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Beyond Carbon Pricing: Policy-Driven Willingness to Pay for e-Fuels in EU Shipping

Santiago Serna Zuluaga[a,*], Timo Gerres[a], Rafael Cossent[a]

[a] *Institute for Research in Technology, Comillas Pontifical University, Rey Francisco 4, Madrid, Spain*

Abstract

The decarbonization of maritime transport requires alternative fuels that are not only technically viable but also economically competitive. We quantify economic competitiveness through the willingness-to-pay (WTP), defined as the maximum e-fuel price at which ship operators remain cost-neutral relative to fossil alternatives. Using this framework, we assess how two EU regulations — the EU Emissions Trading System (EU ETS) and FuelEU Maritime — shape the economic case for e-fuel adoption.

Our results show that FuelEU Maritime is the dominant regulatory driver, accounting for 70–80% of total WTP, while the EU ETS contribution is comparatively modest. Beyond this, the non-linear structure of the FuelEU Maritime non-compliance penalty causes WTP to vary with the vessel's compliance level—defined as the share of low-emission fuel required to meet the GHG emission intensity target in a given year. Consequently, the marginal value of e-fuel is not constant: early units yield smaller penalty reductions than later ones. For instance, in 2050, a compliance level of 50% reduces the non-compliance penalty by only 16%. This structure inherently favors full compliance in individual vessels over partial compliance across fleets, even when aggregate emission reductions are equivalent.

When benchmarking the obtained WTP against current production costs, our results suggest that existing regulation largely bridges the cost gap for most e-fuels, with ammonia emerging as the most cost-competitive option. Although biofuels and fossil fuels with carbon capture may offer lower production costs at comparable WTP levels, but their large-scale deployment faces binding supply-side constraints. E-fuels are therefore expected to play a complementary yet critical role in achieving long-term decarbonization targets as lower-cost alternatives become increasingly scarce.

1. Introduction

Shipping accounted for an estimated 2.3% of global anthropogenic CO_2 emissions annually between 2017 and 2023 [1]. Given this substantial environmental footprint, the sector has assumed an increasingly prominent role in global climate change mitigation, with ambitious targets set to achieve net-zero emissions by 2050. In this context, several regulations are emerging at both global and regional levels. At the global level, the IMO Net Zero Framework (IMO NZF) — already agreed but not yet formally adopted by member states, and therefore currently without legal force— imposes progressively stricter greenhouse gas (GHG) emission-intensity targets, expressed in gCO_2eq/MJ, for the energy consumed on board vessels. At the regional level, two regulations are already in force in Europe: FuelEU Maritime, which mandates GHG emission reductions, and the EU Emissions Trading System (EU ETS), which establishes a carbon price targeting direct CO_2 emissions. Although these are regional regulations, their implications extend well beyond the European market, as they apply to all vessels calling at European ports. Given the central role of European ports in global shipping routes [2], these regional regulations effectively impact vessel operations worldwide.

These mechanisms have been studied from policy [3] and end-user [4] perspectives, but ultimately it is ship operators who must decide how to comply. In this sense, several decarbonization pathways have been identified, including direct electrification, hydrogen, biofuels, and hydrogen derivatives, commonly known as

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[*] Corresponding author: sserna@comillas.edu

e-fuels. Roadmaps proposed by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) [5] consistently highlight e-fuels as the dominant solution to meet net zero emissions in shipping, both projecting e-fuel shares above 50 % by 2050.
Yet, for these scenarios to materialize, it is necessary to determine whether current regulatory mechanisms are sufficient to make e-fuels economically competitive with conventional fuels. The Total Cost of Ownership (TCO) has emerged as the most widely used metric to address this question, enabling cost comparisons across fuels, routes, and operational strategies. Zincir and Zincir [6] applied the TCO at fleet scale, comparing operational costs across different e-fuels and ship types, while Park et al. [7] adopted a cost-minimizing speed approach on a single Asia–Europe route, finding that optimal strategies involve slow steaming in regulated regions and higher speeds elsewhere — potentially leading to higher overall GHG emissions. Other TCO-based studies include Martin et al. [8], Stolz et al. [9], and Lindstad et al. [10], which assess e-fuel competitiveness across different electricity price scenarios.

Despite its widespread use, the TCO is not the only framework proposed in the literature to evaluate e-fuel competitiveness. The Carbon Abatement Cost (CAC) quantifies the carbon price required to achieve cost parity with fossil fuels for a given reference case— typically defined by route, speed, and vessel type. Wahl and Kallo [11] employed this approach combined with a Monte Carlo simulation to account for uncertainty in e-fuel production costs, while Bachorz et al. [12] examines how the CAC evolves as a function of hydrogen and CO_2 costs required for fuel synthesis. Guinane et al. [13] further links carbon pricing to e-fuel market share, finding that high carbon prices drive adoption rates toward 100%, whereas low carbon prices fail to incentivize the transition. The concept of CAC is closely related to Marginal Abatement Cost Curves (MACCs), which aggregate individual abatement options into a system-level representation of decarbonization costs. In this sense, beyond e-fuels, Lagouvardou et al. [14] constructs a MACC for the shipping sector encompassing biofuels and fossil fuels with carbon capture under both high- and low-e-fuel price scenarios.

The practical applicability of both frameworks is constrained by their reliance on upstream production cost assumptions, such as electricity prices, renewable resource profiles, and electrolyzer efficiencies, which vary significantly across geographies and scenarios. Studies assuming favorable conditions, such as abundant renewable availability or low electricity cost, may find e-fuels competitive, whereas those reflecting less favorable conditions may not. As an illustrative example, Martin et al. [8] reports shipping costs ranging from 0.032 to 0.068 €/t-km — a twofold variation driven solely by the choice of electricity source. Consequently, TCO and CAC can characterize specific cases but cannot answer a more policy-relevant question: at what costs should e-fuels be economically competitive under existing regulations, and what cost reductions would be needed to close the remaining gap? This question can only be answered using a Willingness-to-Pay (WTP) approach. The WTP is defined as the maximum e-fuel price at which ship operators remain economically competitive under a given regulatory environment, abstracting from upstream production assumptions. The above discussion is summarized in Figure 1, which contrasts the input requirements of each framework and the key question each is designed to answer.

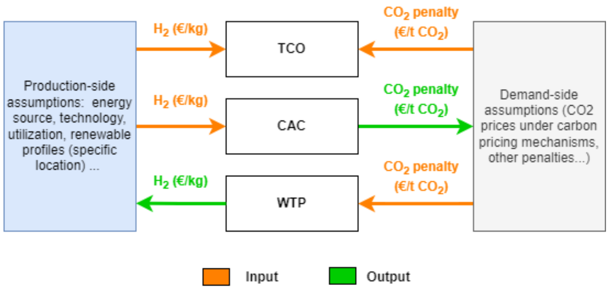

Figure 1: FuelEU Maritime target.

The WTP concept has received considerably less attention in the literature and has been applied mainly in multisectoral analyses encompassing industrial applications, road transport, maritime transport, and aviation, as in Observatory [15] for Europe and Murdoch et al. [16] for the United States. These approaches, however, restrict their regulatory scope to direct carbon pricing mechanisms and do not account for sector-specific regulations. For instance, Observatory [15] reports a WTP of 2.2 €/kg H_2-equivalent for e-fuels in EU shipping without incorporating FuelEU Maritime. More recent studies have partially integrated such sector-specific frameworks;

notably, Du et al. [17] estimates the WTP for zero-emission renewable methanol, accounting for the combined effects of the EU-ETS and FuelEU Maritime. This work provides a valuable foundation; however, three aspects remain unaddressed and motivate the present work.

(i) The analysis assumes full substitution of fossil fuels with zero-emission methanol, implicitly entailing a 100% reduction in greenhouse gas emissions. In practice, however, FuelEU Maritime establishes progressively tightening fuel-intensity targets that enable compliance through blending strategies rather than complete fuel switching. Moreover, the FuelEU Maritime penalty function is non-linear with respect to compliance levels (see section 2), meaning that equivalent emission reductions can yield different penalty savings depending on the distance from full compliance.

(ii) The analysis assumes that methanol has zero Well-to-Wake (WtW). However, FuelEU Maritime does not require zero emissions, and e-fuels may deliver partial emission reductions (e.g., 70 %) while still generating compliance value through associated emission savings. Capturing the relationship between emission savings and WTP is essential for accurately assessing the market value of e-fuels.

(iii) The analysis does not account for the impact of fuel certification labels on the WTP. Under FuelEU Maritime, fuels are classified according to their production pathway into Renewable Fuels of Non-Biological Origin (RFNBOs) and low-carbon fuels, each subject to different regulatory treatment. Beyond the general GHG intensity target, FuelEU Maritime establishes a dedicated 2% sub-target for RFNBOs, creating additional compliance value for fuels carrying this certification. As a result, two e-fuels with equivalent emission-reduction profiles may command different WTP values depending on whether they qualify as RFNBOs, a distinction that the present framework does not capture.

This paper advances the WTP literature by explicitly incorporating regulatory design elements that are typically overlooked in demand-side assessments. The paper makes four main contributions. First, it develops a regulation-consistent framework to estimate WTP under the joint operation of the EU ETS and FuelEU Maritime, explicitly capturing the non-linear structure of the penalty function and its implications for marginal compliance incentives. Second, it incorporates heterogeneity in lifecycle emissions, quantifying how GHG performance drives WTP. Third, it analyses the premium WTP associated with the RFNBO label. Finally, it bridges the demand–supply gap by benchmarking WTP against the production costs of e-fuels and alternative low-carbon options, providing insights into the economic feasibility of different compliance strategies under current regulatory conditions.

2. EU Policy Framework for Shipping decarbonization

The recent interest in decarbonizing maritime transport in Europe dates back to 2019, when the European Commission presented the European Green Deal, a policy framework comprising numerous pieces of legislation, strategies, and funding instruments, with the aim of transforming Europe's economy and society, placing sustainability at the heart of EU policies and aligning all sectors to reach climate neutrality by 2050. Subsequently, the European Climate Law (2021) established the goal of climate neutrality by 2050 as legally binding and set an intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990). To achieve these targets, the EC developed the Fit for 55 Package (2021), a comprehensive legislative package to align EU laws with the 2030 climate target of a 55% reduction. Among others, the Fit for 55 package aimed to extend the EU-ETS to maritime shipping and to develop a new regulation on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime). In the remainder of this section, we further explain each of them in more detail, focusing on the implications these regulations have for the WTP for e-fuels.

*2.1. **EU-ETS and FuelEU Maritime Regulations***

The EU ETS is a "cap-and-trade" carbon market, launched in 2005 to reduce greenhouse gas emissions. It sets a cap on total emissions, and companies buy emissions allowances equivalent to a ton of CO2. The number of allowances is limited by the cap, which decreases in different time windows and phases. Initially, aviation and industry were covered under EU-ETS, but from 2024 onwards, ships above 5,000 GT are covered by the mechanisms. The total emission budget is not increased, and a new sector is incorporated to compete for allowances. The obligated party is the owner of the ship, and a 50 % applies from trips outside the EU to an EU port and 100 % between EU-ports. Emissions under the EU-ETS are Tank-to-Wake emissions of CO2 and other molecules, such as methane and NOx. In practice, the EU-ETS penalizes the use of fossil fuels, increasing the WTP for clean fuels. As this framework penalizes direct emissions, there are several ways to reduce the associated penalty, including route optimization or reduced ship use.

FuelEU Maritime complements EU-ETS, stimulating an increased share of renewable and low-carbon fuels in the fuel mix of international maritime transport by imposing progressively stricter Well-to-Wake (WtW) GHG emission-intensity targets expressed in gCO$_2$eq/MJ. Figure 2 the GHG reduction targets are reduced across successive five-year compliance windows. In addition, FuelEU Maritime introduces a dedicated RFNBO sub-target, requiring a minimum 2% share of Renewable Fuels of Non-Biological Origin after 2034, contingent on the RFNBO share in EU maritime transport remaining below 1% in 2031. As for EU-ETS, the energy covered by FuelEU Maritime in both targets depends on the route: voyages between EU ports are subject to 100% coverage, while those involving a non-EU port are covered at 50%.

Another aspect worth mentioning of FuelEU Maritime is the flexibility mechanisms. FuelEU Maritime introduces some flexibility mechanisms to reduce overall compliance costs, namely banking, borrowing, and pooling. Under the banking provision, a ship that surpasses its GHG intensity or RFNBO target in a given year may carry forward its surplus compliance to the following reporting period. Borrowing allows ships with a compliance deficit to draw an advance surplus from the next period—up to 2% of their annual energy consumption—which must then be repaid in the subsequent year. The pooling mechanism enables companies to aggregate the compliance balances of multiple vessels, allowing surpluses from some ships to offset deficits from others, provided that the total pooled balance remains positive. Importantly, the regulation establishes separate pools for the GHG intensity target and the RFNBO sub-target, so compliance for each objective can be managed independently, and each ship may participate in only one pool per objective.

An important point to highlight is that incentive mechanisms embedded in each regulation diverge significantly. Under the EU-ETS, ship operators face a continuous, linear incentive to reduce emissions: there is no minimum or maximum level of fuel substitution required, as each additional unit of CO$_2$ avoided yields the same marginal economic benefit. By contrast, FuelEU Maritime is structured around target-based GHG intensity thresholds that tighten across successive five-year compliance windows, creating a step-wise rather than continuous incentive. Once the applicable emission-reduction target is met, additional clean fuel uptake provides no further regulatory benefit. The same logic applies to the RFNBO quota, whose compliance benefit is exhausted once the 2% energy share threshold is reached.

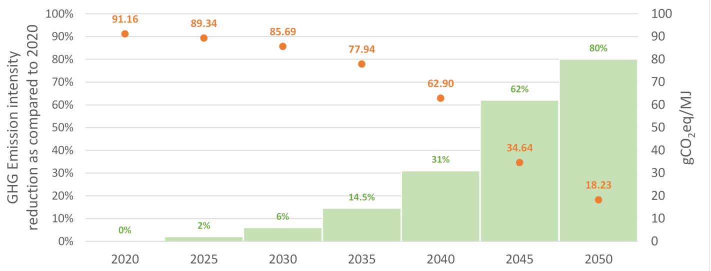

Figure 2: FuelEU Maritime GHG emission reduction targets.

2.2. *RFNBOs and other e-fuels under EU-regulation*

RFNBO is a fuel category first defined in the Renewable Energy Directive (EU) 2018/2001 [**?**]. To qualify as an RFNBO, the electricity used for hydrogen production must be fully renewable, achieved either through a direct physical connection between the electrolyzer and a renewable energy source (RES), or through grid electricity procured via a Power Purchase Agreement (PPA). In both cases, compliance with Delegated Regulation (DR) 2023/1184 [18] is required. Among other conditions, this regulation establishes a temporal correlation criterion for the PPA route, requiring that the renewable electricity generated under the PPA and the electricity consumed by the electrolyzer fall within the same time period — monthly until 2030 and hourly thereafter.RFNBO hydrogen must additionally meet a minimum 70% WtW GHG emission reduction relative to a fossil fuel benchmark of 94 gCO$_2$eq/MJ [19], implying a maximum emission intensity of 28.2 gCO$_2$eq/MJ for qualifying fuels. More recently, the Hydrogen and Decarbonized Gas Market Package [**?**] introduced the concept of low-carbon hydrogen — defined as hydrogen that achieves the same 70% GHG emission reduction threshold but is not sourced from renewable electricity. It can be produced, for example, through steam methane reforming with carbon capture, or via electrolysis using electricity that does not qualify as fully renewable. The methodology for calculating GHG emissions from low-carbon hydrogen is established in DR 2025/2359 [20].

The interaction among fuel categories, GHG emission intensities, and regulatory targets creates a complex landscape in which the drivers of WTP vary across regulations. As summarized in Table 1, two qualities determine the compliance value of an e-fuel: its certification label and its GHG emission intensity. The RFNBO label is mandatory under the FuelEU Maritime RFNBO sub-target, but irrelevant under both the FuelEU Maritime GHG intensity target and the EU-ETS. Regarding GHG emissions, they are irrelevant under the RFNBO sub-target, which is defined in energy terms. Under the GHG intensity target, however, WtW emissions directly determine compliance value, as lower-emission fuels generate greater savings per unit of energy consumed. Under the EU-ETS, only Tank-to-Wake (TtW) emissions are regulated, so both fuel categories provide equivalent compliance values regardless of their upstream emission profiles or label.

Table 1: Main regulatory targets and design features of EU climate instruments relevant for maritime transport

Regulation	**Aim**	**Target**	**Compliance**	**Label**	**GHG reduction > 70 %**
EU-ETS	Reduce absolute CO2 emissions	Direct CO2 emissions (TtW)	Increase efficiency, route optimization fuel switching	X	X
Fuel-EU Maritime	Increase adoption of clean fuels	GHG intensity reduction (WtW)	Fuel switching	X	✓
	Increase adoption of RFNBOs	Specific RFNBO quota*	Increase RFNBO consumption	✓	X

3. Methodology

3.1. *Goal and scope*

This study contributes to evidence-based policy-making through a comprehensive willingness-to-pay (WTP) analysis of e-fuel adoption in EU shipping. The geographic scope covers the European market, focusing on container ships operating exclusively between EU ports with a gross tonnage exceeding 5,000 GT — vessels subject to 100 % penalties under the EU ETS and the FuelEU Maritime regulations. Containerships were selected because they represent the most promising candidates for cleaner fuel adoption, given their substantially high energy consumption. This is reflected in current newbuild orders: out of vessels ordered to run on alternative fuels, container ships account for approximately 250 units already contracted to operate on methanol, with a small number designed for ammonia [**?**]. By definition, WTP analysis requires a reference fuel against which e-fuel adoption costs are benchmarked. This study uses Marine Gas Oil (MGO) as the reference, as it meets low-sulfur emission requirements in Emission Control Areas (ECAs) and enables direct comparison with its synthetic equivalent, e-MGO. While Very Low Sulfur Fuel Oil (VLSFO) represents a cheaper alternative for meeting sulfur limits, no synthetic e-fuel equivalent exists for this fuel type.

The scope of this paper is limited to operational expenditures, specifically fuel and regulatory costs. The primary objective is to isolate and quantify the upper bound of regulatory incentives under an idealized scenario in which CAPEX associated with retrofitting is zero and cargo loss is neglected. Evidence from [14] and [8] estimates only a 10-15% CAPEX premium for ammonia-fueled vessel in the long-run. The latter's results, which do not account for regulation, show that the total cost of a fossil-fueled vessel is 0.012 €/tkm, and that of an e-fuel vessel is 0.2 €/tkm, while the CAPEX increment accounts for just 0.005 €/tkm. This suggests that, in a regulatory cost comparison, CAPEX plays a secondary role and that omitting it does not materially affect the conclusions of this analysis.

3.2. *Penalty Structure and WTP contribution*

With the case study defined, the next step is to formalize how regulation translates into an economic signal for fuel switching. The WTP is defined as the maximum fuel price at which operating a dual e-fuel/fossil ship remains cost-competitive with a conventional fossil-fueled vessel. This cost comparison can be done in different units: total costs, energy costs, or cost per distance (€/t-km). The costs of both ships can be divided into their different components: CAPEX, O&M, fuel costs, and regulatory costs. Under the assumption that CAPEX is the same for both ships and that the e-fuel/fossil ship meets all the regulations and does not have to pay a penalty, the WTP can be expressed as depicted in eq. (1) and in fig. 3 with each term defined per unit of energy. In other words, regulation provides a premium WTP respect to the base floor which is given by the cost of the fossil reference fuel. In the following we analyze each of these components in more detail.

$$\begin{aligned} WTP_{\text{total}} = {} & \text{WTP}_{\text{energy}} + WTP_{\text{ETS}} \\ & + WTP_{\text{FuelEU-GHG}} + WTP_{\text{FuelEU-RFNBO}} \end{aligned} \tag{1}$$

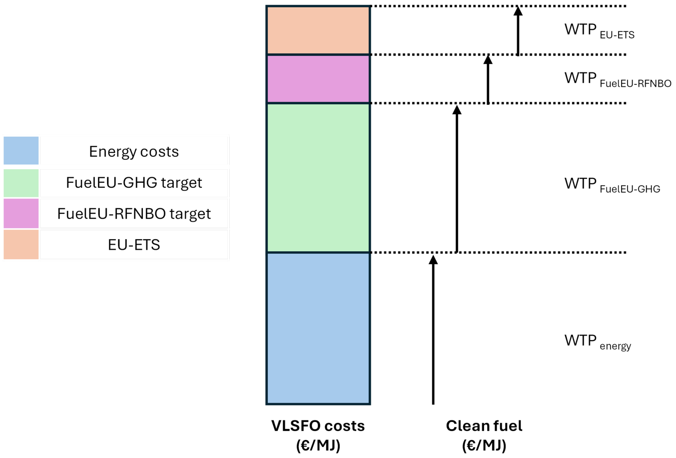

Figure 3: Definition of the willingness to pay (WTP) for e-fuels. For simplicity, CAPEX is assumed to be equal for fossil and clean technologies.

3.2.1. *EU-ETS*

Total CO2 emissions from a fossil-fuelled vessel are determined by the product of its TtW emission factor and its energy consumption. Accordingly, the cost of emissions (C_{ETS}) is given by the product of the TtW emission intensity and the EU ETS allowance price. When a marginal unit of e-fuel $x(\%)$ replaces an equivalent amount of fossil fuel, the vessel avoids the associated CO2 emissions and the corresponding penalty cost. This avoided cost constitutes a monetary saving, which is formalized in eq. (2), where P^{CO2} denotes the EU ETS price, TTW^{fossil} is the tank-to-wake emission factor of the displaced fossil fuel, and E^t is the vessel's total energy demand.

$$\frac{C_{\text{ETS}}}{E^t} = -P^{\text{CO}_2} \cdot TTW^{\text{fossil}} \cdot x \tag{2}$$

The economic relevance of these savings depends on how they evolve as fossil fuels are progressively replaced by e-fuels. This is captured by the marginal effect, defined as the derivative of the ETS cost savings with respect to x. Differentiating eq. (2) yields eq. (3), which is constant in x. This result reflects the linear structure of emissions pricing under the EU ETS: each additional unit of e-fuel displaces the same amount of fossil energy, avoiding an identical quantity of CO2 emissions and ETS costs. Since this marginal effect represents a reduction in costs, the WTP for e-fuel is defined as the negative of the derivative, resulting in a positive value.

$$WTP_{\text{ETS}} = -\frac{d\frac{C_{\text{ETS}}}{E^t}}{d_{\text{x}}} = -\frac{dC'_{ETS}}{dx} = P^{\text{CO}_2} \cdot TTW^{\text{fossil}} \tag{3}$$

3.2.2. *FuelEU Maritime RFNBO quota*

From 2034 onwards, ships may also be subject to a 2% RFNBO quota if their RFNBO use in 2031 falls below this level. The corresponding compliance balance is:

$$CB_{\text{RFNBO}} = 0.02\left(\sum_{i}^{n_{\text{fuel}}} M_i LCV_i\right) - \left(\sum_{i}^{n_{\text{RFNBO}}} M_i LCV_i\right) \tag{4}$$

Defining total fuel consumption ($\sum_i^{n_{\text{fuel}}} M_i LCV_i$) as E^t and RFNBO consumption ($\sum_i^{n_{\text{RFNBO}}} M_i LCV_i$) as $E^t \cdot x$ where x is the amount of RFNBO mixed into the ship. We can express the compliance balance as depicted in eq. (5).

$$CB_{\text{RFNBO}} = (0.02 \times E^t - E^t \cdot x) \tag{5}$$

Then, the RFNBO penalty($C_{FuelEU-RFNBO}$) is expressed as presented in eq. (6), where P_d is the price difference between the RFNBO and the compatible fossil fuel.

$$C_{FuelEU-RFNBO}(€) = (0.02 \times E^t - E^t \cdot x) \cdot \frac{P_d}{41000} \tag{6}$$

Note that 41,000 refers to the lower heating value of VLSFO (MJ/t$_{\text{VLSFO}}$). Consequently, to express the penalty in €, it is necessary to express P_d in tonnes equivalent of VLSFO. Finally, the WTP is the avoided penalty, defined as the derivative of eq. (7)

$$WTP_{FuelEU-RFNBO} == \frac{d\frac{C_{FuelEU-RFNBO}}{E^t}}{dx} = -\frac{dC'_{FuelEU-RFNBO}}{dx} = \frac{P_d}{41000} \tag{7}$$

3.2.3. *FuelEU Maritime GHG emission intensity reduction target*

As demonstrated above, the WTP for EU-ETS or the RFNBO quota does not depend on the amount of e-fuel x, consequently, each marginal increase in x avoids the same penalty value. The FuelEU Maritime GHG target penalty, by contrast, follows a more complex formulation, as presented in section 2.

$$\text{FuelEU Penalty (€)} = \frac{\text{Compliance balance}}{GHGIE_{\text{actual}} \cdot 41\,000} \cdot 2400 \tag{8}$$

The compliance balance represents the annual compliance level expressed in grams of CO$_{2\text{eq}}$, as defined in eq. (A.1).

$$\text{Compliance balance [g CO}_{2\text{eq}}] = \left(GHG_{\text{target}} - GHG_{\text{actual}}\right)\left[\sum_{i}^{n_{\text{fuel}}} M_i\, LCV_i + \sum_{k}^{c} E^k\right] \tag{9}$$

where GHG_{target} denotes the regulatory GHG intensity target for a given year, and GHG_{actual} the observed GHG intensity of the vessel. The term $\sum_i^{n_{\text{fuel}}} M_i\, LCV_i + \sum_k^c E^k$ represents total energy consumption over the year, including both fuel consumption ($\sum_i^{n_{\text{fuel}}} M_i\, LCV_i$) and onboard electricity use ($\sum_k^c E^k$).

Neglecting onboard electricity consumption and defining total energy use as $E^t = \sum_i M_i LCV_i$, substitution of eq. (A.1) into eq. (8) yields the simplified expression in eq. (10)[1].

$$\text{FuelEU Penalty (€)} = \frac{\left(GHG_{\text{actual}} - GHG_{\text{target}}\right) \cdot E^t}{GHG_{\text{actual}} \cdot 41\,000} \cdot 2400 \tag{10}$$

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[1] In this formulation, the positions of GHG_{target} and GHG_{actual} are intentionally reversed. This sign convention ensures that overcompliance—i.e., when actual emissions are below the target—results in a negative balance, while undercompliance yields a positive value. This facilitates interpretation in subsequent economic analysis.

Following the same logic as before, the marginal WTP attributed to FuelEU Maritime is the negative of the derivative of the FuelEU Maritime GHG penalty costs ($C_{FuelEU-GHG}$) eq. (10), which yields eq. (11).

$$WTP_{FuelEU-GHG}\,(x) = \frac{d\frac{C_{FuelEU-GHG}}{E^t}}{dx} = -\frac{dC'_{FuelEU-GHG}}{dx} = \kappa \cdot \frac{GHG^{\text{target}}\left(GHG^{\text{fossil}} - GHG^{\text{e-fuel}}\right)}{[GHG^{\text{fossil}} + x\,(GHG^{\text{e-fuel}} - GHG^{\text{fossil}})]^2} \tag{11}$$

3.3. Economic assumptions

The main economic inputs needed to calculate WTP under the proposed framework are the cost of the fossil reference fuel (MGO) and the EU ETS carbon price that penalizes CO_2 emissions. Both prices are held constant across the different time windows to allow a more straightforward comparison of the yearly regulatory impact. The values adopted are 400 €/t (approximately 38.9 €/MWh) for MGO and 130 €/tCO_2 for the EU ETS.

The WTP does not depend on e-fuel production costs, so no assumptions are required about hydrogen costs, raw CO_2 prices, or the CAPEX and OPEX of the production chain. The only exception is in the calculation of the RFNBO quota contribution, where the regulatory design introduces a dependency on production costs. The penalty associated with this quota is structured around the price differential P_d between e-fuel and MGO, a parameter that has yet to be formally specified by regulation. An estimate of production costs is therefore needed, but only to determine this differential and for no other part of the analysis.

Production price projections for the different e-fuels considered are presented in Annex appendix Appendix B, sourced from [14]. Since the RFNBO quota applies only from 2034 onward, P_d is estimated using projected 2040 prices. As P_d is expressed in VLSFO-equivalent tonnes, both the e-fuel and MGO costs are converted accordingly. The resulting values are 700, 900, 2790, and 2800 €/$t_{\text{VLSFO-eq}}$ for e-ammonia, e-methanol, e-LNG, and e-diesel, respectively.

3.4. Emission intensity assumptions

Well-to-tank and tank-to-wake emissions for MGO and e-fuels are necessary to determine penalties and compliance under EU-regulations. These emissions are sourced from Annex II of the FuelEU Maritime regulation [21]. For MGO, the default WtT emissions are 13.5 gCO2/MJ and 78.24 gCO2eq/MJ for TtW, resulting in a total of 91.74 gCO2eq/MJ. Regarding e-fuels, all of them must be in the range of 0-28.2 gCO2eq/MJ of WtW emissions, and their TtW emissions in this paper are assumed to be zero. Note that direct CO2 emissions are zero for e-fuels, but other molecules, such as N_2O and CH_4, may contribute to the TtW GHG intensity. However, there are no default values for these emissions in the existing regulation; they must be measured.

4. Results

This section presents the results of the proposed framework for evaluating the regulatory design and WTP for e-fuels. First, section 4.1 analyzes the non-linear behavior of the FuelEU Maritime penalty in absolute terms, providing a basis for better understanding its impact on WTP. section 4.2 then presents the WTP for e-fuels under the EU ETS and FuelEU Maritime GHG emission reduction targets. Finally, section 4.3 addresses the premium that RFNBO-compliant fuels can achieve as a result of the RFNBO sub-quota.

4.1. Non-linear behaviour of FuelEU Maritime

As already mentioned, the penalty for non-compliance under the GHG target of FuelEU Maritime (eq. (A.3)) is non-linear, meaning the compliance level and the penalty avoided are not proportional. To illustrate this, we present the avoided penalty as a function of the compliance level, defined as the ratio of the low-emission fuel consumed by the vessel (x) divided by the amount required to achieve a net-zero emissions balance in a given year ($x^{'}$. As these results show, the non-linearity increases markedly as regulatory targets become more stringent over time. In 2030, penalty reductions are approximately linear with respect to compliance; however, in later years, the divergence becomes substantial. For instance, achieving 50% compliance reduces the penalty by approximately

40% in 2040, 27% in 2045, and only 16% in 2050.

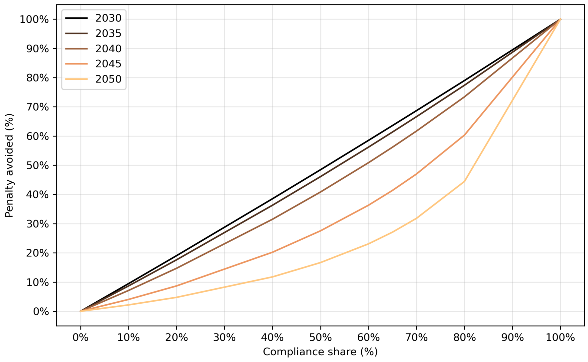

Figure 4: Effect of the non-linear penalty structure under the FuelEU Maritime GHG reduction target, based on eq. (A.3). Extended Data Table 1 provides the parameter values used in this calculation.

4.2. ***WTP for e-fuels under EU policy***

After analyzing the non-linear impact of the FuelEU Maritime GHG reduction target, we explore its effect on WTP when combined with the EU-ETS. With this aim, we defined two extreme values of WtW emission intensity for e-fuels (0–28.2 gCO_2eq/MJ). Under the assumption of zero TtW emissions, WTP depends exclusively on WtW emissions and is therefore independent of the specific fuel pathway. As a result, the estimates can be interpreted as fuel-agnostic and extended to any e-fuel with an equivalent WtW emission intensity. Figure 5 illustrates the annual evolution of WTP as a function of the compliance level (x/x^*), decomposed into three components: energy cost, EU ETS, and FuelEU Maritime GHG reduction target. The upper axis reports the absolute blending level of e-fuels (x), while the right axis presents the corresponding values expressed in €/t (ammonia and methanol) and €/l (e-MGO). Horizontal dotted lines indicate the average WTP under compliance with the FuelEU Maritime target.

We observe that the FuelEU Maritime GHG quota is the primary driver of the WTP, representing around 70-80 % of total WTP. The impact of the EU-ETS is significantly lower, at 30 €/MWh. [2] Beyond the decomposition of WTP by instrument, the shape of the curve reflects the non-linear structure of the FuelEU Maritime GHG target. WTP increases and peaks near full compliance (99.9%), with this difference becoming more pronounced over time as the target strength increases. In 2050, the difference can be as high as 1000 €/MWh for compliance of 1 and 99 % respectively. One interesting result is that, despite these differences, the average WTP in the range $x < x^*$ remains constant for all years despite the more aggressive GHG targets of the regulation. Instead of increasing WTP, tighter targets increase the amount of fuel needed to meet them (x). Thus, we can conclude that WTP is only affected by two factors: the GHG-intensity differential between the fossil reference fuel and the clean alternative (which provides the emission savings), and the penalty cost for non-compliance.

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[2] Note that if TtW emissions are non-zero, the WTP_{EU-ETS} component would be somewhat lower, since it applies to combustion-related CO2. The net effect would be a slight reduction in WTP_{EU-ETS}, but not its elimination. Given its limited weight relative to the FuelEU Maritime quota, this does not change the broader picture.

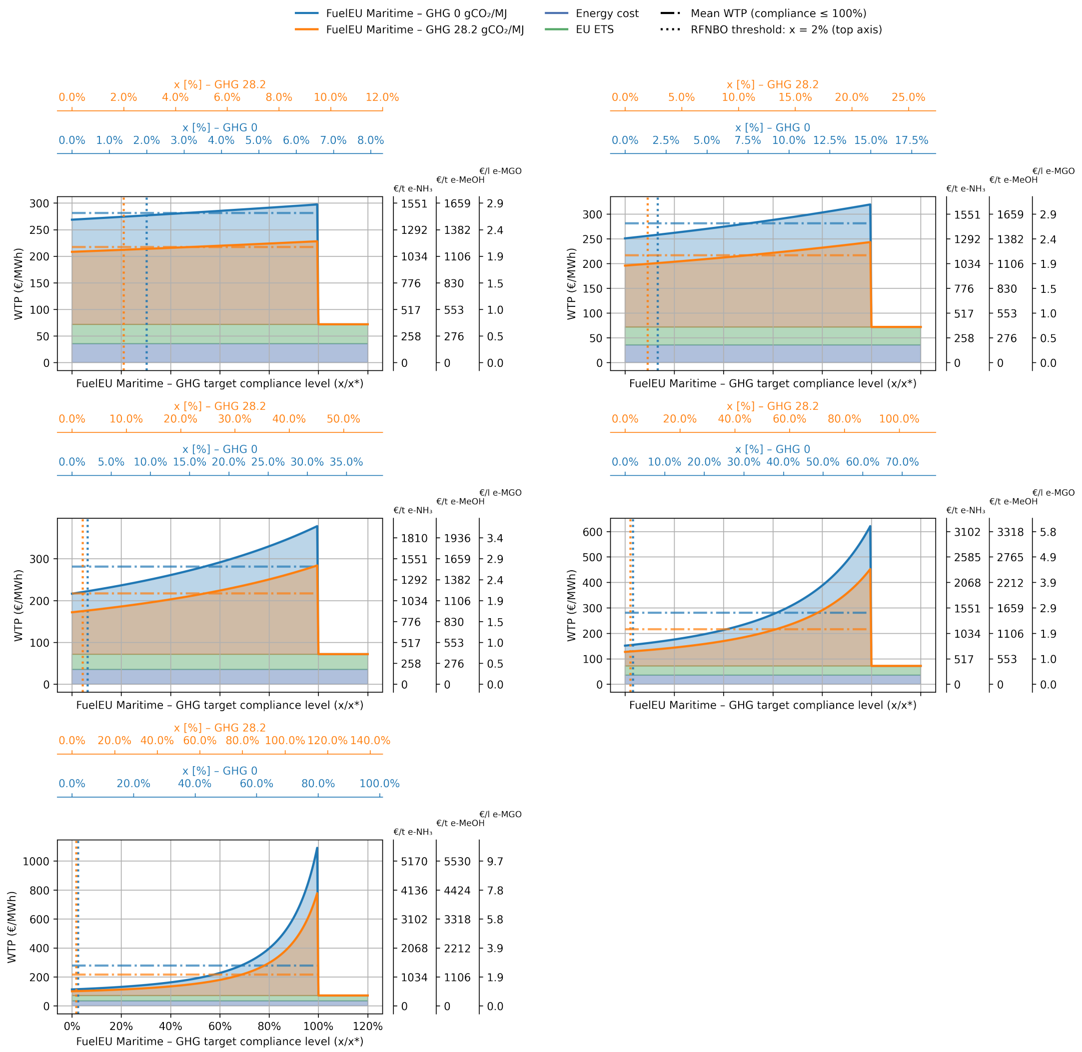


Figure 5: WTP as a function of the compliance level with the FuelEU Maritime GHG-intensity target, using MGO as the fossil reference fuel. The blue and orange curves correspond to ammonia with different lifecycle GHG intensities. The horizontal dotted lines indicate the average WTP under compliance with the FuelEU Maritime target, while the vertical dotted line marks the 2% compliance share potentially subject to the RFNBO sub-quota.

Regarding the impact of e-fuel GHG emissions, our results show that e-fuels with higher GHG intensities require larger fuel shares to achieve compliance (x^{*}). This is intuitive: the higher a fuel's emission intensity, the more of it is needed to achieve the same overall emissions reduction. This relationship is specific to emission-based targets and does not arise under energy quota schemes (e.g., RFNBO sub-quotas). Note that for $x > x^{*}$, e-fuel GHG intensity no longer affects total WTP, as the EU ETS only penalizes TtW emissions. For $x < x^{*}$, we find an average difference of approximately 50 €/MWh between fuels with GHG intensities of 0 and 28.2 gCO$_2$-eq/MJ, respectively. This difference is not constant across compliance levels; it widens as compliance approaches 100 %, increasing the value of zero-emission fuels.

4.3. *Premium WTP for RFNBO under the FuelEU Maritime specific quota*

Finally, we quantify the impact of the RFNBO sub-quota on WTP, introducing an additional source of value exclusive to RFNBO-compliant e-fuels. This sub-quota would apply only from 2031 onwards, and the mechanisms governing its implementation and adoption remain largely undefined. Under the current regulatory framework, the non-compliance penalty is based on the price differential between the e-fuel compatible with the vessel and the fossil fuel counterfactual, meaning the penalty varies depending on which e-fuel a given vessel is compatible with. table 2 estimates the WTP associated with this sub-quota for different e-fuels. For a vessel compatible solely with MGO, the price differential between e-MGO and MGO (P_d) is substantial, resulting in a correspondingly

Table 2: WTP for the RFNBO subquota under FuelEU Maritime.

Fuel	P_d (€/t-eq VLSFO)	WTP (€/MWh)	WTP (€/t)
e-Ammonia	700	61	317.6
e-Methanol	900	79	428.0
e-LNG	2790	245	3402.4
e-MGO	2800	246	2916.1

high penalty and a WTP of up to 2,900 €/t. Conversely, a vessel made compatible with ammonia would face a significantly lower penalty, with a WTP of only 317 €/t NH_3. This penalty structure may incentivize operators to retrofit their vessels solely for compliance purposes—i.e., to reduce their penalty exposure without consuming any e-fuel. As the regulation has yet to be fully specified, we do not assert that this will occur in practice, but point it out as a relevant consideration.

Regardless of the regulatory details, this quota has the potential to create a relevant premium for RFNBO fuels, but only to a limited extent, up to 2% per ship. It is also worth noting that this premium remains constant until reaching that 2 % and that, as it is set in energy terms, the GHG emissions of the RFNBO above the 70 % threshold are not relevant.

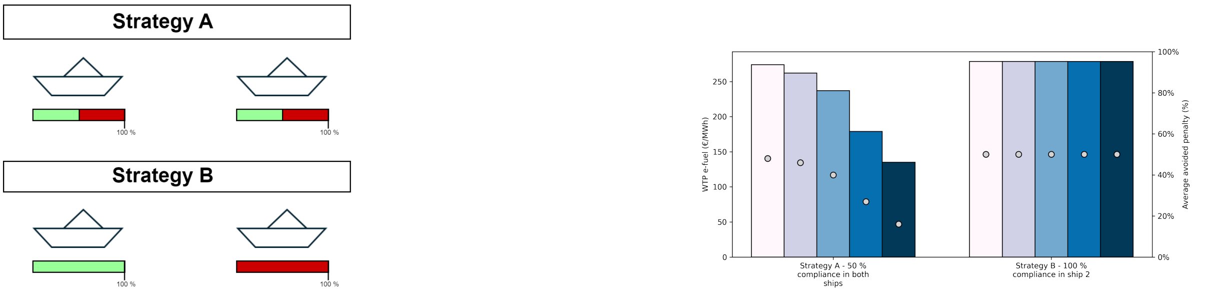
5. Discussion

Our results show that current regulations can significantly increase WTP for e-fuels relative to fossil MGO, with the FuelEU Maritime emission-reduction target emerging as the primary driver. The non-linear structure of this regulation can substantially influence the compliance strategies available to ship operators, which we discuss in section 5.1. However, while WTP is shown to increase considerably, it remains uncertain whether this increase is sufficient to enable commercial e-fuel adoption. Answering this question requires comparing our WTP estimates against projected production costs — an analysis we carry out in section 5.2, where we also consider alternative compliance pathways, such as biofuels and fossil fuels with carbon capture.

5.1. Implications in compliance strategies for ship operators

Our results show that the main regulatory driver increasing WTP for e-fuels in the EU is the FuelEU Maritime emission-reduction target, whose strongly non-linear structure—particularly after 2040—has significant implications for ship operators' compliance strategies and the value e-fuels deliver. One key implication is that the same amount of fuel is worth more when used to achieve full decarbonization (100%) in a single vessel than when used to achieve partial decarbonization (50%) in two vessels, even though both options yield the same aggregate emission reduction. Consider an operator managing two ships running on MGO who holds a contract for a fixed amount of zero-emission e-fuel covering 50% of their combined consumption. The operator faces two possible allocations: (A) assign all e-fuel to one vessel, reaching full compliance in that ship while paying the full penalty for the other; or (B) distribute the e-fuel evenly, reaching 50% compliance in both vessels and paying the remaining penalty in each.

Figure 6 shows the WTP per MWh of e-fuel and the average avoided penalty (%) associated with each strategy across different years. In the early compliance windows, differences between strategies are relatively limited; however, as regulatory targets increase, these differences become more pronounced. In particular, by 2050, Strategy A yields a WTP of 130 €/MWh, and a 50% compliance level avoids only 18% of the total penalty per ship (i.e., 36% of the combined 200% penalty across both vessels). By contrast, under Strategy B, the WTP remains constant at 260 €/MWh, and the avoided penalty amounts to 100% in one ship and 0% in the other (i.e., 100% of the combined 200% penalty). Consequently, operators must carefully understand the regulatory framework and adopt optimal allocation strategies to avoid diminishing the effective value of a given quantity of fuel.



(a) Description of different strategies

(b) Comparison of compliance allocation strategies.

Figure 6: Comparative penalty costs under full- versus partial-compliance allocation strategies. The compliance level refers to the GHG emission target of FuelEU Maritime. Potential revenues from the RFNBO subquota are not included in this figure.

As explained in section 2, FuelEU Maritime includes flexibility mechanisms such as banking and pooling.[3] These mechanisms apply when a ship operator exceeds the 100% compliance level. In such cases, operators can either bank the surplus for the following year or transfer it to other vessels within the same pool. Note that each vessel can belong to only one pool in a given year. To illustrate these mechanisms, consider an operator managing two vessels and who brings the first vessel to a compliance level of 125%, thereby generating a compliance surplus. Three alternative allocation strategies can be considered: (A) using the surplus to bring the second vessel to 25% compliance; (B) banking the surplus and applying it in the following year, thereby reaching 50% compliance in the second vessel in year $Y + 1$; or (C) transferring the surplus to another operator within the same pool whose vessel already close to reach full compliance (e.g., at 75%). Figure 7 summarizes these strategies over two consecutive compliance years (Y and $Y + 1$).

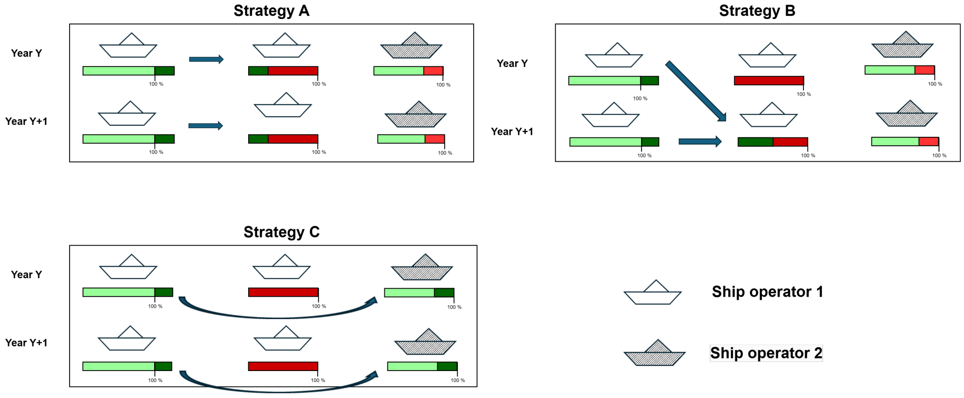


Figure 7: Description of different strategies

The strategies are compared in pairs to illustrate differences in WTP and average penalty avoidance across the two consecutive years. Figure 8a and Figure 8b compare strategies A–B and A–C, respectively, and demonstrate that the impact of banking grows over time — as expected, given the increasing prevalence of non-linear behavior. After 2040, banking consistently yields better outcomes in terms of penalties avoided; consequently, the WTP for an equivalent surplus is higher, reflecting the greater value that banking provides to ship operators. Strategy C, however, substantially outperforms both alternatives, with WTP values up to five times higher than those of strategy A. This highlights that even a modest allocation of surplus can be decisive in determining the overall value that the regulation delivers to ship operators.

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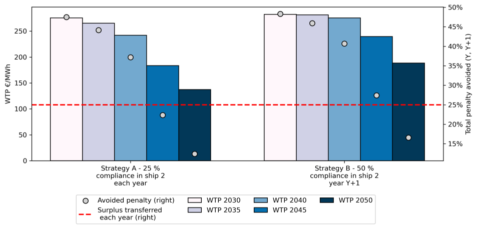
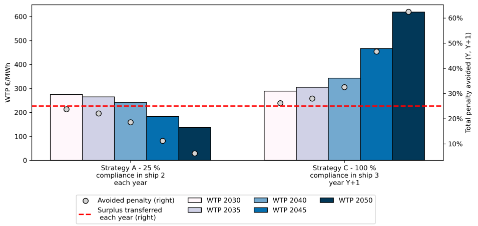
[3] The regulation also includes a borrowing mechanism, which is not considered in this analysis.



(a) Strategy A vs Strategy B



(b) Strategy A vs Strategy C

Figure 8: Comparative surplus allocation strategies under pooling- versus banking-based flexibility strategies. The compliance level refers to the GHG emission target of FuelEU Maritime. Potential revenues from the RFNBO subquota are not included in this figure.

Two aspects of the flexibility mechanisms merit attention. First, under the EU ETS, emission reductions are attributed to the year of fuel consumption, regardless of any banking or pooling arrangements under FuelEU Maritime. Consequently, even when over-compliance is transferred to another vessel, the ship generating the surplus retains the associated CO_2 emission reductions and avoids the corresponding payments. Second, over-compliance with the GHG and RFNBO targets is managed through separate accounting pools, allowing each objective to be met independently. Therefore, if an operator exceeds the 2% RFNBO sub-quota, the surplus compliance units may be transferred to other vessels without sacrificing the emission-reduction benefits attributable to RFNBO use, which continue to count toward the GHG-intensity target. This decoupling effectively increases the potential RFNBO premium beyond its nominal 2% energy share.

The optimal allocation strategies discussed in this paper are specific to FuelEU Maritime and cannot be directly extended to policy schemes with linear penalties — such as the proposed IMO NZF — where compliance levels and penalty savings are strictly proportional. How these two regulatory frameworks will coexist and interact in practice remains uncertain, and their potential misalignment risks generating conflicting signals for shipowners and fuel suppliers alike. A further point of divergence concerns the RFNBO sub-quota mechanism under FuelEU Maritime. While FuelEU Maritime establishes a specific sub-target for RFNBO fuels, the IMO NZF includes no equivalent provision. Accordingly, the premium incentive associated with RFNBOs has no direct counterpart in the IMO framework, although the latter introduces a reward mechanism for so-called Zero and Near-Zero (ZNZ) fuels — defined as fuels with a carbon intensity below approximately 14–19 gCO_{2eq}/MJ — whose specific reward level has yet to be determined.

5.2. *Benchmarking demand and supply*

Our previous results characterize consumers' WTP for e-fuels across different time horizons, GHG-reduction levels, and certification labels. However, WTP alone does not determine market viability: what ultimately matters is whether consumers' WTP exceeds the cost of actually producing these fuels. In this section, we benchmark our demand-side estimates against current and projected e-fuel production costs, as well as against the costs of competing low-carbon alternatives, such as advanced biofuels and fossil fuels with carbon capture and storage (CCS). Figure 9 shows the production costs of different fuels and compares them with the WTP for fuels with 0 and 28.2 gCO2eq/MJ in WtT. As this figure shows, regulation is effective in bridging the cost gap between production and consumption for almost all e-fuels, with ammonia being the most competitive one. Other e-fuels are associated with greater uncertainty and, in some scenarios, can exceed WTP. These fuels share a common dependence on CO_2 as a feedstock, and their competitiveness is sensitive to its source: while industrial or biogenic capture can supply CO_2 at relatively low cost, Direct Air Capture (DAC) remains expensive. Regarding alternative fuels, biofuels offer the lowest-cost options, while blue ammonia, which combines relatively low production costs with moderate emission reductions.

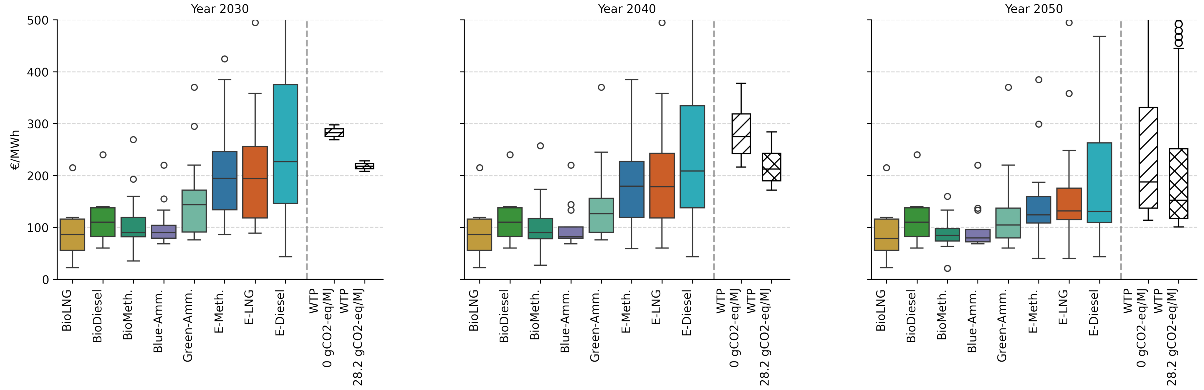


Figure 9: Benchmarking of WTP and production costs for different clean fuels. WTP is represented by the dotted boxes for two WtW emission: 0 and 28.2 gCO2-eq/MJ. Sources for the production of e-fuels are summarized in appendix Appendix B

However, economic competitiveness alone does not adequately capture the relative performance of biofuels and fossil fuels with CCS. Those types of fuels are characterized by a wide range of WtW emission intensity. In the case of biofuels, WtW emissions depend heavily on the feedstock used for production, whereas in fossil fuels with CCS, emissions depend on methane leaks or carbon capture and storage efficiencies. Figure 10 complements this analysis by benchmarking lifecycle GHG emissions against the FuelEU Maritime targets for 2045 and 2050. The results show that blue ammonia meets the targets, while biodiesel, biomethane, and biomethanol may also meet the targets depending on the feedstock used. Notably, certain feedstocks—such as animal manure—can result in negative lifecycle emissions.

EU policy fully restricts the use of first-generation biofuels, those that compete with human food and can cause land-use changes. Consequently, there may be limitations in the availability of sustainable feedstocks for biofuel production due to scarcity or due to competition with other uses (e.g., aviation, road transport, and industry), which may restrict their large-scale adoption in the maritime sector. A similar argument applies, albeit through different mechanisms, to blue ammonia. While it offers relatively low-cost abatement, its scalability depends on the availability of carbon capture and storage infrastructure, access to suitable geological storage sites, and the control of methane leakage along the natural gas supply chain. Taken together, these findings suggest that e-fuels are likely to play a critical role in ensuring full compliance with long-term decarbonization targets. Unlike biofuels or blue ammonia, whose deployment may be limited, e-fuels can provide a flexible compliance pathway when other options become scarce or insufficient to meet these stringent targets.

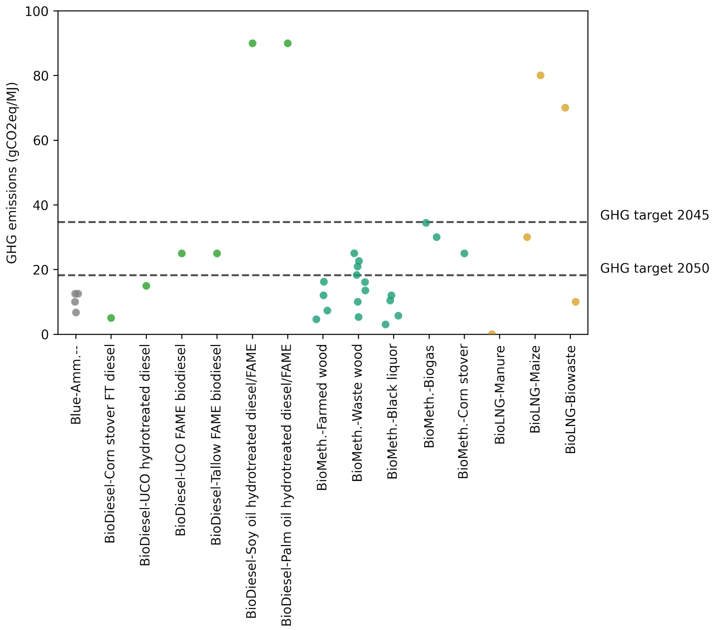


Figure 10: GHG emission benchmarking across alternative fuels. Grey, green, blue, and yellow markers correspond to blue ammonia, bio-MGO, biomethanol, and bio-LNG, respectively. The dotted lines represent the FuelEU Maritime GHG intensity targets for 2045 and 2050. Fuel-cycle emission factors are sourced from appendix Appendix C.

6. Conclusions

This paper presents a framework to evaluate the impact of EU regulation in reducing the cost gap between production and willingness to pay for off-takers for e-fuels in the maritime sector. The first regulatory instrument is the EU Emissions Trading System (EU ETS), which imposes a direct cost on emissions derived from fossil fuel consumption. The second is FuelEU Maritime, which establishes two distinct compliance targets: a GHG emission intensity target, mandating a progressive reduction in the lifecycle greenhouse gas intensity of the energy mix used by ships, and a potential sub-quota for Renewable Fuels of Non-Biological Origin (RFNBOs), requiring that a minimum share of 2% of the total energy consumed by a vessel be sourced from these fuels by 2034. Together, these instruments create the economic incentives for the adoption of alternative fuels in maritime transport. Our results show that regulatory penalties significantly increase the WTP for e-fuels, with the FuelEU Maritime GHG emission target emerging as the dominant driver, accounting for 70–80% of total WTP. We also found that two key parameters determine the market value of an e-fuel: GHG emission intensity and label. Under the FuelEU Maritime GHG reduction target, GHG emission intensity is critical: fuels with lower emissions generate greater savings per unit of energy, and therefore command higher WTP. By contrast, the potential target for RFNBOs is set in energy terms, making a fuel's GHG emissions irrelevant for that sub-quota while the RFNBO label becomes mandatory to define its market value. This label premium can meaningfully increase WTP, although it applies only to a small share of total energy consumption (2%).

Beyond the drivers of market value, regulations also differ in their penalty structures. EU ETS and the RFNBO sub-quota penalty follow a linear structure, in which compliance and the avoided penalty increase proportionally with e-fuel uptake. The FuelEU Maritime GHG reduction target, however, presents a non-linear behavior. Under this target, a vessel achieves *compliance* when its blended energy mix meets the prescribed GHG intensity threshold — that is, when the share of e-fuels or other low-emission alternatives is sufficient to bring average emissions down to exactly the required level, without necessarily replacing all fossil fuel consumption. Any e-fuel consumption beyond this threshold results in *surplus compliance*, meaning the vessel's actual emissions performance exceeds the regulatory requirement. The non-linear penalty structure implies that the last unit of e-fuel consumed before reaching compliance incurs a much larger penalty than the first: for example, in 2050, reaching 50% compliance saves only 16% of the total penalty. This design promotes full compliance on individual vessels over partial compliance spread across multiple ships, even when both strategies yield identical aggregate emission reductions.

This non-linearity also makes it essential to understand the flexibility mechanisms embedded in FuelEU Maritime — namely, banking and pooling — as these can unlock substantially higher WTP levels. Under banking, operators can carry surplus compliance generated in one year forward to the following year. Because of the non-linear penalty structure, concentrating this surplus on a single vessel approaching full compliance generates greater avoided penalties than spreading it across multiple ships. Similarly, pooling allows surplus compliance to be transferred to other vessels close to full compliance, where each additional unit of e-fuel avoids a disproportionately large penalty and thus delivers higher economic value.

Finally, benchmarking our WTP estimates against the production costs of e-fuels, biofuels, and fossil fuels with CCS reveals that regulation is largely effective in bridging the cost gap for most e-fuels, with ammonia emerging as the most competitive option. Biofuels currently offer the lowest-cost compliance pathway, while blue ammonia combines moderate production costs with reasonable emissions performance. However, the large-scale deployment of these alternatives faces supply-side constraints: biofuels are limited by feedstock availability and competition from other sectors such as aviation and heavy industry, while blue ammonia depends on carbon capture infrastructure, suitable geological storage, and methane leakage control. These constraints suggest that e-fuels are likely to play a complementary yet critical role in ensuring full compliance with long-term decarbonization targets as other alternatives become scarce or unable to meet the most stringent regulatory thresholds.

Overall, this paper demonstrates that regulatory design plays a decisive role in shaping the economic viability of e-fuels in maritime transport. While the current framework is largely effective in bridging the cost gap, its non-linear incentive structures and fuel-specific distortions highlight the need for careful policy refinement. Several limitations should be acknowledged. First, our WTP estimates do not account for capital costs associated with retrofitting vessels for e-fuel use, nor for the economic impact of potential cargo loss — though their inclusion is unlikely to alter the broader conclusions. Second, the analysis does not fully account for non-CO_2 pollutants such as NO_x, CH_4, and methane slip within the Tank-to-Wake emissions framework, whose regulatory values remain to be defined and could meaningfully affect the relative competitiveness of certain fuels; a dedicated sensitivity analysis would be necessary to assess their impact properly. Future research could incorporate these parameters into the WTP framework and extend the analysis beyond EU regulation — in particular, calculating WTP under the IMO Net Zero Framework would capture the interplay between the two regulatory regimes as both continue to evolve.

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Appendix A. Derivative of the FuelEU Penalty

The FuelEU Maritime Regulation sets limits on the GHG emission intensity of energy used on board commercial vessels, relative to a reference value. Each ship must determine an annual compliance balance, expressed in tonnes of CO_{2eq}, as shown in eq. (A.1).

$$\begin{gathered}\text{Compliance balance } [\text{g}\,\text{CO}_{2\text{eq}}] = \\ \Big(GHG_{\text{target}} - GHG_{\text{actual}}\Big)\left[\sum_{i}^{n_{\text{fuel}}} M_i\, LCV_i \quad + \sum_{k}^{c} E^k\right]\end{gathered} \tag{A.1}$$

Were GHG_{target} is the target GHG emissions in a given year, GHG_{actual} the actual GHG emissions of a ship in that year and $\sum_i^{nfuel} M_i \cdot LCV_i + \sum_k^c E_k$ represents the total energy consumption of the fuel that year including fuel ($\sum_i^{nfuel} M_i \cdot LCV_i$)and electricity consumption on board ($\sum_k^c E_k$).

Assuming no on-board electricity use and defining $E^t = \sum_i M_i LCV_i$ as the total energy consumption. We can express the compliance balance as depicted in eq. (A.2). Note that in this formulation, the position of GHG_{target} and GHG_{actual} is intentionally reversed. This sign convention ensures that overcompliance—i.e., actual emissions below the regulatory target—appears as a negative balance, while undercompliance (non-compliance) yields a positive balance. The convention is adopted to simplify the economic interpretation in subsequent sections.

$$\begin{gathered}\text{Compliance balance } [\text{g}\,\text{CO}_{2\text{eq}}] = \\ \Big(GHG_{\text{actual}} - GHG_{\text{target}}\Big) \cdot E^t\end{gathered} \tag{A.2}$$

If the ship fails to achieve the required reduction, it must pay a penalty computed according to Annex IV (eq. (A.3)).

$$\text{FuelEU Penalty } (€) = \frac{\text{Compliance balance}}{GHGIE_{\text{actual}} \cdot 41\,000} \cdot 2400 \tag{A.3}$$

Combining eq. (A.2) and eq. (A.3) and defining κ as a constant conversion factor ($\frac{2400}{41000}$), we obtain eq. (A.4).

$$Penalty(€) = \kappa\, E^t \left(1 - \frac{GHG^{\text{target}}}{GHG^{\text{actual}}}\right) \tag{A.4}$$

where $\kappa = \frac{2400}{41000}$ is a constant conversion factor, and E^t is the total annual energy consumption of the ship.
Unitl now, no expression in our equation depends on x, the x dependence is introduced by the term GHG^{actual} as presented in eq. (A.5).

$$\begin{aligned} GHG^{\text{actual}}(x) &= GHG^{\text{fossil}}(1 - x) + GHG^{\text{e-fuel}}\, x \\ &= GHG^{\text{fossil}} + x\,(GHG^{\text{e-fuel}} - GHG^{\text{fossil}}) \end{aligned} \tag{A.5}$$

Following the same logic as with EU-ETS penalty, the marginal WTP attributed to FuelEU Maritime is the negative of the derivative of eq. (A.4). The derivative of the constant term is zero, implying

$$\frac{d}{dx}\left(1 - \frac{GHG^{\text{target}}}{GHG^{\text{actual}}(x)}\right) = -\frac{d}{dx}\left(\frac{GHG^{\text{target}}}{GHG^{\text{actual}}(x)}\right)$$

Because GHG^{target} is constant, this expression can be rewritten as

$$-GHG^{\text{target}} \frac{d}{dx}\left(GHG^{\text{actual}}(x)^{-1}\right)$$

Applying the chain rule yields

$$\frac{d}{dx}\left(GHG^{\text{actual}}(x)^{-1}\right) = -\frac{1}{(GHG^{\text{actual}}(x))^2}\frac{d\,GHG^{\text{actual}}(x)}{dx}.$$

Combining terms, the derivative of the inner expression becomes

$$\frac{GHG^{\text{target}}}{\left(GHG^{\text{actual}}(x)\right)^2}\frac{d\,GHG^{\text{actual}}(x)}{dx}$$

Substituting this result into the original expression for the penalty derivative leads to

$$\frac{d\,\text{Penalty}}{dx} = -\kappa\,E^t \cdot \frac{GHG^{\text{target}}}{\left(GHG^{\text{actual}}(x)\right)^2}\frac{d\,GHG^{\text{actual}}(x)}{dx}$$

The marginal willingness to pay (WTP), defined as the negative of the derivative of the penalty cost with respect to the e-fuel share, can be written as

$$WTP_{FuelEU}\,(x) = \kappa\,E^t \cdot \frac{GHG^{\text{target}}\left(GHG^{\text{fossil}} - GHG^{\text{e-fuel}}\right)}{\left[GHG^{\text{fossil}} + x\left(GHG^{\text{e-fuel}} - GHG^{\text{fossil}}\right)\right]^2} \tag{A.6}$$

Appendix B. Fuel prices

Table B.3: Cost assumptions and energy properties of fuels across time horizons.

Fuel	Specifications			Cost (USD/t)								Cost (USD/MWh)								Source
				2020		2030		2040		2050		2020		2030		2040		2050		
	Sp. gravity (kg/m^3)	LHV (MJ/kg)	LHV (MJ/m^3)	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	
Blue-Amm.	626	18.6	11644	350	400	350	400	350	400	350	400	68	77	68	77	68	77	68	77	[14]
Blue-Amm.	626	18.6	11644	484	502	446	465	465	428	409	428	94	97	86	90	90	83	79	83	[14]
Blue-Amm.	626	18.6	11644	553	553	467	467	414	414	373	373	107	107	90	90	80	80	72	72	[14]
Blue-Amm.	626	18.6	11644	521	856	484	800	446	744	428	707	101	166	94	155	86	144	83	137	[14]
Blue-Amm.	626	18.6	11644	413	1137	413	1137	413	1137	413	1137	80	220	80	220	80	220	80	220	[14]
Blue-Amm.	626	18.6	11644	250	480	250	480	250	480	250	480	69	133	69	133	69	133	69	133	[22]
Green-Amm.	626	18.6	11644	650	850	650	850	400	600	400	600	126	165	126	165	77	116	77	116	[14]
Green-Amm.	626	18.6	11644	911	1004	707	818	818	614	446	521	176	194	137	158	158	119	86	101	[14]
Green-Amm.	626	18.6	11644	409	1135	409	1135	409	1135	409	1135	79	220	79	220	79	220	79	220	[14]
Green-Amm.	626	18.6	11644	749	1085	568	930	465	723	310	620	145	210	110	180	90	140	60	120	[14]
Green-Amm.	626	18.6	11644	414	1135	414	1135	414	1135	414	1135	80	220	80	220	80	220	80	220	[14]
Green-Amm.	626	18.6	11644	468	469	470	471	472	473	474	475	91	91	91	91	91	92	92	92	[14]
Green-Amm.	626	18.6	11644	1023	1786	874	1525	725	1265	558	1023	198	346	169	295	140	245	108	198	[14]
Green-Amm.	626	18.6	11644	775	1912	775	1912	775	1912	775	1912	150	370	150	370	150	370	150	370	[14]
Green-Amm.	626	18.6	11644	391	688	391	688	391	688	391	688	76	133	76	133	76	133	76	133	[14]
Green-Amm.	626	18.6	11644	518	1008	288	576	270	522	252	468	144	280	80	160	75	145	70	130	[22]
BioDiesel	900	42.7	38430	216	468	216	468	216	468	216	468	60	130	60	130	60	130	60	130	[14]
BioDiesel	900	42.7	38430	288	504	288	504	288	504	288	504	80	140	80	140	80	140	80	140	[14]
BioDiesel	900	42.7	38430	324	864	324	864	324	864	324	864	90	240	90	240	90	240	90	240	[14]
BioLNG	450	50	22500	1200	1250	1050	1150	1150	1000	850	950	86	90	76	83	83	72	61	68	[14]
BioLNG	450	50	22500	300	614	112	614	112	614	112	614	22	119	22	119	22	119	22	119	[14]
BioLNG	450	50	22500	1234	1646	1234	1646	1234	1646	1234	1646	89	118	89	118	89	118	89	118	[14]
BioLNG	450	50	22500	772	773	774	775	776	777	778	779	56	56	56	56	56	56	56	56	[14]
BioLNG	450	50	22500	1374	2986	1374	2986	1374	2986	1374	2986	99	215	99	215	99	215	99	215	[14]
BioLNG	450	50	22500	405	1600	405	1600	405	1600	405	1600	29	115	29	115	29	115	29	115	[14]
BioMeth.	791	19.5	15425	507	585	488	488	488	468	449	468	94	108	90	90	90	86	83	86	[14]
BioMeth.	791	19.5	15425	488	867	488	867	488	867	488	867	90	160	90	160	90	160	90	160	[14]
BioMeth.	791	19.5	15425	360	523	360	523	360	523	360	523	66	97	66	97	66	97	66	97	[14]
BioMeth.	791	19.5	15425	561	561	416	416	324	324	252	252	104	47	35	35	27	27	21	21	[14]
BioMeth.	791	19.5	15425	449	449	449	449	449	449	449	449	83	83	83	83	83	83	83	83	[14]
BioMeth.	791	19.5	15425	488	650	488	650	488	650	488	650	90	120	90	120	90	120	90	120	[14]
BioMeth.	791	19.5	15425	410	722	410	722	410	722	410	722	76	133	76	133	76	133	76	133	[14]
BioMeth.	791	19.5	15425	327	764	293	693	260	623	227	553	91	212	82	190	72	174	63	153	[23]
BioMeth.	791	19.5	15425	455	1013	421	970	388	927	355	884	127	281	118	270	108	257	99	245	[23]
E-Diesel	900	42.7	38430	512	598	512	598	512	598	512	598	43	50	43	50	43	50	43	50	[14]
E-Diesel	900	42.7	38430	1549	5014	1549	5014	1549	5014	1549	5014	131	423	131	423	131	423	131	423	[14]
E-Diesel	900	42.7	38430	5551	8882	4868	7771	4227	6661	3544	5551	468	749	410	655	356	562	299	468	[14]
E-Diesel	900	42.7	38430	3886	4782	2647	3203	3203	2220	1495	1836	328	403	223	270	270	187	126	155	[14]
E-Diesel	900	42.7	38430	3288	4057	2263	2733	2733	1879	1238	1537	277	342	191	230	230	158	104	130	[14]
E-LNG	450	50	22500	1601	4971	1601	4971	1601	4971	1601	4971	115	358	115	358	115	358	115	358	[14]
E-LNG	450	50	22500	1707	1707	1059	1059	713	713	480	480	144	144	89	89	60	60	40	40	[14]
E-LNG	450	50	22500	3450	5650	3000	4900	2550	4200	2100	3450	248	407	216	353	184	302	151	248	[14]
E-LNG	450	50	22500	1659	6872	1659	6872	1659	6872	1659	6872	119	495	119	495	119	495	119	495	[14]
E-LNG	450	50	22500	3450	3900	2700	3100	3100	2400	1800	2050	248	281	194	223	223	173	130	148	[14]
E-LNG	450	50	22500	3000	3300	2400	2700	2700	2100	1600	1850	216	238	173	194	194	151	115	133	[14]
E-Meth.	791	19.5	15425	813	1571	758	1300	650	1029	596	813	150	290	140	240	120	190	110	150	[14]
E-Meth.	791	19.5	15425	627	2085	627	2085	627	2085	627	2085	116	385	116	385	116	385	116	385	[14]
E-Meth.	791	19.5	15425	742	742	466	466	318	318	219	219	137	137	86	86	59	59	40	40	[14]
E-Meth.	791	19.5	15425	1638	2652	1424	2301	1229	1970	1014	1619	302	490	263	425	227	364	187	299	[14]
E-Meth.	791	19.5	15425	1385	1560	1073	1229	1229	917	663	780	256	288	198	227	227	169	122	144	[14]
E-Meth.	791	19.5	15425	2950	3300	2350	2650	2650	2000	1450	1750	212	238	169	191	191	144	104	126	[14]
E-Meth.	791	20.0	15425	820	1620	630	1290	440	960	250	630	228	450	175	358	122	267	69	175	[23]
E-Meth.	791	20.0	15425	1120	2380	843	1797	567	1213	290	630	311	661	234	499	157	337	81	175	[23]

Appendix C. GHG Emissions of Fuels Different from e-Fuels

Table C.4: GHG emissions intensity of alternative fuels by feedstock.

Category	Subcategory	GHG (gCO_2eq/MJ)	References
Blue-Amm.	–	12.5	[22]
Blue-Amm.	–	12.5	[22]
Blue-Amm.	–	10.0	[22]
Blue-Amm.	–	6.7	[22]
BioDiesel	Corn stover FT diesel	5	[24]
BioDiesel	UCO hydrotreated diesel	15	[24]
BioDiesel	UCO FAME biodiesel	25	[24]
BioDiesel	Tallow FAME biodiesel	25	[24]
BioDiesel	Soy oil hydrotreated diesel/FAME	90	[24]
BioDiesel	Palm oil hydrotreated diesel/FAME	90	[24]
BioMeth.	Farmed wood	12.0	[23]
BioMeth.	Farmed wood	16.2	[23]
BioMeth.	Farmed wood	7.3	[23]
BioMeth.	Farmed wood	4.6	[23]
BioMeth.	Waste wood	10.0	[23]
BioMeth.	Waste wood	13.5	[23]
BioMeth.	Waste wood	16.1	[23]
BioMeth.	Waste wood	22.6	[23]
BioMeth.	Waste wood	5.3	[23]
BioMeth.	Waste wood	18.3	[23]
BioMeth.	Waste wood	25.0	[23]
BioMeth.	Waste wood	20.9	[23]
BioMeth.	Black liquor	10.4	[23]
BioMeth.	Black liquor	12.0	[23]
BioMeth.	Black liquor	3.0	[23]
BioMeth.	Black liquor	5.7	[23]
BioMeth.	Biogas	34.4	[23]
BioMeth.	Biogas	30.0	[23]
BioMeth.	Corn stover	25.0	[24]
BioLNG	Manure	0	[25]
BioLNG	Manure	−90	[25]
BioLNG	Maize	80	[25]
BioLNG	Maize	30	[25]
BioLNG	Biowaste	70	[25]
BioLNG	Biowaste	10	[25]