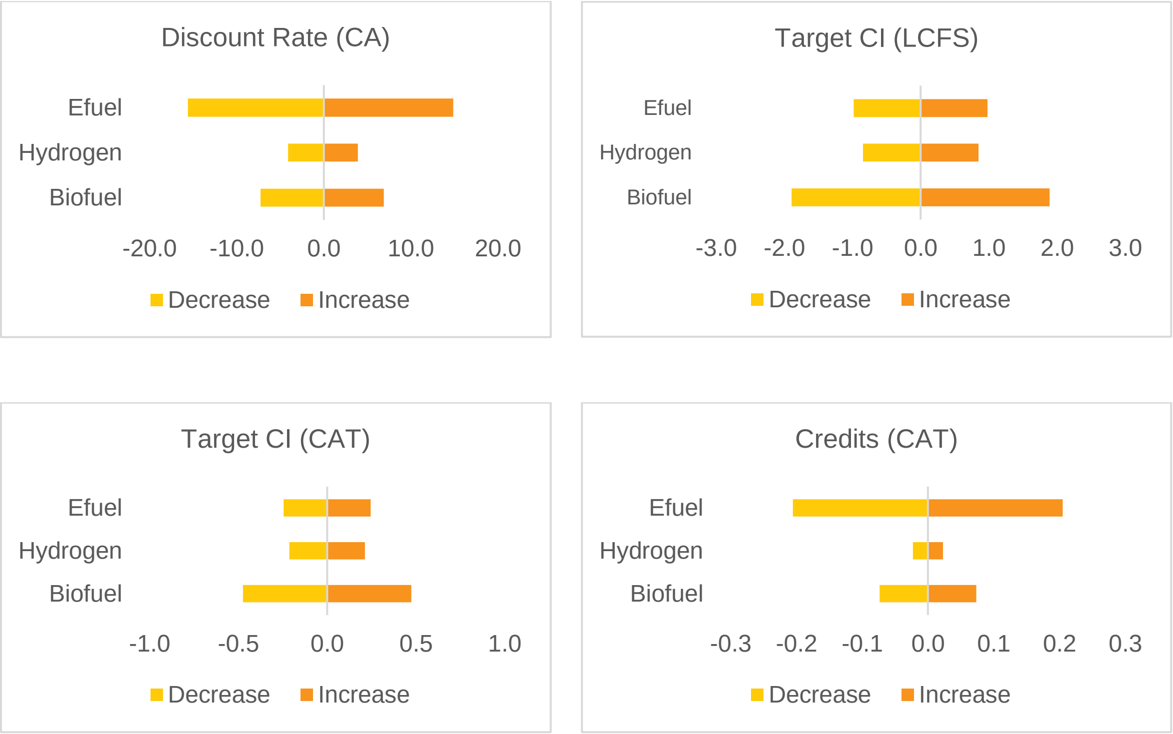


Figure 13. Effect of key input parameters on MAC in CA. This figure shows change of MAC from decrease and increase of discount rate, Target CI from LCFS and CAT, and credits from CAT

From Figure 14, the discount rate in the EU ETS has less effect than in the US. However, credit value has a higher influence on the EU MAC. This sensitivity comparison shows that climate policy needs to be carefully made to decrease the MAC level. For example, Efuels are most susceptible to discount rates, but hydrogen is most driven by credit values in the EU.

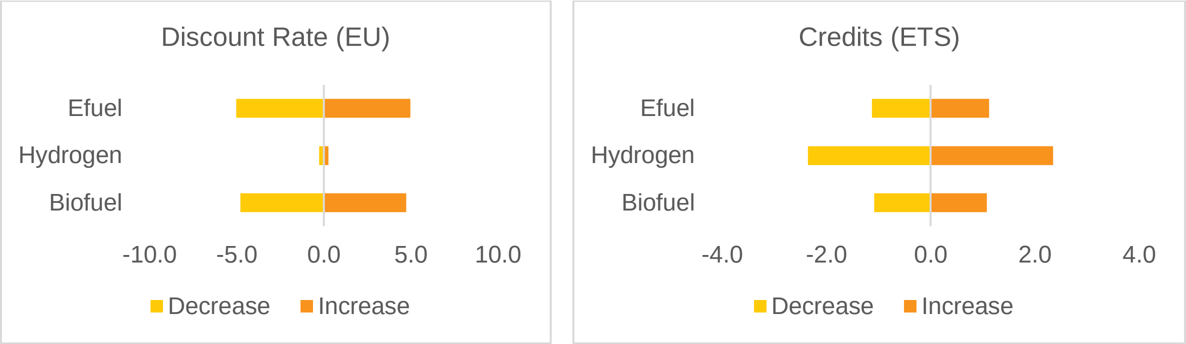


Figure 14. Effect of key input parameters on MAC in EU. This figure shows change of MAC from decrease and increase of discount rate, and credits from ETS

Policy implications

In the model of this study, it is assumed that the policy, both subsidy and target CI, remain unchanged. Also, emissions levels are assumed not to change with time passage. Any severe economic events, such as Covid19 have not been considered. These uncertainties could be captured by the Monte Carlo simulation in TAC in Phase II and the discount rate in MAC in Phase III.

Nevertheless, it is important to be aware of the uncertainty of continuing support by policy. For example, in 2007, the required RVO[16] under RFS set a target of 36 billion gallons per year by 2022. However, only around 15 billion gallons of RVO will be achieved as of 2022. Also, the EPA waived part of this RVO under RFS due to a shortfall of production and harmed the economy (Maria Gerveni, 2023). Also, IRA incentives for SAF are only valid until 2027. SAF from LCFS and RFS regulation is considered an ‘opt-in’ fuel, which means SAF is not obligated to meet the requirement from LCFS but is eligible to generate credits. This can also be another weak point, as it does not stimulate the demand for SAF. Another

---

[16] Annual biofuel volume requirement of renewable fuel that need to be blended to gas supply (EPA, 2023)

federal policy (i.e., RFS) lacks enforcement with the use of clean fuel without penalty, but CA supplemented with a strong penalty for fuels CI.

However, the EU gives strong signals to the clean fuel market in aviation and maritime with recently enacted regulations (i.e., RefuelEU aviation and FuelEU maritime). As shown in the result of phase I, the high level of penalty allows the investment in clean fuel to look attractive. The floor of a carbon price in emission trading platforms and long-term policy for direct incentives would reduce policy uncertainty for the investment of clean energy technologies.

The quantitative analysis in the study helps policymakers to diagnose the current and future status of clean energy sources in the fuel market. The findings from phase I suggest that clean fuel would need continued financial support to lower emissions until the development of technology secures the scale of economies. The results of phases II and III show that mixed use of alternative fuels should be expected due to the limited availability, different geological characteristics, and infrastructure. It is important to continue investing in technology development so that various low-carbon fuels can be investigated.

The results in three phases show the challenge of decarbonization that policymakers are facing. As we confirmed in Phase I, imposing high penalties and mandating would induce an increase in clean fuel use, but it could harm economic status by increasing the production cost of all goods. While the results of TAC from Phase II show an increase from 2030 to 2050, and MAC from Phase III shows a decrease from 2030 to 2050. This is mainly due to the low level of target CI in 2050. For example, the emissions of biofuels are around 40, the target CI of LCFS is nearly 40 gCO2e/MJ, but the target of EU maritime is around 19 gCO2e/MJ. However, when we accounted for the accumulated emissions abatement, the marginal cost actually decreased, indicating improved cost-effectiveness over time. This finding suggests that policy measures need to be carefully designed to manage these rising costs, potentially focusing on the most cost-effective abatement options and fostering innovations that can counteract the overall trend of increasing costs.

Conclusion

The quantitative analysis from this study demonstrates the current and future position of low-carbon fuels in three different forms (i.e., point estimates, distribution, and marginal abatement curve). This allows policymakers to explore various possible scenarios to develop more effective policies. Also, the analysis results align with previous papers' findings. For example, a study from Brynolf in 2022 projected the MAC of Efuel abatement in 2022 at 300 - 1200 \$/tCO_2e and estimates MAC in 2035 at 46-724 \$/tCO_2e (Brynolf, 2022; Martin, 2023). This study estimates that costs in 2030 range from 318 to 1023 \$/tCO_2e.

The abatement costs need to be interpreted in the context of the social cost of carbon (SCC). SCC quantifies the monetary value of damage attributed to emissions, whereas abatement costs represent the expenses required to decrease emissions (Hickey, 2023). This study estimates the abatement costs in shipping and aviation at 220-1089 \$/tCO_2e, which is lower than the estimates from Martin's study at 420-1200 \$/tCO_2e[17] (Martin, 2023). However, the SCC from Rennert's study is estimated at 185 \$/tCO_2e (with a range of 44-413 \$/ tCO_2e), which is far lower than the value of this study (Rennert, 2022). Aviation and shipping sectors cost more to decarbonize, as Martin's study revealed that

---

[17] Converted from € to \$, Assuming 1€ equals 1.1\$.

road carbon abatement costs could be ten times lower than shipping and aviation (Martin, 2023).

There is a debate over the magnitude of SCC due to the uncertainty of estimations, but SCC is being used as a benchmark for making public policy decisions (Richard S.J. Tol, 2023). If the advantages of reducing emissions are determined solely by SCC, it may be challenging to justify the investment in emissions reduction in aviation and shipping. It is important to explore the risk of over-investment, but the moral duty of protecting the environment should be measured as well. Hickey suggested several different approaches to examine the relations among SCC, abatement costs, and moral duty (Hickey, 2023). However, in terms of risks of overpricing or underpricing emissions, we should weigh more on the value of underpricing cases. The possible results from overpricing can be representative of lower GDP, while the consequence of underpricing may be devastating, leading to a climate catastrophe. A study from Havard states that $1 spent on mitigation could save $11 in the future (Havard, 2023).

In addressing the limitations of this study, several important considerations must be highlighted. We did not consider nonquantifiable policies, such as the mandate for the share of renewable energy in the EU and the biofuel production requirement in the US. The enforcement would induce a larger scale of economy, reducing production costs in the long term. Additionally, the production cost and emission of each fuel might be different by region. However, this study employed a single dataset for quantitative analysis of the EU and US due to the limited available sources.

Future research is needed to consider the potential scale of fuel demand for aviation and shipping sectors. Possible scenarios of fuel mixes need to be presented to policymakers. Also, the sensitivity of production costs to each policy would allow us to find cost-effective policies. Lastly, our study raises the question of the interaction of abatement costs, SCC, and moral duty. It would be great if we could assign an appropriate monetary value to moral obligation and incorporate it into the model. By considering all of those options, future research would demonstrate a more thorough examination of low-carbon fuels.

Appendix

Figure 15 shows the VAR model's results for credit prices on three different platforms. All credits will increase toward 2050. While LCFS and CAT show a more slowly increasing trend, ETS has a greater increase in the model. These results align with the increasingly stringent regulations, driving the cost of compliance higher over time.

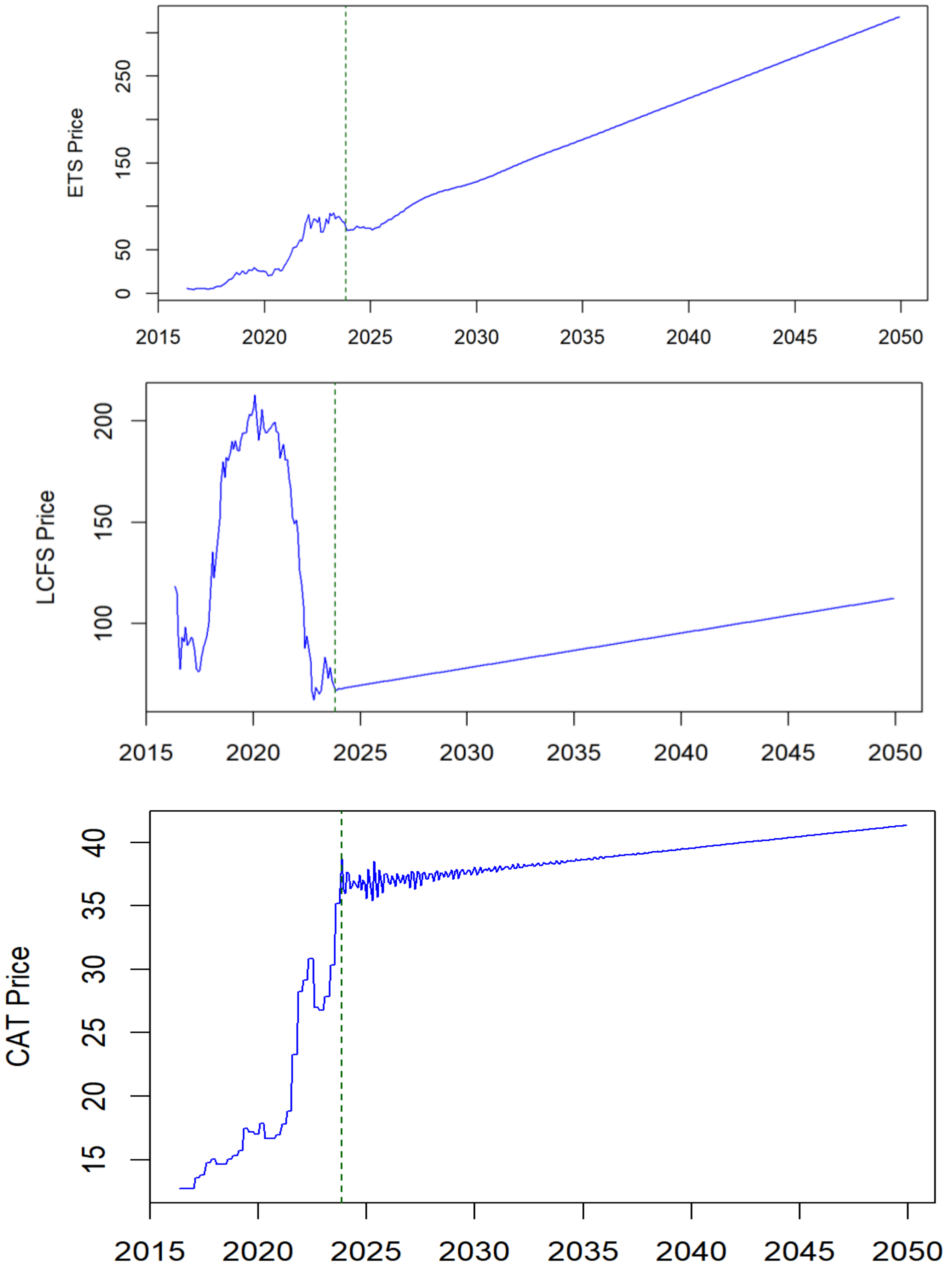
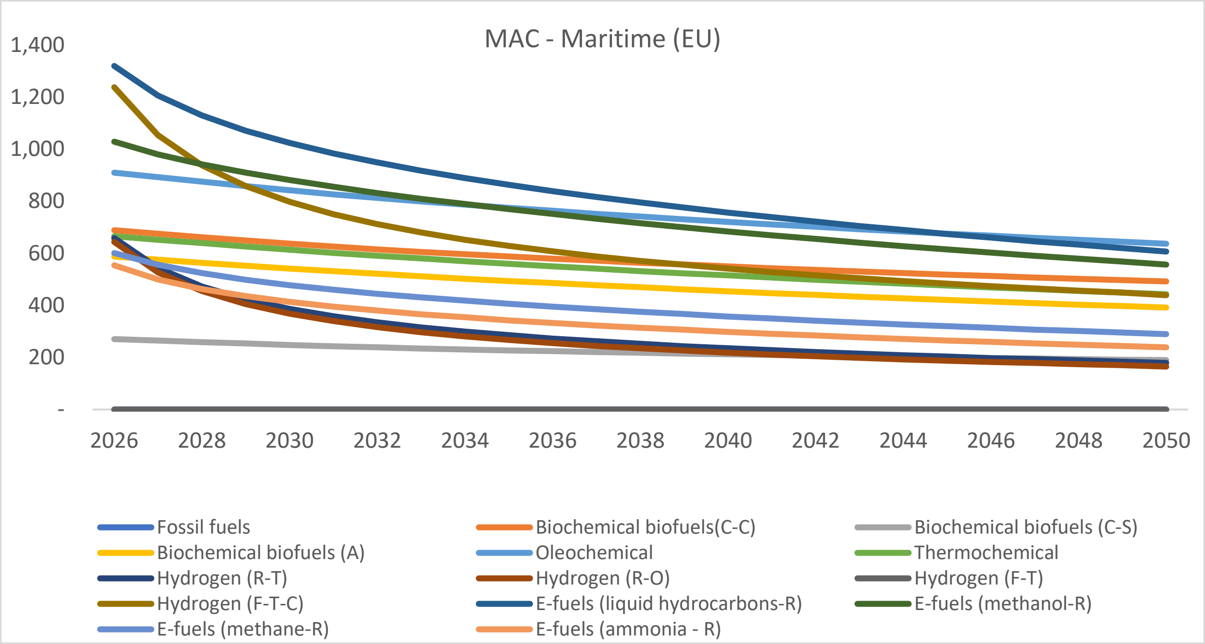


Figure 15. Forecast of carbon credits price

Figure 16 shows slightly higher MACs in the EU across most fuel types compared to the US.



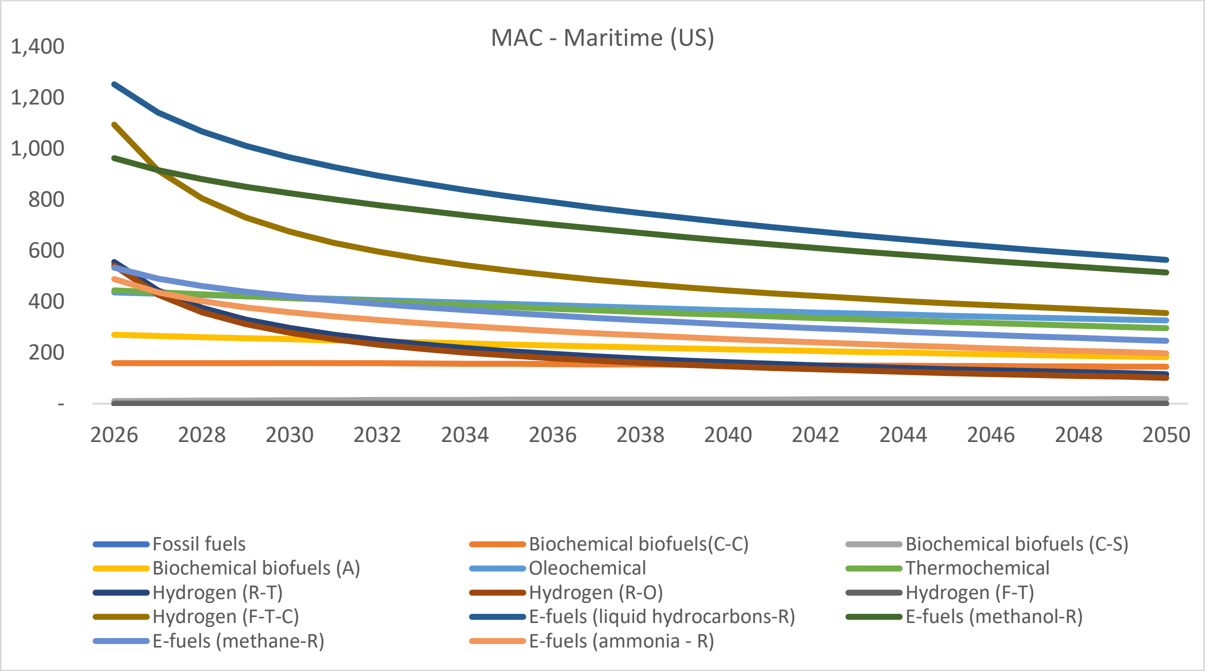
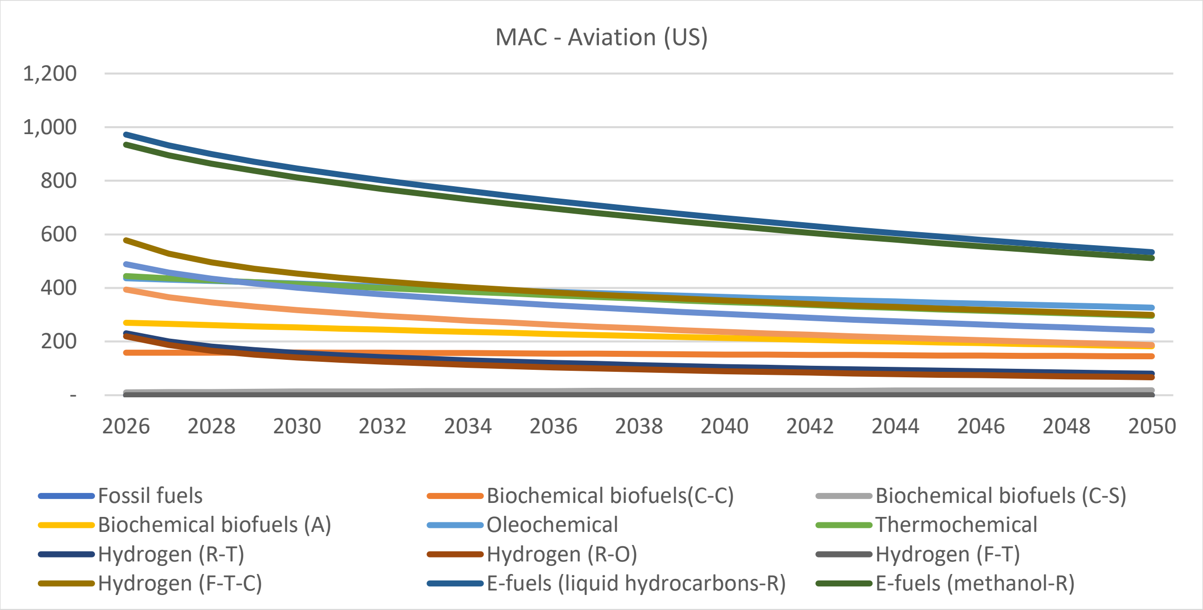


Figure 16. Forecast of MAC in maritime

Figure 17 show a general downward trend in MAC across all fuel types, indicating that the cost of reducing emissions decreases over time. Fossil fuels consistently maintain the highest MAC, while clean fuels generally show lower MACs towards 2050.



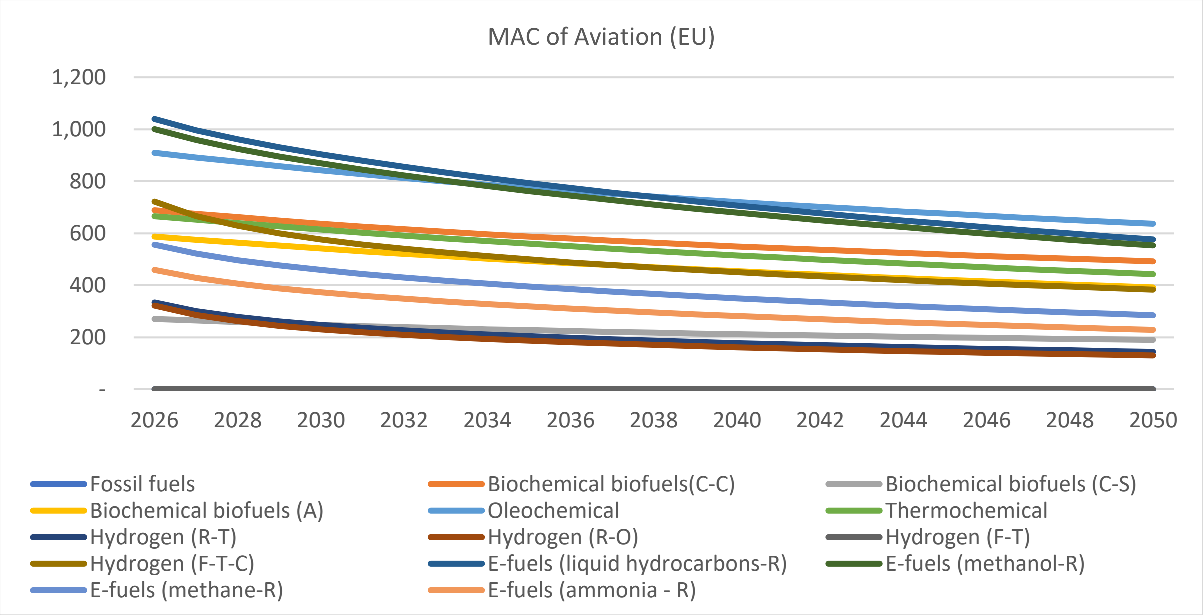


Figure 17. Forecast of MAC in aviation

[Reference]

Air transport statistics - Statistics Explained. (n.d.). Retrieved March 17, 2024, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Air_transport_statistics

Autoregressive Conditional Heteroskedasticity (ARCH) Explained. (n.d.). Retrieved March 17, 2024, from https://www.investopedia.com/terms/a/autoregressive-conditional-heteroskedasticity.asp

Bjerkan, K. Y., & Seter, H. (2019). Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports? *Transportation Research Part D: Transport and Environment*, *72*, 243–260. https://doi.org/10.1016/J.TRD.2019.05.003

By 2030 EVs represent more than 60% of vehicles sold globally, and require an adequate surge in chargers installed in buildings – Analysis - IEA. (n.d.). Retrieved March 17, 2024, from https://www.iea.org/reports/by-2030-evs-represent-more-than-60-of-vehicles-sold-globally-and-require-an-adequate-surge-in-chargers-installed-in-buildings

Canabarro, N., Soares, J. F., Anchieta, C. G., Kelling, C. S., & Mazutti, M. A. (2013). Thermochemical processes for biofuels production from biomass. *Sustainable Chemical Processes 2013 1:1*, *1*(1), 1–10. https://doi.org/10.1186/2043-7129-1-22

Carbon Offsetting and Reduction Scheme for International Aviation | Federal Aviation Administration. (n.d.). Retrieved March 17, 2024, from https://www.faa.gov/about/office_org/headquarters_offices/apl/aee/corsia

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). (n.d.). Retrieved March 17, 2024, from https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

Chevallier, J. (2011). A model of carbon price interactions with macroeconomic and energy dynamics. *Energy Economics*, *33*(6), 1295–1312. https://doi.org/10.1016/J.ENECO.2011.07.012

Dotson, G., & Maghamfar, D. (2023). *The Clean Air Act Amendments of 2022: Clean Air, Climate Change, and the Inflation Reduction Act*. https://papers.ssrn.com/abstract=4338903

Ethanol vs. Petroleum-Based Fuel Carbon Emissions | Department of Energy. (n.d.). Retrieved March 17, 2024, from https://www.energy.gov/eere/bioenergy/articles/ethanol-vs-petroleum-based-fuel-carbon-emissions

EUR-Lex - 52019DC0640 - EN - EUR-Lex. (n.d.). Retrieved March 17, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

Federal Register :: Renewable Fuel Standard (RFS) Program: Standards for 2023-2025 and Other Changes. (n.d.). Retrieved March 17, 2024, from https://www.federalregister.gov/documents/2023/07/12/2023-13462/renewablEfuel-standard-rfs-program-standards-for-2023-2025-and-other-changes

Global Oleochemicals Market Report 2022: Environmental Benefits of Biofuels Driving Growth - ResearchAndMarkets.com | Business Wire. (n.d.). Retrieved March 17, 2024, from https://www.businesswire.com/news/home/20221214005930/en/Global-Oleochemicals-Market-Report-2022-Environmental-Benefits-of-Biofuels-Driving-Growth---ResearchAndMarkets.com

Gnanasekaran, T. (2022). Handling and operations of liquid metal systems. *Science and Technology of Liquid Metal Coolants in Nuclear Engineering*, 155–238. https://doi.org/10.1016/B978-0-323-95145-6.00005-6

Gorre, J., Ortloff, F., & van Leeuwen, C. (2019). Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. *Applied Energy*, *253*, 113594. https://doi.org/10.1016/J.APENERGY.2019.113594

Green hydrogen Cost reduction scaling up electrolysers to meet the 1.5°C climate goal (2020). *www.irena.org/publications*

Jalil, A., & Rao, N. H. (2019). Time Series Analysis (Stationarity, Cointegration, and Causality). *Environmental Kuznets Curve (EKC): A Manual*, 85–99. https://doi.org/10.1016/B978-0-12-816797-7.00008-4

Karka, P., Johnsson, F., & Papadokonstantakis, S. (2021b). Production costs of advanced biofuels using a multi-component learning curve model. *Computer Aided Chemical Engineering*, *50*, 1937–1942. https://doi.org/10.1016/B978-0-323-88506-5.50300-4

Lagemann, B., Lindstad, E., Fagerholt, K., Rialland, A., & Ove Erikstad, S. (2022). Optimal ship lifetime fuel and power system selection. *Transportation Research Part D: Transport and Environment*, *102*, 103145. https://doi.org/10.1016/J.TRD.2021.103145

Liquid Hydrocarbon - an overview | ScienceDirect Topics. (n.d.). Retrieved March 17, 2024, from https://www.sciencedirect.com/topics/engineering/liquid-hydrocarbon

Machaj, K., Kupecki, J., Malecha, Z., Morawski, A. W., Skrzypkiewicz, M., Stanclik, M., & Chorowski, M. (2022). Ammonia as a potential marine fuel: A review. *Energy Strategy Reviews*, *44*, 100926. https://doi.org/10.1016/J.ESR.2022.100926

New study launched on the integration of sustainable aviation fuels at airports | ACI World. (n.d.). Retrieved March 17, 2024, from https://aci.aero/2022/06/09/new-study-launched-on-the-integration-of-sustainable-aviation-fuels-at-airports

Oecd, & Itf. (n.d.). *The Potential of Efuels to Decarbonise Ships and Aircraft Corporate Partnership Board Report*.

Renewable energy directive. (n.d.). Retrieved March 17, 2024, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

Rep. Yarmuth, J. A. [D-K.-3]. (2022). *H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022*. https://www.congress.gov/bill/117th-congress/house-bill/5376

Riviera - News Content Hub - IMO vote provides major boost to wider adoption of biofuels. (n.d.). Retrieved March 17, 2024, from https://www.rivieramm.com/news-content-hub/news-content-hub/imo-vote-provides-major-boost-to-wider-adoption-of-biofuels-72290

Technologies Office, B. (n.d.). Sustainable Aviation Fuel: Review of Technical Pathways Report.

The scale of investment needed to decarbonize international shipping. (n.d.-a). Retrieved March 17, 2024, from https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping

The scale of investment needed to decarbonize international shipping. (n.d.-b). Retrieved March 17, 2024, from https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping

Unit Root In Time Series. In data science we talk a lot about… | by Andrew Ozbun | CodeX | Medium. (n.d.). Retrieved March 17, 2024, from https://medium.com/codex/unit-root-in-time-series-38d451d742ce

Zhou, Y. J., Buijs, N. A., Zhu, Z., Qin, J., Siewers, V., & Nielsen, J. (2016). Production of fatty acid-derived oleochemicals and biofuels by synthetic yeast cell factories. *Nature Communications 2016 7:1*, *7*(1), 1–9. https://doi.org/10.1038/ncomms11709