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E-diesel in the shipping sector: Prospects and challenges

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It is noted that the authors bear sole responsibility for any errors, omissions, opinions, and interpretations presented herein.

Introduction

According to the European Commission (European Commission 2023a), the maritime transport sector, mainly based on petroleum products derived from crude oil, currently emits around 11% of the transport global greenhouse gases (GHGs), while handling over 90% of the world's goods (King 2022). These emissions are expected to increase significantly by 2050 in various development scenarios, representing a potential increase about 130% compared to 2008 (European Commission 2023b).

To address this challenge, the International Maritime Organization (IMO) has formulated ambitious targets with the aim to phase out fossil fuels, peak total GHG emissions from international shipping as soon as possible and achieve a reduction of at least 50% by 2050 compared to 2008 levels (European Commission 2023b). Accomplishing these objectives poses significant challenges given the increased propulsion power needed and the constrained space available for expanding the required renewable infrastructure. This sector, known as "hard-to-abate" sector, poses a particular difficulty for decarbonization (Neuling and Berks 2023).

In principle, liquid fossil fuels can be replaced by alternative options such as biofuels or electricity-based fuels (e-fuels). Biofuels, which are derived from microbial, plant, or animal materials, are characterized by significantly lower GHG emissions compared to fossil fuels and therefore contribute to reducing the climate impact of the transport sector (Neuling and Berks 2023). This advantage arises from the fact that biofuels originate from organic matter such as plants or algae, which sequester carbon dioxide during their growth phase. Consequently, when biofuels are burned, the released CO_2 is partially offset by the carbon previously absorbed during the feedstock's cultivation, resulting in reduced net carbon emissions relative to fossil fuels (Litvak and Litvak 2020). Particularly, advanced biofuels crafted from waste materials or algae hold promise for achieving carbon neutrality or even negativity (Litvak and Litvak 2020). However, these fuels, especially conventional biofuels from cultivated biomass, inherently require a lot of water and land, which potentially competes with food cultivation. They can therefore at best be regarded as a temporary transitional solution but not for the long-term (Neuling and Berks 2023).

E-fuels, produced by extracting hydrogen using electricity from renewable sources, offer a sustainable alternative which can significantly reduce GHG emissions whilst not jeopardizing other environmental requirements regarding biodiversity, air quality and material sourcing. Notably, a recent survey conducted by Accelleron, involving high-level executives from Germany, the Netherlands, Belgium, and Spain, revealed that about 93% of maritime companies envision e-fuels as pivotal in fostering more sustainable shipping (Acceleron 2023). A notable research project demonstrating progress in this field is the Clean Maritime Demonstrator Competition, where CATAGEN led a consortium that won funding for a techno-economic feasibility study to explore the production and distribution of e-diesel, aiming to deliver significant decarbonization to the UK's maritime activities (McKeown 2024). Supported by the UK Department for Transport and Innovate UK, this project seeks to determine the commercial viability of using CATAGEN's E-FUEL GEN technology to produce e-diesel. Moreover, it aims to establish a replicable model for adoption across various harbors and ports in the UK, with potential global applicability (McKeown 2024).

Nevertheless, the decarbonization of the maritime sector should encompass considerations beyond environmental aspects alone to comprehensively evaluate the feasibility of these alternative fuels. So how viable are e-fuels, specifically liquid e-fuels, in the process of decarbonizing the shipping sector, and under what conditions can they successfully compete with conventional maritime fuels?

This paper is centered on examining the potential contribution of liquid e-fuels, specifically e-diesel, within the maritime sector. It addresses the environmental and economic viability of e-diesel in the maritime context and the essential considerations for its successful competition with traditional marine fuels like Marine Diesel Oil (MDO), Marine Gasoil (MGO), and Heavy Fuel Oil (HFO) until the year 2050.

1. E-diesel: Production process and implementation challenges

In the journey towards decarbonizing the maritime sector, e-diesel stands out as a promising alternative fuel synthesized through the Fischer-Tropsch process and renewable electricity (McGill et al. 2013). As an alternative to fossil marine fuels, e-diesel holds appeal owing to its high drop-in quality. It boasts a very high energy density per km and its high cetane number enhances engine efficiency, facilitating a swift market penetration (Fasihi et al. 2016). It closely resembles petroleum-based diesel fuel, boasting compatibility with both new and existing diesel engines and fuel systems. Moreover, it adheres to current diesel fuel specifications (ASTM D 975) and maintains safety standards akin to traditional diesel fuel (Medrano-García et al. 2022). This allows it to be legally used in existing diesel infrastructure and ships. Additionally, its superior low-temperature operability compared to biodiesel makes it a viable option for deployment in colder climates without operational issues like gelling or clogging fuel filters (Medrano-García et al. 2022). Regarding storage and logistics, liquid e-diesel enjoys favorable conditions, leveraging existing storage facilities owing to their compatibility. When sourced from renewable energy, e-diesel presents a climate-friendly marine fuel, showcasing a substantial reduction in greenhouse gas (GHG) emissions (Fasihi et al. 2016). Moreover, this fuel holds the potential to significantly lower sulfur and nitrogen oxide emissions, contributing to improved air quality and ecosystem health in coastal areas and sensitive marine ecosystems (McGill et al. 2013).

While the use of e-diesel in the shipping sector opens various opportunities, its widespread adoption is accompanied by significant challenges. Primarily, e-diesel production faces hurdles concerning production scalability, cost competitiveness, infrastructure readiness, and policy frameworks (Medrano-García et al. 2022; Neuling and Berks 2023). Compared to the direct utilization of electricity, e-diesel production incurs high energy conversion losses, leading to an overall efficiency of less than 50%, resulting in substantially higher costs compared to using electricity directly (Neuling and Berks 2023; Zang et al. 2021).

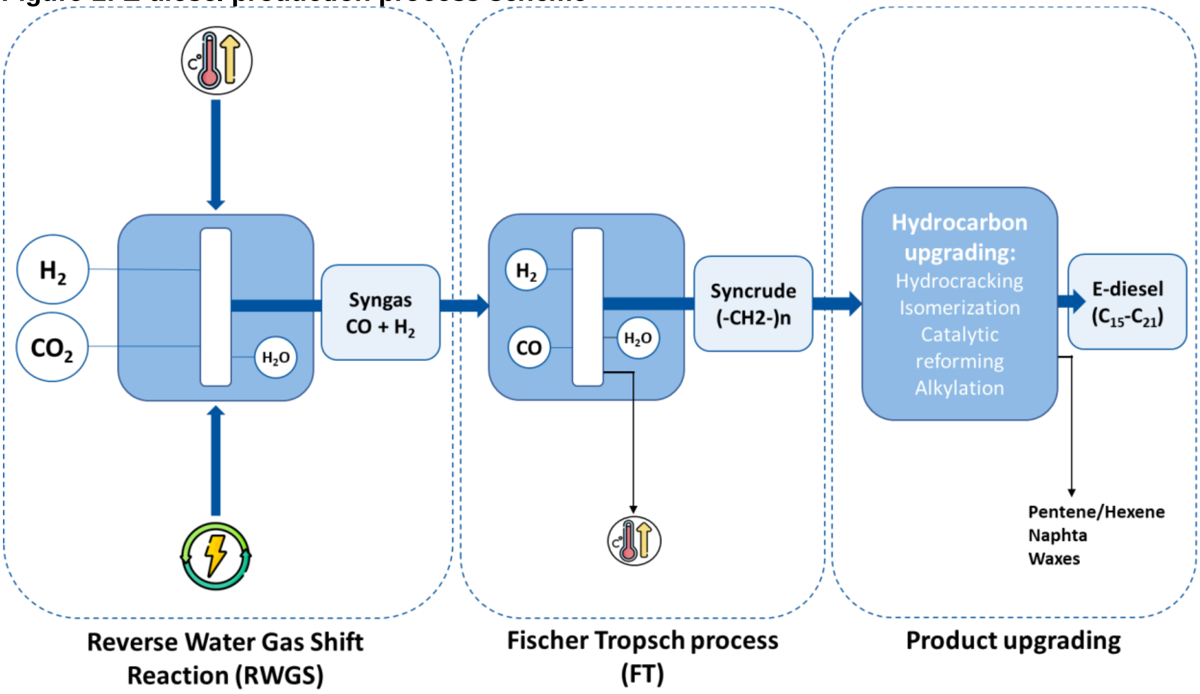
Moreover, the current availability of e-diesel remains limited, with only a handful of companies investing in its production. For instance, the U.S. currently has a capacity of 297 million gallons of e-diesel, while Neste Oil in Europe has a capacity of approximately 244 million gallons (Tan and Tao 2019). Other companies, such as Nippon Oil in Japan, BP in Australia, Syntroleum and Tyson Foods in the United States (Dynamic Fuels), and UOP-Eni in Italy and the United States have plans to produce e-diesel in the future (Tan and Tao 2019).

Another significant challenge for the use of e-diesel in the shipping sector arises from the lack of established policy frameworks and certifications, hindering the widespread adoption of e-diesel and other e-fuels in the maritime sector. Indeed, e-diesel lacks clear guidance for its production and use (Foreticha et al. 2021; Neuling and Berks 2023). Addressing these policy gaps and establishing robust regulatory frameworks are crucial steps towards facilitating the integration of e-diesel into the maritime industry's sustainable transition.

Having outlined the challenges and opportunities surrounding the adoption of e-diesel in the maritime sector, it's imperative to delve into its production process. This mainly requires hydrogen and carbon dioxide inputs (See figure 1).

Electrolysis is considered one of the simplest and cleanest methods of producing hydrogen. It demands approximately 50 kWh of electricity to split water into H_2 and O_2 and produce one kg of green hydrogen (Bullmann et al. 2020). Depending on the temperature level at which this process takes place, a distinction can be made between so-called low-temperature and high-temperature electrolysis (Bullmann et al. 2020). The most widely used low-temperature technology at present is the alkaline electrolysis (AEL). In recent years, polymer electrolyte membrane electrolysis (PEMEL) and anion exchange membrane electrolysis (AEMEL) have gained prominence as alternative low-temperature electrolysis processes, offering greater load flexibility, especially when coupled with variable renewable electricity sources. Solid oxide electrolysis (SOEL) is a high-temperature electrolysis that works at significantly higher temperatures and requires water vapor as an input material (Bullmann et al. 2020). One variant of SOEL is the so-called co-electrolysis, in which CO_2 is used as a starting material in addition to water vapor, resulting directly in a syngas consisting of hydrogen and carbon monoxide (CO). This variant could be interesting to produce e-diesel. However, compared to the low-temperature electrolyzers, high-temperature processes have so far only been realized in smaller demonstration plants (Bullmann et al. 2020; Neuling and Berks 2023)

Figure 1: E-diesel production process scheme



Source: Author's own illustration.

This paper focuses on employing AEL technology as the primary method for supplying green hydrogen for e-diesel synthesis, due to its maturity and lower costs, as it has been used in industry for around 100 years (Bullmann et al. 2020). Furthermore, in terms of durability, cold-start capability and system costs, alkaline electrolysis is currently still ahead of the other three processes (Bullmann et al. 2020). However, it is important to mention that in terms of compactness and flexibility (partial load capability and ramp-up speed), PEM electrolysis is more advantageous and that in the long term, SOEC electrolysis is expected to have considerable potential for cost degression and increased efficiency (Bullmann et al. 2020).

Carbon dioxide can be sustainability collected with Direct Air Capture (DAC) technology. A comprehensive explanation for choosing this method over other more economical alternatives will be elucidated in the climate change assessment. The DAC process captures CO_2 directly from the atmosphere with three basic steps that produce two outputs: concentrated CO_2 and filtered air (Pues 2022). First, fans are used to direct ambient air onto a sorbent (Pues 2022). This binds the CO_2 to itself and helps separating CO_2 from the other substances in the air. In a further process step, the CO_2 is separated from the sorbent again, usually by adding thermal energy, so that pure CO_2 is available at the end of the process chain. This can then finally be used to produce e-diesel (CBinsights 2021; Neuling and Berks 2023).

Direct Air Capture (DAC) currently incurs costs ranging from 800-1000 $\$/t_{(CO2)}$ (Webb et al. 2023). However, according to estimates by Climeworks, these costs are projected to decrease to 400-700 $\$/t_{(CO2)}$ by 2030 and further down to 100-300 $\$/t_{(CO2)}$ by 2050 (Webb et al. 2023). These costs can be further reduced through supportive policies, market development, commercialization, and mass deployment (CBinsights 2021; Pues 2022).

In the fuel synthesis stage, hydrogen combines with captured carbon dioxide in a Reverse Water Gas Shift (RWGS) reactor to generate carbon monoxide (CO). The produced mixture, characterized by a H_2/CO ratio of two, is then introduced into the Fischer-Tropsch (FT) reactor. The Fischer-Tropsch synthesis is a mature technology which has been known since the beginning of the 20th century and was originally developed to produce synthetic diesel from coal gasification (Grahn et al. 2022). The product of the subsequent FT synthesis is a mixture of different hydrocarbons, which is often referred to as synthetic crude oil or syncrude for short. This syncrude can be further processed in conventional refinery processes (including cracking, isomerization and distillation) to produce e-diesel (Marchese et al. 2021; Neuling and Berks 2023).

The realization of the RWGS reaction is currently the biggest technical challenge in e-diesel production. In fact, for commercial implementation of RWGS at the scales needed to replace fossil feedstocks with CO_2, new catalysts must be developed to suppress the competing methanation reaction completely while maintaining stable performance at elevated temperatures and high conversions producing large quantities of water (Grahn et al. 2022).

2. Environmental requirements for the production and use of liquid e-fuels in the maritime sector

The escalating contributions of shipping to acidification, eutrophication, climate change, and the adverse effects on human health have become a growing cause for concern. These contributions stem from the increasing emissions released into the air by shipping (Toscano 2018). Notably, approximately 70% of air emissions from shipping occur within a 400-kilometer radius of land, underscoring the particularly significant potential impact on coastal communities (Toscano 2018).

The United Nations Framework Convention on Climate Change (UNFCCC) identifies carbon dioxide (CO_2), Methane (CH_4), and nitrous oxide (N_2O) as primary contributors to climate change that must be mitigated within the shipping sector (Beverly et al. 2022). Furthermore, the International Maritime Organization (IMO) has delineated six additional substances, including nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter, carbon monoxide, non-methane volatile organic compounds, and soot, whose emissions necessitate control measures (Beverly et al. 2022).

These complexities highlight the importance of analyzing the sustainability of e-diesel for the shipping sector. However, this analysis should extend beyond emissions, encompassing various factors. This section explores the prerequisites for environmentally friendly e-diesel, examining diverse aspects of sustainability beyond environmental concerns to encompass social dimensions.

If derived from renewable sources like wind or solar power, resulting e-diesel achieves a 99% reduction in GHG emissions, from a well-to-wake perspective, whereas e-diesel from fossil electricity sources is estimated to be more harmful than conventional marine fuels which emphasizes the importance of using renewable electricity (Lindstad et al. 2021). In light of the prevailing global electricity mix, which is predominantly fueled by non-renewable sources, the demand for dedicated facilities for hydrogen and e-fuels production arises, aimed at preventing conflicts with other ongoing decarbonization efforts (Neuling and Berks 2023). Ensuring an overlay of electricity generation is therefore crucial for enhancing the accessibility of international projects and balancing these considerations is pivotal for the sustainable development of e-diesel and e-fuels more generally on a global scale (Umwelt Bundesamt 2023). Moreover, achieving independent renewable electricity sources for a specific sector or project proves technically intricate, requiring separation from the existing complex grid, and entails governmental interventions and permissions.

The considerable renewable electricity demand comes also with land use aspect which demands attention. Indeed, the annual global marine fuel consumption is projected to be around 330 million metric tons (87 billion gallons) annually and is expected to double by 2030 due to the increase in global trade (Tan et al. 2020). To produce this quantity entirely synthetically, an approximately estimated 6,700 terawatt-hours of renewable electricity would be required. This is roughly 27% of the global electricity consumption in 2022. If this electricity were to be generated using photovoltaic installations in one of the world's most cost-effective locations in South America, around 2,948 GW would need to be newly installed (Neuling and Berks 2023). This corresponds to about 2.5 times the installed photovoltaic capacity in the entire world (1,185 GW) (iea 2023). The required area for this would be approximately 67,737 km^2, based on calculations conducted by the author. To put this into perspective, this area surpasses more than twice the land area of Belgium (WorldData 2024).

With onshore wind turbines, the required capacity (2,948 GW) would be lower due to achieving more full load hours compared to photovoltaic installations, however, the land area needed for onshore wind turbines would be about 349,829 km^2 (Neuling and Berks 2023). Nevertheless, the spacing areas between the wind turbines can be repurposed for other uses, significantly reducing the net land requirement (Neuling and Berks 2023). The desert Atacama in Chile is one of the driest places in the world and one of the few where annual irradiance exceeds 2,500 $kWh.m^2$ (Neuling and Berks 2023). Producing the entire fuel demand in the EU for the marine sector, which represents about 19% of the global marine fuel consumption, counts for 1,273 TWh from photovoltaic installations. This would require approximately 509.2 km^2 for 21.7 GW, which represents three times the installed capacity in the whole country in 2023 (Statista 2023). This is only for the shipping sector which represents about 10% of the demand for gasoline and diesel in the Europe (Neuling and Berks 2023). Any additional transportation segment adopting e-diesel or e-fuels in general implies further utilization of significant land areas and favorable locations for power generation in other countries. However, such regions are globally scarce and require efficient utilization. This example illustrates that e-diesel cannot realistically be an option for achieving a complete substitution of marine fuels consumption in the EU, even with imports from favorable regions.

Another factor to consider is the substantial volumes of freshwater required for the production of e-diesel. Specifically, the production of one liter of e-diesel requires approximately 3.6 liters of high-quality drinking water, primarily for hydrogen electrolysis (Bullmann et al. 2020). Recognizing the escalating water demand due to population growth, industrial projects like e-fuel production must not exacerbate freshwater availability or compromise quality for local communities, mindful of present and future needs amidst the backdrop of climate change (Beverly et al. 2022). Consequently, in arid regions, distinguished by ample solar energy potential, the imperative for seawater desalination becomes apparent, albeit with the associated consequence of a further increase in electricity demand.

Another essential consideration in e-diesel production is the source of carbon dioxide, which should adhere to a closed cycle. This mandates the utilization of renewable carbon with a focus on avoiding negative externalities such as adverse impacts on land use (Mahler 2021; Neuling and Berks 2023). The first possibility is to gather CO_2 from biomass, biogas, and biogenic residues. Nevertheless, this may rise sustainability concerns, encompassing land competition with the food industry and indirect land-use changes, limiting the future's sustainable carbon availability (Pues 2022). As consequence, relying solely on carbon from biogenic sources might fall short of meeting the long-term demand for e-fuels needed to achieve climate objectives (Neuling and Berks 2023). A second alternative is to collect CO_2 from industrial point sources, such as emissions from coal plants. Nevertheless, this method lacks the assurance of a closed carbon cycle and cannot be deemed renewable (Mahler 2021).

Direct Air Capture (DAC) stands out as a method providing a fully closed carbon cycle for liquid e-fuels production. DAC ensures a complete carbon cycle closure, recycling all the CO_2 it produces, so that when the synthetic fuel is utilized, only the previously extracted atmospheric CO_2 is released (Mahler 2021; Neuling and Berks 2023). Moreover, DAC's advantages extend to its siting flexibility, as it does not require arable land and its location independence allows it to tap into significant atmospheric CO_2 for synthesis processes (Mahler 2021). Despite its potential, the current low scalability of DAC, coupled with relevant energy requirements due to the low CO_2 concentration in the atmosphere, renders this method scarce and expensive (Neuling and Berks 2023). However, there are high expectations for cost reduction until 2030 and beyond (CBinsights 2021; Webb et al. 2023).

Another critical aspect involves resource utilization in e-diesel production. The synthesis processes' catalysts contain rare metals like platinum or iridium, limited to a few extraction sites (Bullmann et al. 2020). It is therefore imperative to conduct further research to reduce the required quantities and explore substitution and recycling methods (Bullmann et al. 2020).

3. Economic efficiency assessment

A model has been formulated to evaluate the economic efficacy of e-diesel, considering the technologies outlined in the environmental assessment. The scenarios under consideration are introduced alongside the assumptions made, and detailed explanations are provided regarding the cost calculations. The formula used for cost estimation is outlined in the Appendix A.1. Additionally, a sensitivity analysis is conducted, followed by a comprehensive discussion of the overarching results.

3.1 Scenarios development

Given that electricity costs are the predominant factor influencing e-diesel production costs (Fasihi et al. 2016; Neuling and Berks 2023), the selection of scenarios is guided by the search for regions characterized by the lowest and most competitive costs of renewable energy sources. This paper considers photovoltaic (PV) and wind power plants as sources of renewable electricity. The chosen countries for examination are Chile, Australia, and the United States. This choice primarily stems from the availability of data and the clear commitment of these nations to participate in hydrogen-based projects globally (IRENA 2023).

Table 1: Anticipated Levelized Costs of Electricity (LCOE) across the three examined regions through 2050

Region	Technology	Scenario	Optimistic	Reference	Pessimistic
		Unit	$/MWh(el)	$/MWh(el)	$/MWh(el)
Chile (Atacama)	**PV**	**Present**	42[1]	42[1]	42[1]
		2030	15[2],[3],[4]	18.75[Average]	30[5]
		2050	12[4]	13.33 [Average]	14[6],[7]
Chile (Patagonia)	**Wind Onshore**	**Present**	30[1]	30[1]	30[1]
		2030	20[8],[9]	22	24[10,11]
		2050	10[8]	14.5[Average]	19[12]
Australia	**PV**	**Present**	41[1]	41[1]	41[1]
		2030	20[12]	24.75[Average]	27[13],[14]
		2050	16.92[15]	19.97[Average]	23[16]
United States	**Wind Onshore**	**Present**	32[1],[20]	32[1],[20]	32[1],[12]
		2030	28[17]	28.67[Average]	30[18],[19]
		2050	24[1]	25[Average]	26[18]

Sources:

(1) (IRENA 2023), (2) (Tai et al. 2022), (3) (Hydrogen Central 2021), (4) (Smart city Korea 2021), (5) (Bellini 2019), (6) (Wood Mackensie 2022), (7) (Djunisic 2022), (8) (Satymov et al. 2022), (9) (Fasihi et al. 2016), (10) (Breyer 2018), (11) (Heuser 2020), (12) (Prié 2019), (13) (Carroll 2023), (14) (Kitchen 2022), (15) (Csiro 2022), (16) (Mayer 2015), (17) (Wiser and Bolinger 2022), (18) (Kramer and Jones 2020), (19) (OffshoreWind.biz 2021), (20) (Berkeley Lab 2021)

The paper thoroughly investigates the chosen regions across three scenarios: optimistic, reference, and pessimistic. The optimistic scenario prioritizes the most advantageous values, whereas the pessimistic scenario integrates the least favorable ones. In the reference scenario, an average is computed from all available sources. Various Levelized Costs of Electricity (LCOE) are analyzed for the years 2023, 2030, and 2050, presenting a comparative overview of the four regions. Detailed numerical data can be referenced in Table 1 above.

Chile: Atacama Desert and Patagonia Region

Chile is a key player in renewable energy, leveraging PV technology in the Atacama Desert and harnessing wind energy in the Patagonia region. On the one hand, renowned for having one of the highest solar irradiance levels globally, Chile's northern region, marked by high altitude, frequent cloud absence, and lower levels of ozone and water vapor, emerges as a prime location for photovoltaic (Hydrogen Central 2021; IRENA 2023). The Atacama Desert demonstrates a photovoltaic (PV) capacity of 1,800 GW, surpassing the capacity factors of the best locations in Africa, the Middle East, and Australia by over 20% (IRENA 2023). On the other hand, the Patagonia region in Chile exhibits very high onshore wind capacity factors (IRENA 2023). Moreover, Chile's ambitious plans for hydrogen electrolysis, targeting a Levelized Cost of Green Hydrogen (LCOH) below 1.50 \$/kg$_{(H_2)}$ by 2030, positions the country as a competitive hub for e-diesel production (Smart city Korea 2021).

Australia: Solar Energy

Leveraging its high solar irradiation levels on the western and southern coasts, Australia anticipates solar PV to be the most cost-effective energy source by 2050 (iea 2023). The country has an established access to critical natural resources, a high GDP per capita, and a robust supply-chain infrastructure.

Additionally, Australia demonstrates one of the lowest estimated levelized costs of hydrogen globally, expected to reach approximately 1.7 $/kg_{(H2)}$ by 2030 (Smart city Korea 2021). This positions Australia as a key player in the pursuit of cost-effective and sustainable e-diesel.

United States: Wind Energy

As the world's largest economy with abundant renewable resources, endowed with abundant renewable energy resources, the US is positioned to establish a secure and dependable energy system founded on renewable energy (IRENA 2023). Notably, the United States possesses renewable resources that surpass its annual electricity needs by a factor of 100, underscoring its immense potential for renewable energy utilization. The wind energy sector plays a pivotal role in the country's energy landscape. Furthermore, the US aims for a remarkably low estimated cost of green hydrogen production, projected to be as low as 2.1 $/kg_{(H2)}$ by 2030 (Smart city Korea 2021). This positions the US as a significant player in the global pursuit of affordable and environmentally friendly liquid e-diesel.

3.2 Assumptions

The analytical framework of this research relies on a series of fundamental assumptions. Firstly, the production of e-diesel is presumed to occur without interference from regulatory hurdles, legal challenges, or external disturbances. Geopolitical stability is assumed, with conflicts and international tensions excluded from the analysis. Additionally, unimpeded public acceptance of e-diesel is assumed, without significant resistance or social barriers. The assumption extends to unrestricted e-diesel production, implying that resource availability, technological limitations, and logistical constraints will not impede the process.

The primary focus is on e-diesel, leveraging existing infrastructure. Co-location of renewable energy, hydrogen, and e-diesel synthesis is assumed to reduce transport and distribution costs, streamline infrastructure development, and enhance overall efficiency. The model assumes exclusive reliance on renewable electricity sources to meet the energy demands of the entire process. Given the limited availability and geographical dispersion of surplus electricity, occurring for only a few hours annually in small quantities, it is assumed that electricity is derived from supplementary and newly established renewable capacities. Moreover, capacity limitations for renewable energy sources are not factored into the analysis, with the assumption that a sufficient electricity supply exists to meet the requirements of the whole process.

The closed carbon dioxide cycle with Direct Air Capture (DAC) is considered, in spite of the current demonstration phase and associated limitations. Despite these limitations, the analysis considers large-scale conversion facilities, leveraging economies of scale and anticipating future market penetration for additional cost reductions (Neuling and Berks 2023). It is important to mention that the electricity requirement for the DAC process step is heavily influenced by whether waste heat from other subprocesses available and what portion of the heat demand is needed to be generated electrically (Neuling and Berks 2023; Pues 2022). Since a detailed process simulation is beyond the scope of this paper, an assumption of an independent electricity requirement for the carbon dioxide is made.

The model restricts the analysis to low-temperature electrolysis for hydrogen production, a decision driven by the developmental phase of solid oxide electrolysis cell (SOEC) electrolysis and the uncertainty surrounding its future applications. Moreover, the limitations of high-temperature electrolyzers, characterized by constrained dynamic response and mechanical strain on ceramic materials during temperature fluctuations, render them less suitable for volatile energy systems compared to the more dynamically responsive low-temperature water electrolysis processes (Bullmann et al. 2020; Kasten 2020). The model's foundation rests on the application of alkaline electrolysis (AEL), while the utilization of proton exchange membrane (PEM) technology is reserved for examination within the scope of sensitivity analysis, due to supply risks associated with critical elements such as platinum and iridium (Ausfelder and Dura 2018). The assessment also considers efficiency losses, conversion costs, and technological advances. Water desalination is the exclusive source of water, and associated costs are integrated into the model.

In the Fischer-Tropsch process, carbon monoxide is generated from carbon dioxide through the reverse water-gas shift (RWGS) reaction, validated by literature, and identified as the most suitable approach for producing carbon monoxide within the context of the Fischer-Tropsch process. The Fischer Tropsch plant's capacity is contingent on the electrolyzers capacity, but when accounting for existing e-diesel projects, the Fischer Tropsch plant's capacity can potentially extend to 250 MW, as illustrated in Table A.2 in Appendix A.2.

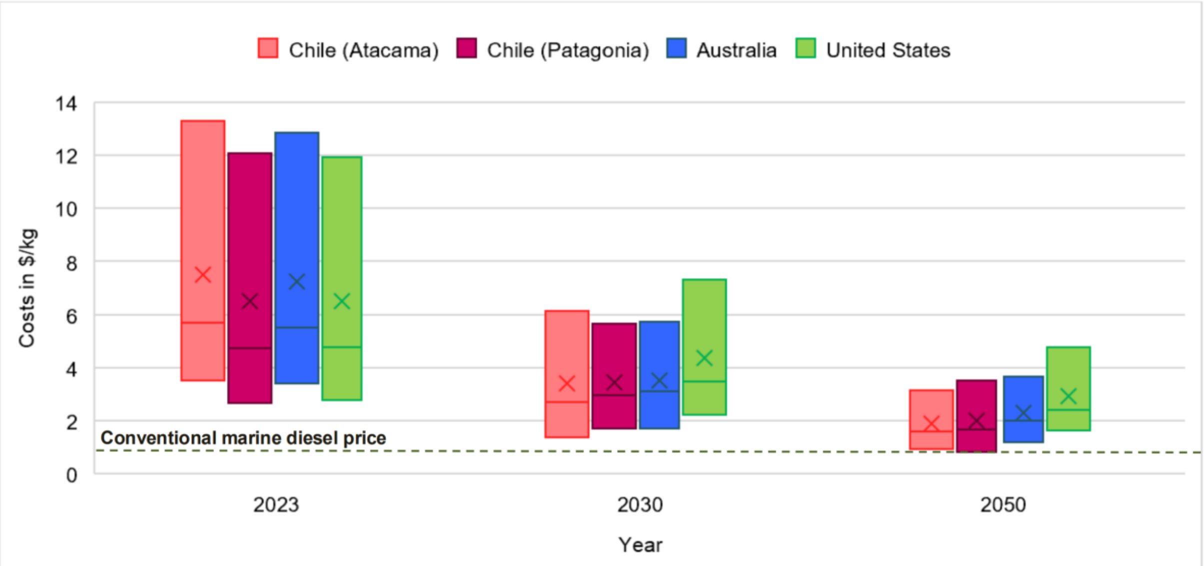
To align the entire process with Fischer-Tropsch requirements, hydrogen storage is incorporated, ensuring uninterrupted fuel synthesis (Kasten 2020). For the utilization of compressed hydrogen storage, a well-established method, costs remain consistent across countries and are derived from average values reported in existing literature, amounting to 0.35 $/kg_{(H2)}$ (Guel 2022; Perner et al. 2018; Schimmel 2022). The annual stored volume of hydrogen is calculated by deducting the quantity required for the Fischer-Tropsch process from the total produced, while considering the remaining volume stored from the previous year.

These collective assumptions form the foundation for the comprehensive cost calculation presented in this paper. The overall costs are computed using the annuity method. An annuity is a regular payment over a certain period of time (Moser 2020). According to the annuity method, the sequence of periodic variable payments and receipts, considering the interest effect, is converted into annual average values (Moser 2020). The calculation includes capital investment[1], operating costs[2], anticipated efficiency improvements[3], and refining, processing, and conditioning costs. Load hours are determined based on the full load hours of corresponding technologies.

3.3 Findings and interpretation

In the following examination, the model outcomes are unveiled, delving into the economic aspects of e-diesel expenses across three crucial timeframes: 2023 (Present), 2030, and 2050. The estimated production costs for e-diesel across various regions and scenarios are depicted in Figure 2 using a box and whisker diagram. Within the diagram, the upper portion of the box represents the pessimistic scenario, the cross inside the box represents the reference scenario, and the lower portion of the box reflects the optimistic scenario.

Figure 2: Estimated e-diesel production costs



Source: Author's own calculation and illustration.

[1] Specific power costs for the Fischer Tropsch plant in $/MW: Present (2023): optimistic scenario: 424,000, reference scenario: 913,000, pessimistic scenario: 2,226,000; 2030: optimistic scenario: 318,000, reference scenario: 653,000, pessimistic scenario: 1,091,000;2050: optimistic scenario: 212,000, reference scenario: 414,000, pessimistic scenario: 562,000.

[2] Fixed operating cost per year for the Fischer Tropsch plant in %: Optimistic scenario: 3%, reference scenario: 3.25% , pessimistic scenario: 4%

[3] Efficiency for the Fischer Tropsch plant in %: Present (2023): optimistic scenario: 80%, reference scenario: 73.6% , pessimistic scenario: 59%; 2030-2050: optimistic scenario: 80%, reference scenario: 76.3% , pessimistic scenario: 73%

Present perspective (2023): Unveiling the current economics of e-diesel

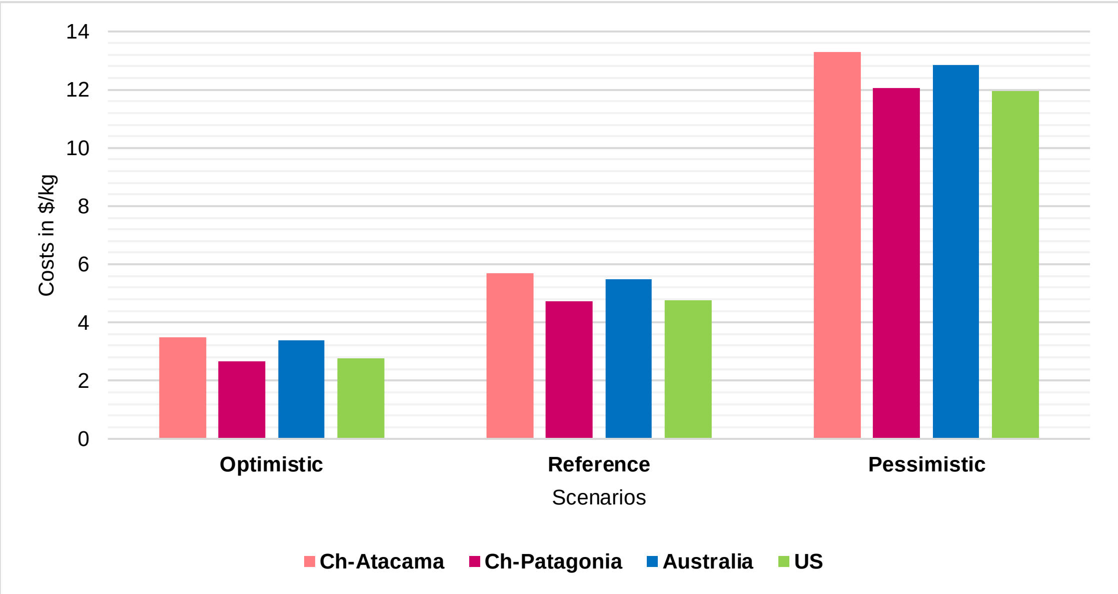
In light of the current costs of renewable energies across the considered regions, which have been derived from the data provided in Table 1, with wind energy averaging a levelized cost of electricity (LCOE) of 31 $/MWh and solar PV at 41 $/MWh, the production of one kg of green hydrogen incurs average costs of 3.52 $/kg and 4.04 $/kg, respectively. Water desalination facilities can generate water at an average cost of 0.52 $/t$_{(H2O)}$ with wind energy and 0.56 $/t$_{(H2O)}$ with solar energy equivalent to 0.162 $/MWh$_{(H2)}$ and 0.172 $/MWh$_{(H2)}$ of hydrogen output, considering that the production of one kilowatt-hour of hydrogen necessitates approximately 0.31 kilograms of water (Bullmann et al. 2020; Schimmel 2022) The average cost of capturing CO_2 from ambient air is 152.71 $/t$_{(CO2)}$ for wind energy and 174 $/t$_{(CO2)}$ for solar PV.

The outcomes highlight that electricity costs, impacted by factors such as technology, capital costs, and regional capacity factors, play a pivotal role in influencing production costs. Differences in the Weighted Average Cost of Capital (WACC) among locations have a noteworthy impact on investment costs, yet the predominant influence is attributed to electricity costs. This can be illustrated by the example of wind onshore Chile Patagonia with a higher WACC (6.1%) compared to the US (5.2%), but the costs per ton of CO_2 captured, as well as per kg of H_2 and e-diesel produced, are lower, underscoring the pivotal role of electricity costs (Neuling and Berks 2023).

The detailed outcomes regarding the production costs of one kilogram of e-diesel in the present (2023) are presented in Figure 3 below. Analysis of these costs for the US in 2023 showcases significant variations among scenarios. For instance, in the US, despite identical LCOE values, total costs per kg of e-diesel range from $2.76 (optimistic) to $11.94 (pessimistic). This emphasizes the substantial impact of factors beyond LCOE, underscoring the significance of investments and fixed operating costs.

To facilitate a deeper understanding of the cost breakdown in the final production expenses, the example of the United States, evaluating both pessimistic and optimistic scenarios, is scrutinized. In the optimistic scenario, the investment costs, encompassing RWGS, Fischer-Tropsch, and fuel upgrading are equal to 0.0531 $/kg$_{(e\text{-}diesel)}$ (1.92% of the total costs). Conversely, in the pessimistic scenario, these costs experience a significant escalation, reaching 0.3779 $/kg$_{(e\text{-}diesel)}$ (3.17%). Similarly, fixed operating costs demonstrate a noteworthy rise from 0.0016 $/kg$_{(e\text{-}diesel)}$ (0.06%) in the optimistic scenario to 0.0151 $/kg$_{(e\text{-}diesel)}$ (0.13%) in the pessimistic scenario.

Figure 3: Estimated e-diesel production costs in 2023 in $/kg$_{(e\text{-}diesel)}$



Source: Author's own calculation and illustration.

Electricity costs remain consistent across all scenarios at 0.0347 $/kg$_{(e\text{-}diesel)}$ (1.26%, optimistic and 0.29%, pessimistic) at the present time. Since the LCOE represents actual costs, these figures remain uniform for the three scenarios in 2023. It is imperative to note that the electricity costs mentioned pertain exclusively to the electricity consumed during FT synthesis, with the costs incurred in the preceding processes like the water electrolysis included in the corresponding input. This principle applies also to both operating and investment costs (OPEX and CAPEX).

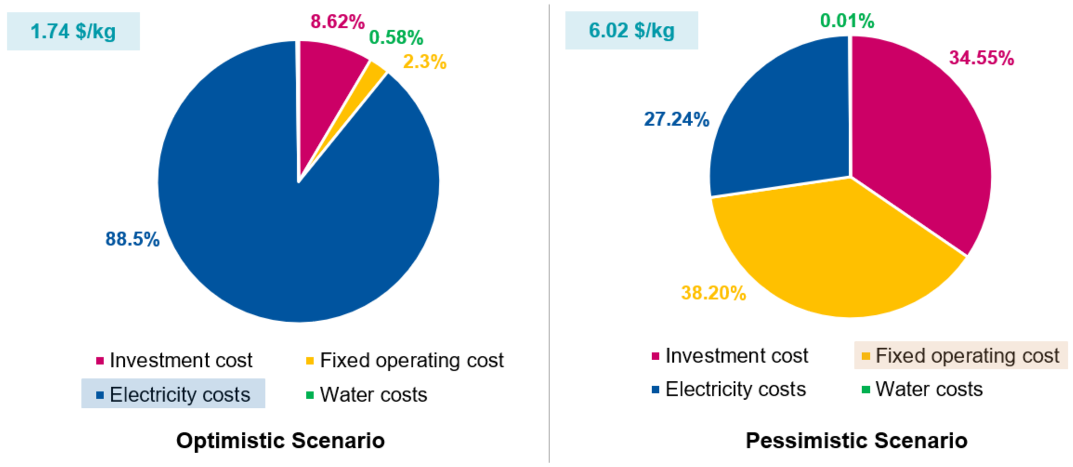
Hydrogen costs, constituting the largest share of total costs, undergo a sharp increase from 2.3337 $/kg_{(e\text{-}diesel)}$ (84.51%) to 10.9773 $/kg_{(e\text{-}diesel)}$ (91.94%). This consistent prominence underscores the critical and prevailing role of hydrogen production costs, maintaining a significant proportion of the final costs per kg of e-diesel produced. Upon analyzing the composition of hydrogen production costs, depicted in Figure 4 below, marked distinctions emerge across the optimistic and pessimistic scenarios.

For instance, investment costs account for 8.62% of total costs in the optimistic scenario, while in the pessimistic scenario, they rise significantly to 34.55%. Fixed operating costs rise from 2.30% in the optimistic scenario to 38.20% in the pessimistic scenario. Meanwhile, electricity costs remain relatively stable in terms of amount but decrease significantly in percentage terms (from 88.51% to 27.24). This deviation indicates that electricity costs consistently play a central role in the overall cost structure, regardless of fluctuations in the scenarios. The cumulative effect of these factors contributes to a substantial increase in total costs, from 1.74 $/kg_{(H2)}$ to 6.02 $/kg_{(H2)}$, primarily driven by elevated investment and operational costs in less favorable conditions.

While relatively minor compared to other components, hydrogen storage costs exhibit an increasing trend from 0.0036% in the optimistic scenario to 0.074% in the pessimistic scenario. Despite constituting a very small percentage of the total costs in both scenarios, the variability in storage costs—despite a consistent cost per stored kilogram of hydrogen—can be attributed to variable efficiencies and nominal power of electrolysis and Fischer-Tropsch plants. These factors impact the quantities of hydrogen and e-diesel produced and, consequently, the stored quantities of hydrogen per year. While optimizing produced quantities to minimize stored hydrogen may be a sensible approach, such considerations fall outside the scope of this paper.

In total, the costs associated with producing one kilogram of e-diesel experience a substantial increase from 2.7614 $/kg_{(e\text{-}diesel)}$ in the optimistic scenario to 11.9397 $/kg_{(e\text{-}diesel)}$ (4.32 times higher) in the pessimistic scenario, underscoring the cumulative impact of various cost components, particularly the significant rise in hydrogen costs. Many of these factors will undergo further examination in the sensitivity analysis provided in section 4.

Figure 4: Cost breakdown per kg of green hydrogen produced in the US (2023) in $/kg_{(H2)}$



Source: Author's own calculation and illustration.

In essence, the contrast between pessimistic and optimistic scenarios highlights how e-diesel production costs are intricately influenced by several factors, notably electricity costs, WACC, and investment costs. Additionally, technical considerations such as plant efficiency and lifespan also play significant roles. These results emphasize the importance of sound financial planning and risk management strategies to ensure the economic viability of e-diesel production projects, especially in challenging scenarios.

2030 forecast: Navigating e-diesel costs in the near future

The total production costs for e-diesel witness a significant decline by 2030, averaging a 42% reduction for the optimistic scenario, 40% for the reference scenario, and 50% for the pessimistic scenario. This notable decrease can be attributed to various factors and parameters, primarily stemming from lower electricity generation costs that impact all input costs, especially hydrogen and carbon dioxide costs. Additionally, both the CAPEX and OPEX of each technology decrease, accompanied by efficiency improvements, particularly in hydrogen production and Direct Air Capture (DAC), given that Fischer Tropsch synthesis is a mature technology with limited room for substantial improvements.

Looking at the estimated costs of renewable energies in the regions analyzed, the average LCOE for wind energy is 25.44 $/MWh (31 $/MWh in 2023) and 22.58 $/MWh (41$/MWh in 2023) for solar PV. The production costs for wind energy amount to 2.28 $/kg for green hydrogen and 3.84 $/kg for e-diesel (3.52 and 6.48 in 2023, respectively). For solar PV, the production costs are 2.15 $/kg for green hydrogen and 3.45 $/kg for e-diesel (4.04 $/kg$_{(H2)}$ and 7.37 $/kg$_{(e\text{-}diesel)}$ in 2023).

To explore further the factors influencing the significant decrease in hydrogen costs and, by extension, e-diesel production costs, some data for the years 2023 and 2030 are presented in Table 2 below. This data considers scaling effects and enhancements in efficiency and costs over time.

As evident from the table, there is an overall enhancement in various parameters. Efficiency and nominal power show an increase, specific power costs experience a reduction, the system's lifespan extends, and both fixed and variable OPEX as well as the LCOE and water costs, witness a decline. The cumulative impact of these enhancements significantly contributes to the notable reduction in production costs. For the identified average LCOE, water desalination facilities can produce water at an average cost of 0.46 $/t$_{(H2O)}$ with wind energy (0.52 in 2030) and 0.44 $/t$_{(H2O)}$ with solar PV (0.56 in 2030), equivalent to 0.141 $/MWH$_{(H2)}$ (0.159 in 2030) and 0.138 $/MWH$_{(H2)}$ (0.172 in 2030).

The average cost of capturing CO_2 from ambient air is projected to be 82.83 $/t$_{(CO2)}$ (152.71 in 2030) for wind energy and 77.82 $/t$_{(CO2)}$ (174 in 2030) for solar PV. This reduction is foreseen through the implementation of deployment strategies and innovative approaches (Neuling and Berks 2023). Expenses related to Direct Air Capture (DAC) are contingent on factors such as capture technology, energy costs, plant configuration, and financial assumptions (Webb et al. 2023).

In regions abundant in renewable energy resources, as depicted in the studied scenarios, coupled with advanced technologies for electricity and heat generation, it is conceivable that DAC costs may dip below 100 $/t$_{(CO2)}$ by 2030, as evidenced in the developed model (European Commission 2023b; Guel 2022). Indeed, aligning global DAC deployment rates with The Net Zero Emissions by 2050 Scenario, a normative pathway outlining how the global energy sector can achieve net-zero CO_2 emissions by 2050, and which aims to capture 90 million tons of CO_2 in 2030 and 980 million tons in 2050, could result in a substantial reduction in Capital Expenditure (CAPEX) (Guel 2022).

This reduction is projected to be substantial, with a potential decrease of 49-65% in 2030 and 65-80% in 2050 compared to 2020 levels. Regionally, it is anticipated that the CAPEX will be comparatively lower in China, the Middle East, the Russian Federation, and North Africa than in Europe and the United States. This regional variation is attributed to the availability of more cost-effective materials and manufacturing processes (Guel 2022). However, realizing this cost reduction potential is contingent upon increased support from both the public and private sectors for innovation and widespread deployment efforts (European Commission 2023b).

Table 2: Average production costs of green hydrogen by renewable electricity sources

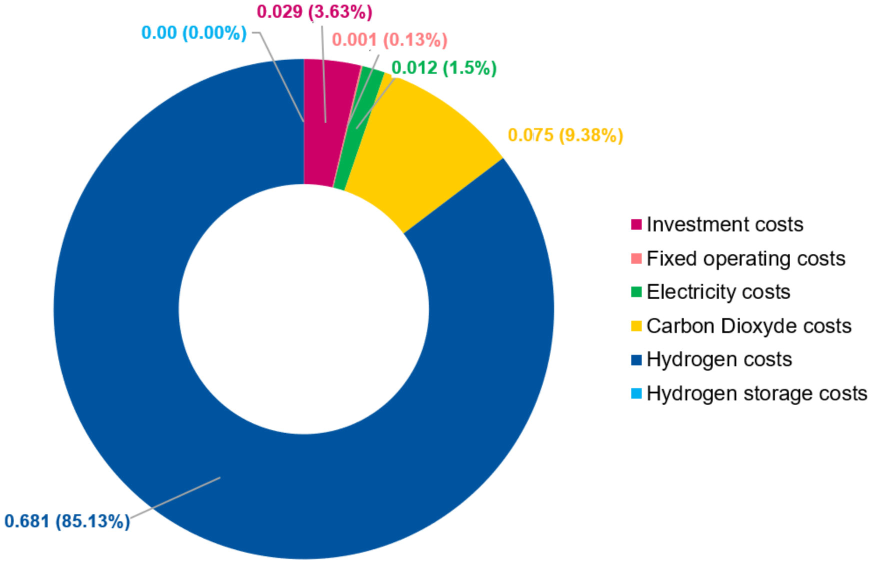
	Unit	2023			2030		
		Optimistic	Reference	Pessimistic	Optimistic	Reference	Pessimistic
Efficiency	**%**	69	66	65	71	69	66
Nominal Power	**MW**	220	140	100	750	425	100
Specific power cost	**$/MWh**	338,000	949,000	1,145,000	289,000	623,000	750,000
Lifetime	**year**	25	22	20	30	23	20
Annual CAPEX	**$, y**	5,382,278	10,278,291	9,344,225	14,422,974	20,001,281	6,120,671
OPEX factor	**%**	2	3,66	9	2	3.2	5
Annual fixed OPEX	**$, y**	1,487,200	4,871,533	10,305,000	4,335,000	8,472,800	3,750,000
Electricity demand	**MWh, y**	1,760,000	620,620	230,000	6,000,000	1,884,025	230,000
LCOE	**$/MWh**	41	41	41	20	24.75	27
Annual electricity costs	**$, y**	72,160,000	25,445,420	9,430,000	120,000,000	46,629,619	6,210,000
Water costs per kWh H_2 output	**$/kg**	0.0001151	0.0001598	0.0002147	0.0000890	0.0001292	0.0001952
Annual H_2O costs	**$, y**	139,802	65,656	32,101	379,076	167,970	29,633
Total annual OPEX	**$, y**	73,787,002	30,382,609	19,767,101	124,714,076	55,270,389	9,989,633
Total annual costs	**€, y**	79,169,280	40,660,900	29,111,325	139,137,049.76	75,271,670	16,110,305
Costs pro kg H_2	**$/kg**	2.17	3.30	6.4	1.09	1,93	3.53

Sources: (Matthes et al. 2020), (Grahn et al. 2022), (Mendelevitch et al. 2023) , (Wilms et al. 2018), (Hank et al. 2023), (Marchese et al. 2021), (Lövenich et al. 2018)

2050 Vision: Anticipating the economic landscape of e-diesel

In the 2050 findings, more favorable outcomes are revealed, showcasing a spectrum of total production costs for one kg of e-diesel between $0.79 and $1.61 for the optimistic scenario, $1.59 and $2.39 for the reference scenario, and $3.15 and $4.75 for the pessimistic scenario. These reductions are primarily attributed to the same factors observed in the 2030 scenario, where both hydrogen electrolysis and Direct Air Capture experience efficiency enhancements and decreased investment costs. Additionally, the continued decline in the Levelized Cost of Electricity significantly impacts overall costs.

Figure 5: Cost Breakdown for e-diesel production in \$/kg$_{(H2)}$ Chile Patagonia - 2050



Source: Author's own calculation and illustration.

Within the optimistic scenario unfolding in Chile's Patagonia, identified as the most promising, the production costs dipping below \$0.80 per kilogram of e-diesel underscore the significance of hydrogen, even amid higher efficiencies and more favourable conditions (see Figure 5). Indeed, hydrogen emerges as the most substantial cost component (85.13%), highlighting its pivotal role in the e-diesel production process even in the optimistic scenario, which foresees an exceptionally low hydrogen cost, indicative of heightened efficiency and access to competitive renewable electricity.

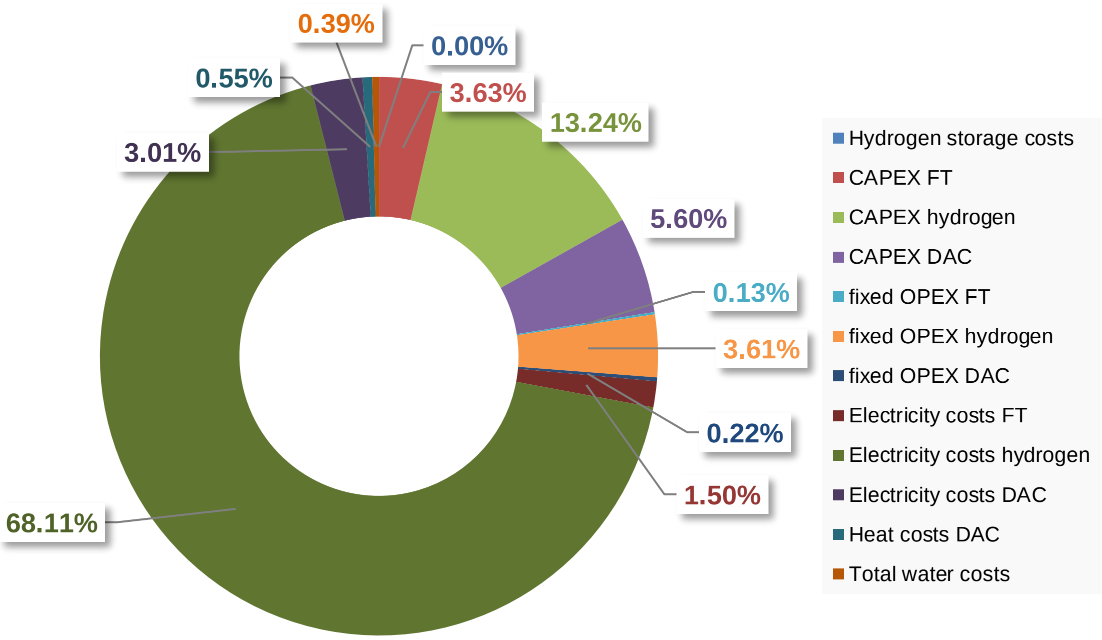
The scenario envisions a moderate electricity cost of \$0.012 per kilogram of e-diesel, implying the accessibility to cost-effective renewable energy sources. Carbon dioxide costs are notably low at \$0.075 per kilogram of e-diesel, with capturing costs at \$34.42 per ton of CO_2. This underscores the strategic importance of promptly considering carbon capture as an offset strategy, enabling the realization of learning effects in the near future and the sustainable and efficient mitigation of CO_2 emissions.

Significantly, investment costs for FT- plants stand at \$0.029 per kilogram of e-diesel, indicating highly favorable conditions and consequently resulting in exceedingly low fixed operating costs at \$0.001 per kilogram of e-diesel. Hydrogen storage costs prove negligible in all scenarios, indicating the effectiveness and cost-effectiveness of storage solutions.

In summary, the optimistic scenario portrays a cost-effective and efficient e-diesel production process characterized by minimal investment, operating, and environmental mitigation costs. The judicious management of hydrogen, a key component, further augments the overall competitiveness of e-diesel production in Chile's Patagonia and in the other regions in the year 2050.

Figure 6 provides an alternative perspective on the cost breakdown for e-diesel production, integrating hydrogen production, Direct Air Capture, and Fischer Tropsch costs individually. The alkaline electrolyser, operating at 82% efficiency, emerges as the primary consumer of electricity with over 68%. Considering the utilization of excess heat from the Fischer Tropsch plant, there is potential to boost overall plant efficiency by up to 9%, leading to a hydrogen electrolysis efficiency of 93% and a reduction in production costs to \$0.446 per kilogram of green hydrogen and \$0.71 per kilogram of e-diesel.

Figure 6: Cost breakdown for e-diesel production in % in Chile Patagonia, 2050 – alternative perspective



Source: Author's own calculation and illustration.

Exploring the potential utilization of excess heat generated by the Fischer Tropsch plant to power the overall system could enhance overall plant efficiency by up to 9% (Fasihi et al. 2016). This improvement results in a hydrogen electrolysis efficiency of 93%, potentially leading to a reduction in electricity demand and consequently lowering production costs to $0.446 per kilogram of green hydrogen and $0.71 per kilogram of e-diesel. The second-highest cost component, representing over 13% of the total costs, is also hydrogen, with its investment costs. Direct Air Capture (DAC) holds the third position, accounting for 5.60% of the total costs.

3.4 Comparative assessment of the results

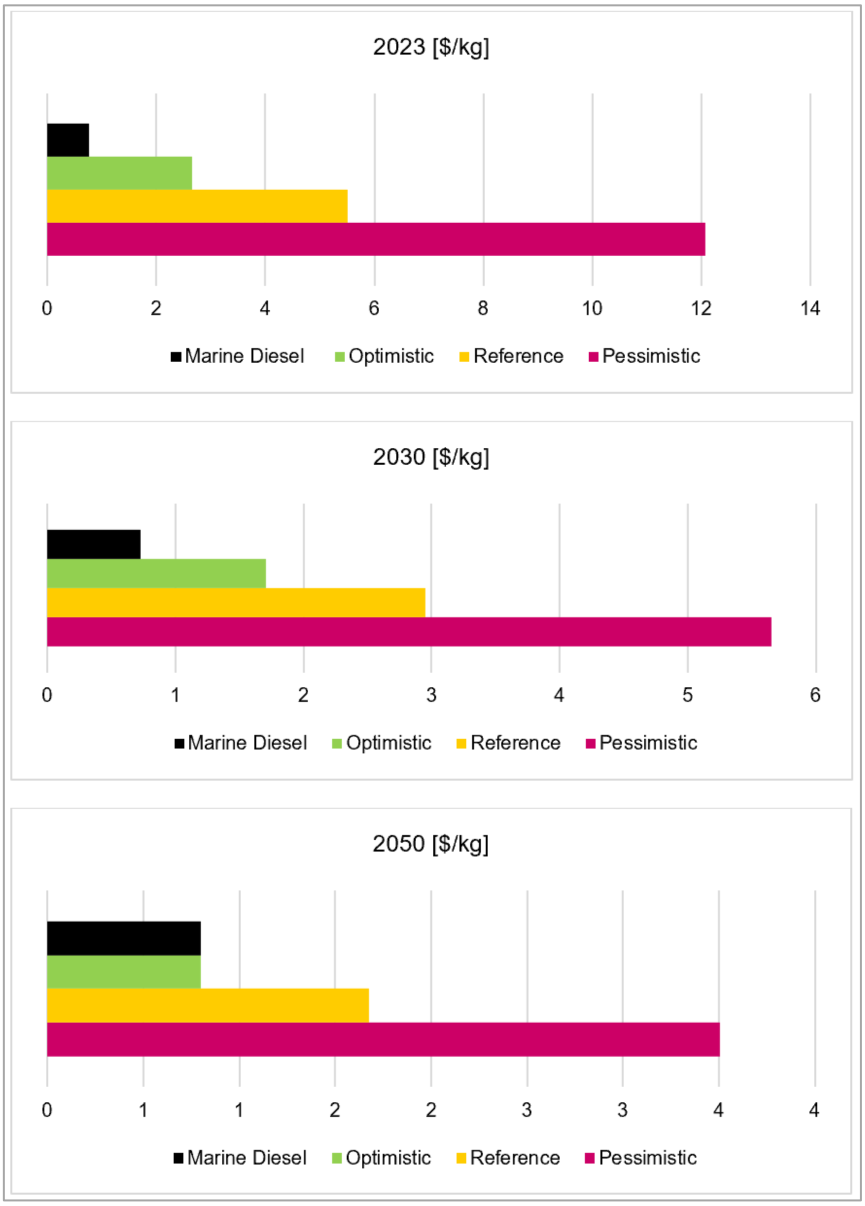
This analysis embarks on a comparative exploration of the potential trajectories for e-diesel within the context of maritime transport. Three key comparisons are undertaken to delineate its cost competitiveness, validity, and broader positioning among renewable alternatives.

The first comparison involves juxtaposing the model results with the anticipated marine diesel prices for 2023, 2030, and 2050. The aim of this analysis is to determine the cost competitiveness of e-diesel and the feasibility of its market introduction by identifying potential market entry points over time.

Considering the 13-year sustainable average ratio, where the cost of one barrel of diesel (consisting of crude oil consumption and refining costs) is equal to 118.76% of the price of marine diesel (Fasihi et al. 2016), the costs for marine diesel are estimated based on the crude oil projections provided by the U.S Energy Information Administration (EIA) (EIA 2023). Accordingly, the costs for 2023 are established at 0.76 $/kg$_{(e\text{-}diesel)}$ and the projected costs are set at 0.73 $/kg$_{(e\text{-}diesel)}$ for 2030 and 0.80 $/kg$_{(e\text{-}diesel)}$ for 2050.

The comparison between the costs of producing one kilogram of e-diesel in Chile's Patagonia, expected to have the lowest production costs in the long term according to the model calculations, with conventional marine diesel, is illustrated in Figure 7 below. Even under the optimistic scenario, the price of e-diesel is projected to be 3.5 times higher in 2023 compared to the current costs, with even less favorable figures for the reference scenario (7.23 times higher) and the pessimistic scenario (15.9 times higher). Despite relevant cost decreases projected for 2030, the production of e-diesel remains uncompetitive against conventional marine diesel in all scenarios, with a 2.34 times higher cost for the optimistic scenario, 4 times higher for the reference scenario, and almost 8 times higher for the pessimistic scenario. By 2050, the costs for e-diesel align with the price of conventional marine diesel in the optimistic scenario, are almost 2 times higher for the reference scenario, and 4.4 times higher for the pessimistic scenario.

Figure 7: Cost comparison of e-diesel production costs in Chile, Patagonia with conventional marine diesel



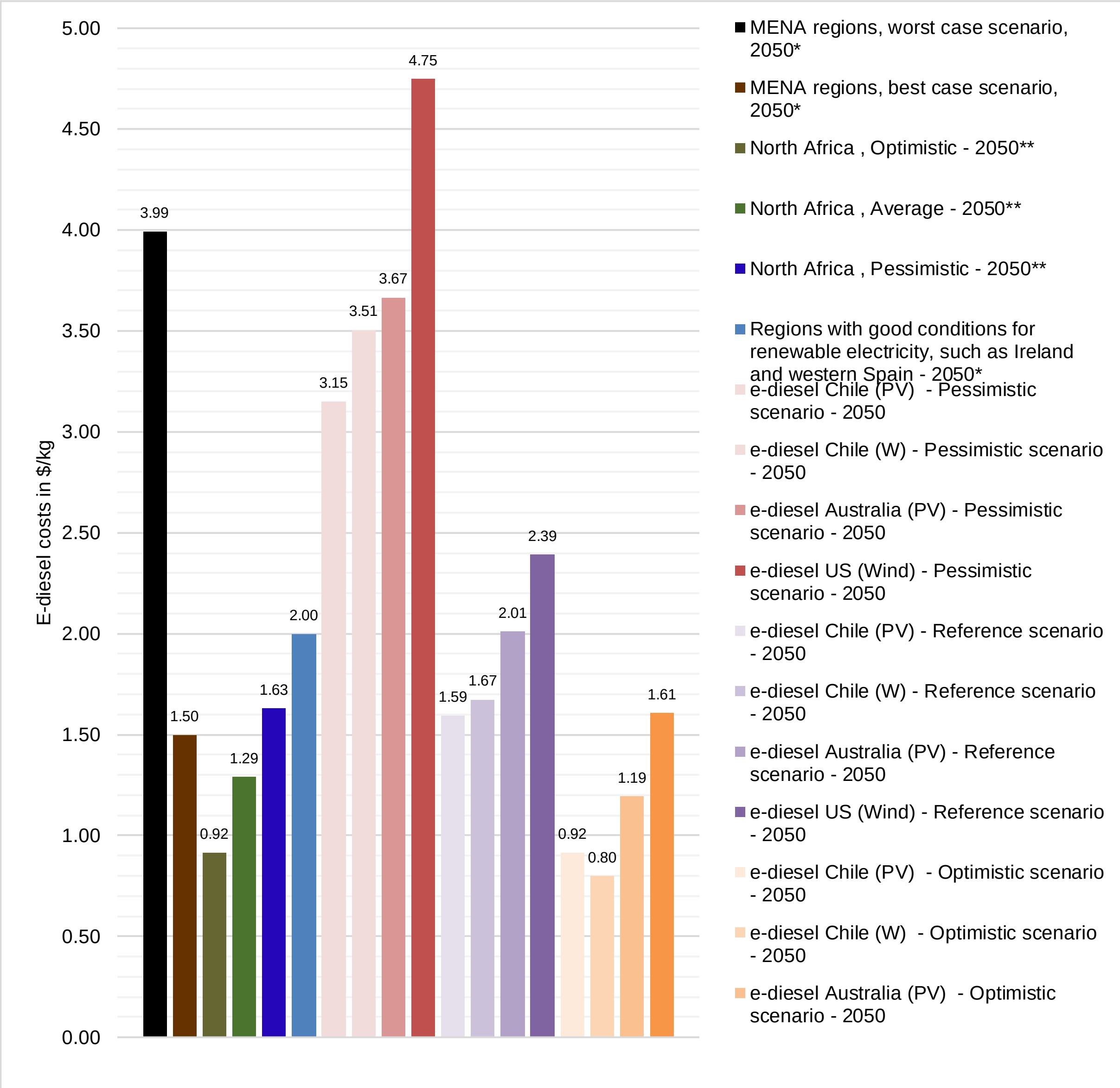
Source: Author's own calculation and illustration.

Identifying the primary drivers of cost reduction and analyzing scenario variances is therefore instrumental in discerning controllable factors that can mitigate costs. However, the nascent stage of technology indicates that major cost reductions are not anticipated in the near future. Therefore, government intervention becomes imperative, exemplified by the need for carbon taxes on conventional fuels to level the playing field and make e-diesel competitive.

The second comparison, illustrated in Figure 8, entails aligning the model results with findings for 2030 and 2050 from other studies on e-diesel, serving as a litmus test to assess the relative validity and robustness of the model estimations (Grahn et al. 2022). This test aims to validate the credibility of the model against existing research in the field.

The analysis of studies on current and future expected costs to produce e-diesel reveals a significant variation in projected costs based on assumed factors such as the plant location, WACC, renewable electricity costs, or plant efficiency. On average, production costs of approximately 3.47 $/kg$_{(e\text{-}diesel)}$ are calculated until 2030. Particularly low costs are reported in studies that assume highly cost-effective power sources with high full load hours, such as hydropower combined with CO_2 from point sources (Neuling and Berks 2023). However, the available potential for both is very limited, rendering them unsuitable for mass e-fuel production. Moderate costs arise from a combination of affordable electricity with high full load hours and an expensive CO_2 source like DAC or lower capacity hours in electricity generation (Neuling and Berks 2023).

Figure 8: Benchmarking estimates: Validating e-diesel model results through literature review



Source: Author's own illustration.

**This source examines the production costs of e-diesel in the Middle East and North Africa (MENA) region, as well as in European regions known for their low renewable electricity costs, such as Spain (solar photovoltaic) and Ireland (wind). The study considers various scenarios, including an optimistic one characterized by the most favorable economic conditions (e.g., lowest capital expenditure, lowest levelized cost of electricity) and a worst-case scenario reflecting the least favorable economic conditions (Grahn et al. 2022).*

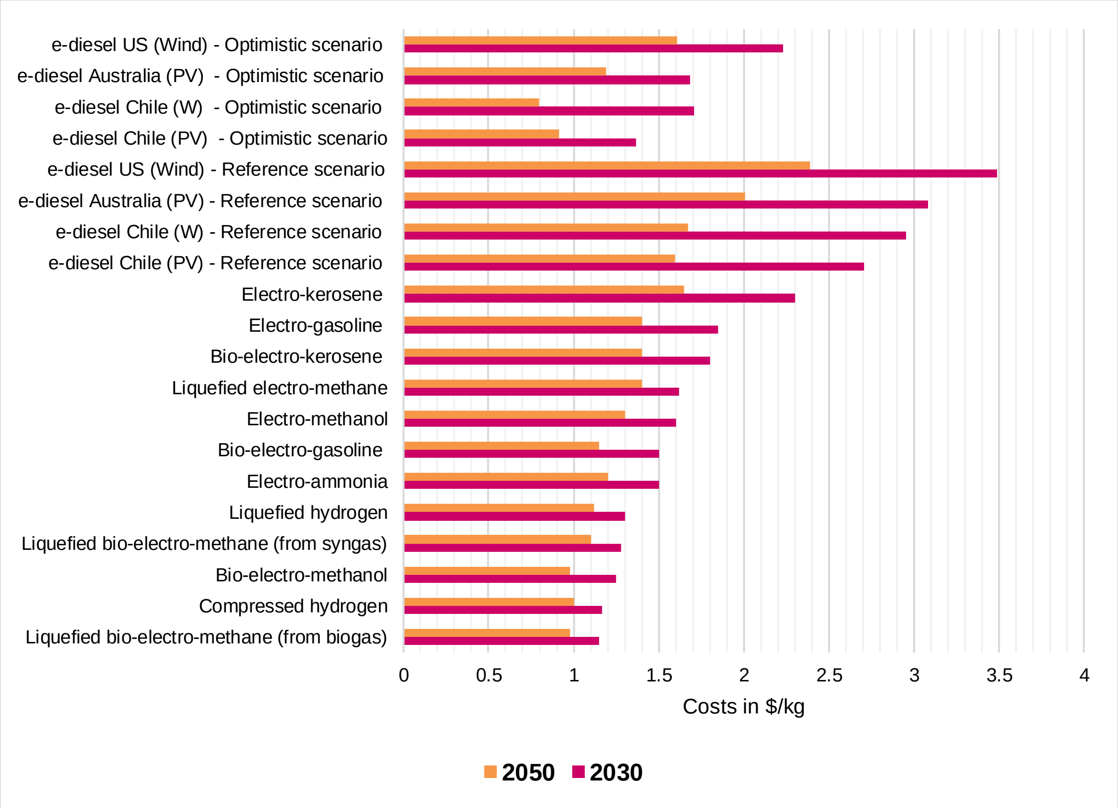
*** This source conducts a detailed analysis of the production costs associated with PtX (Power-to-X) products, such as e-diesel, focusing on North Africa as well as other regions. It employs a comprehensive model to calculate costs across various production stages, incorporating estimates for renewable energy costs as well (Andrea et al. 2018)).*

The average production cost for regions with very low renewable energy costs is projected to be 2.01 $/kg$_{(e\text{-}diesel)}$ in 2030, as indicated by various sources 2030 [(1): (Fasihi et al. 2016); (2): (Grahn et al. 2022); (3): (Andrea et al. 2018), in comparison with the 1.74 $/kg$_{(e\text{-}diesel)}$ average for the optimistic scenario in this study's model. Looking ahead to 2050, literature with conditions similar to those in this study presents production costs ranging from 0.92 $/kg$_{(e\text{-}diesel)}$ (MENA regions, worst-case scenario, (Grahn et al. 2022)) to 3.99 $/kg$_{(e\text{-}diesel)}$, (North Africa, average scenario, (Andrea et al. 2018) (see Figure 8).

The final comparison extends to evaluating the model results against alternative renewable fuels for the shipping sector, drawing on cost data sourced from pertinent literature. This comparative analysis aims to contextualize the competitiveness of e-diesel within the broader landscape of renewable fuels for maritime transport.

In Figure 9, production costs for various biofuels and e-fuels, calculated as averages from different sources, are presented and compared with the results of the model's optimistic and reference scenarios (Grahn et al. 2022; Kopp et al. 2017). Near-term production costs fall within the range of approximately 1.52 $/kg$_{(e\text{-}diesel)}$, with the lowest cost being 1.15 $/kg$_{(e\text{-}diesel)}$ for liquefied bio-methane produced with electricity from biogas, and the highest at 2.3 $/kg for e-kerosene through the methanol-to-jet process. The estimated costs for e-diesel production in the model are the highest, remaining uncompetitive even with other renewable alternatives for marine diesel until 2030.

Figure 9: Production costs for renewable fuels in 2030 and 2050



Source: Author's own illustration.

Figure 9 also illustrates that bio-e-fuels have lower production costs than their e-fuel counterparts. Although hydrogen is employed in producing all types of e-fuels it is noteworthy that the costs for hydrogen are not necessarily lower than those for e-fuels and bio-e-fuels when considering costs for liquefaction or compression. All analysed fuel options have the potential for production costs between 0.98 $/kg and 1.65 $/kg in the long term. Consequently, all renewable fuels maintain higher costs than e-diesel for the optimistic scenario in Chile's Patagonia (0.79 $/kg$_{(e\text{-}diesel)}$,). In the short- and long-term all e-fuels, except e-diesel, exhibit higher production costs than fossil diesel assuming an oil price of 0.73 $/kg for 2030 and 0.80 $/kg for 2050.

4. Sensitivity assessment

This section delves into a sensitivity analysis to further elucidate the robustness of the findings and identify key drivers impacting the economic efficiency of e-diesel production.

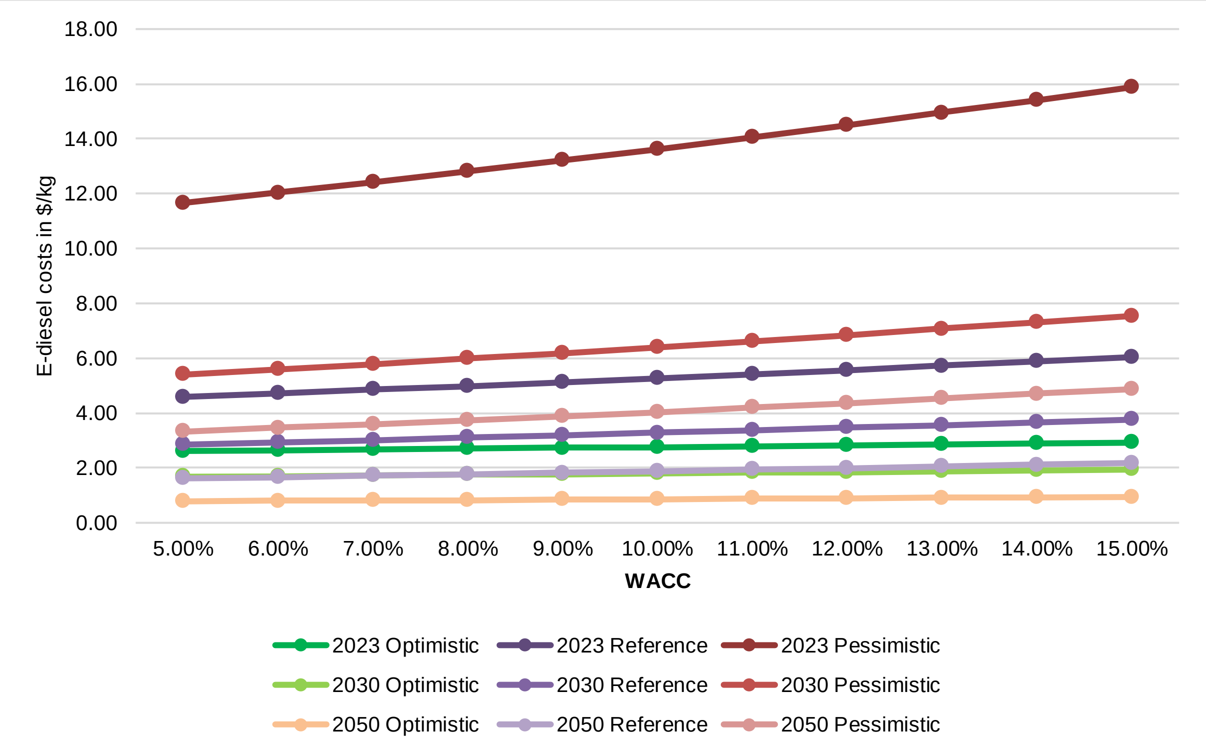
4.1 WACC

The first analyzed sensitivity analysis pertains to the adjustment of the Weighted Average Cost of Capital (WACC), a comprehensive measure encompassing a company's average after-tax cost of capital from diverse sources, including ordinary shares, preference shares, bonds, and other forms of debt. Essentially, the WACC reflects the average interest rate that a company is likely to have to pay to finance its business activities (Folger 2022).

In this case, the impacts of adjusting the WACC within the range of 5% to 15% for the four studied regions are investigated. The sensitivity analysis results, presented in figure 10, outline the impact on the production costs of e-diesel for the years 2023, 2030, and 2050 across the different scenarios (Optimistic, Reference, Pessimistic).

A consistent trend is observed, whereby higher production costs are associated with higher WACC values, highlighting the sensitivity of costs to changes in the cost of capital. In the optimistic scenario, lower WACC percentages are correlated with decreased production costs, while significantly higher costs are evident in the pessimistic scenario with higher WACC values.

Figure 10: Variation of e-diesel production costs in Chile, Patagonia for different WACC



Source: Author's own calculation and illustration.

These findings underscore the pivotal role played by the WACC in determining the economic viability and competitiveness of e-diesel production. The necessity for meticulous consideration of capital costs in future planning and decision-making is emphasized by these insights. While the WACC is not directly controlled by the government, its economic policy and regulatory decisions can have a significant indirect impact on the factors contributing to the WACC for companies operating within a specific jurisdiction. Variables such as interest rates, regulations, and tax policies can be influenced, highlighting the interconnected nature of economic policies and the e-diesel production landscape.

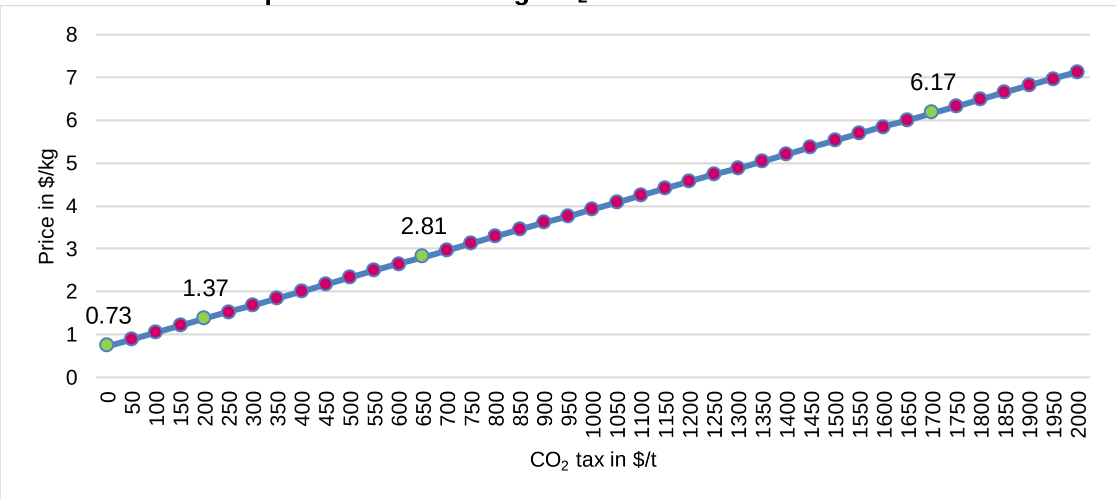
4.2 CO_2 Prices

The second presented sensitivity analysis revolves around the implementation of a carbon dioxide price on conventional marine diesel. As highlighted earlier, the primary motivation for integrating liquid e-fuels into the shipping sector lies in sustainability goals, aiming to reduce greenhouse gas (GHG) emissions and achieve carbon neutrality by 2050. To leverage this goal, it is essential to recognize that the current use of conventional marine diesel is environmentally harmful, and introducing a carbon price can potentially increase its costs.

Traditional diesel, currently in use, generates approximately 20.2 tons of carbon per terajoule ($t_{(C)}$/TJ), equivalent to 74.02 tons of CO_2 per terajoule ($t_{(CO2)}$/TJ). This translates to approximately 3.2 kg of CO_2 per kg of diesel ($kg_{(CO2)}$/ $kg_{(D)}$) (Fasihi et al. 2016). The introduction of a carbon tax emerges as a pivotal factor that can significantly impact the competitive landscape between conventional and e-diesel. To explore this impact, the model systematically escalates the carbon tax from 0 to 2000 \$/$t_{(CO2)}$, aiming to identify the threshold price at which e-diesel becomes competitive across the three scenarios.

In the short term (See Figure 11), particularly within both reference and pessimistic scenarios, it becomes evident that significantly elevated carbon prices are imperative, reaching figures of 618.75 \$/$t_{(CO2)}$ and 1700 \$/$t_{(CO2)}$, respectively. For the optimistic scenario, a minimum carbon price of 200 \$/$t_{(CO2)}$ until 2030 is identified as necessary to ensure its economic viability.

Figure 11: Marine diesel price with increasing CO_2 tax - 2030

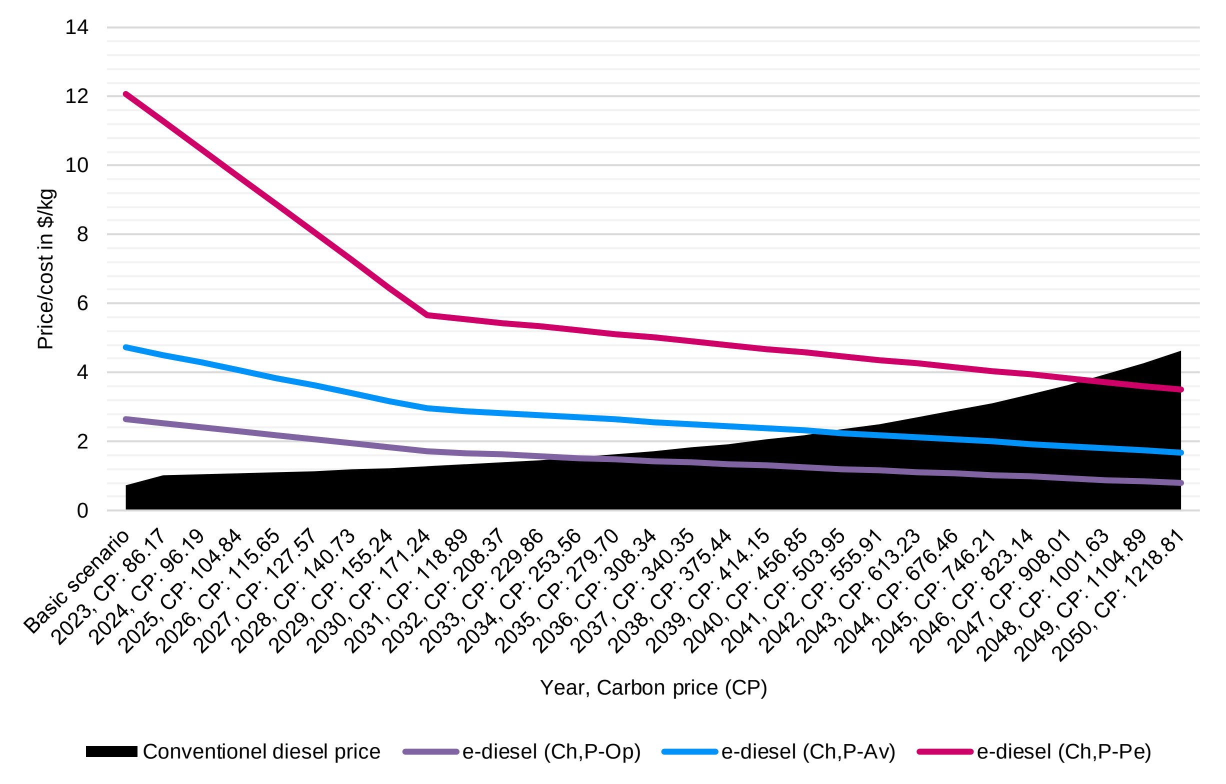


Source: Author's own calculation and illustration.

Examining the current global carbon pricing landscape reflects the challenges of imposing such higher carbon prices, especially in the pessimistic scenario. Indeed, Uruguay currently holds the highest global carbon tax at an initial rate of 137 \$/$t_{(CO2)}$. In Europe, Sweden leads with a carbon tax rate of 129.89 \$/$t_{(CO2)}$, followed by Switzerland and Liechtenstein (World Resources Institute 2021).

Based on estimated carbon pricing for the EU ETS according to Statista for the years 2024 and 2025, the projected costs for CO_2 until 2050 may show an exceptional increase. However, this may be considered a very optimistic approach. The graph below (Figure 12) indicates that the costs for e-diesel remain uncompetitive until 2034, even in the optimistic scenario, with a necessary carbon price of approximately 230 \$/$t_{(CO2)}$. For the reference scenario, a breakeven point is expected in 2040 for a carbon price of approximately 456 \$/$t_{(CO2)}$, and the pessimistic scenario remains uncompetitive until 2047, reaching a carbon price of more than 900 \$/$t_{(CO2)}$.

Figure 12: Marine diesel price with increasing CO_2 tax versus e-diesel production costs in Chile Patagonia



Source: Author's own calculation and illustration.

A more comprehensive strategy could involve incorporating financial support for saved CO_2. If e-diesel is produced from renewable energy, approximately 3.2 kg of CO_2 is mitigated for every 1.0 kg of e-diesel produced. For instance, at a CO_2 credit of 150 $\$/t_{(CO2)}$, costs are 0.48 $\$/t_{(CO2)}$ lower compared to the base case with no carbon price. This underscores the potential effectiveness of combining carbon pricing with financial incentives for carbon reduction in optimizing the economic viability of e-diesel production.

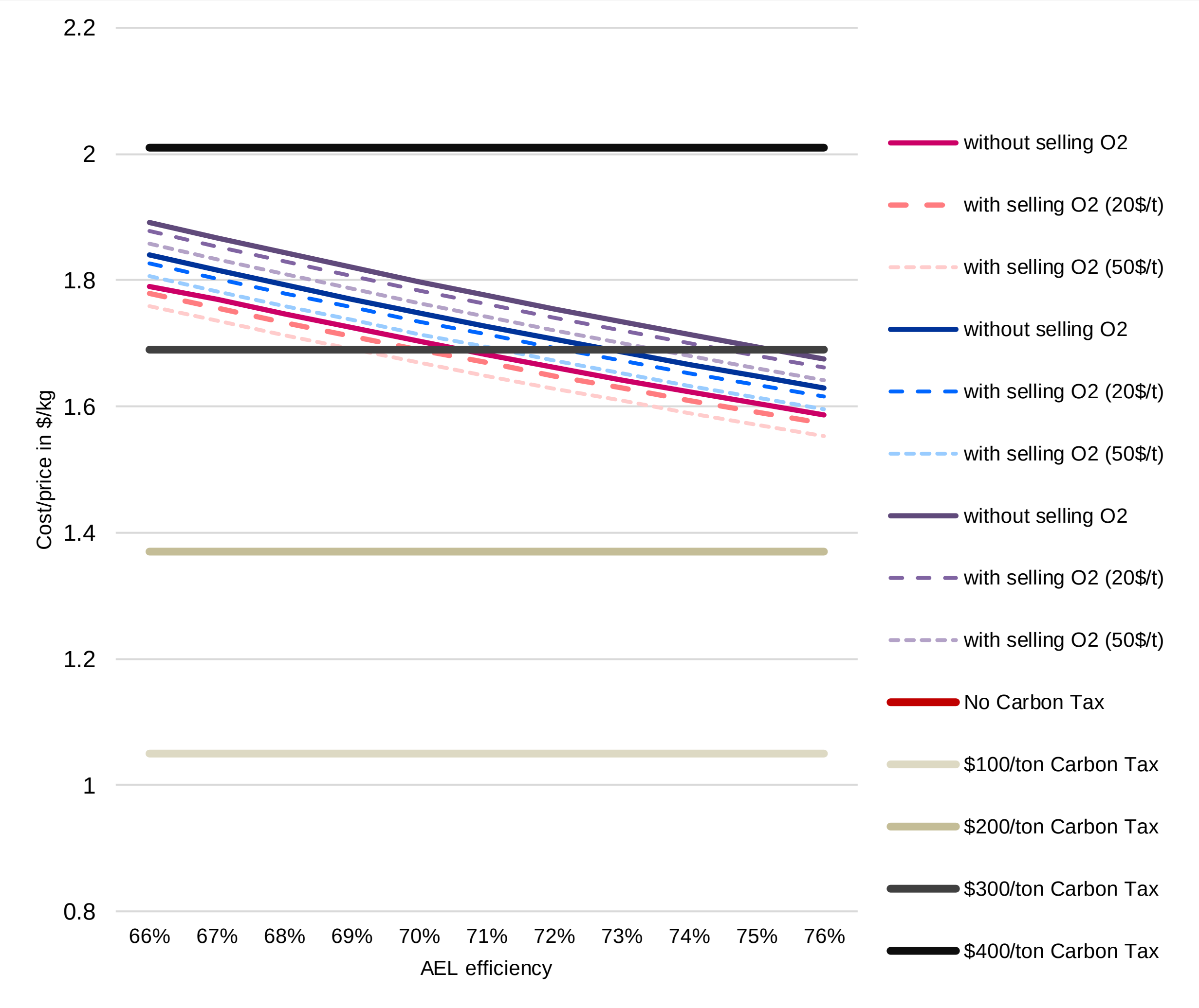
4.3 Multifaceted sensitivity assessment: Analysing the collective impact of various elements

As it has been shown, the viability of e-diesel in the shipping industry is influenced by various determinants. Consequently, the consideration of multiple elements becomes imperative to enhance its potential. One crucial aspect identified in the prior analysis is the breakdown of e-diesel costs, with approximately 70% being allocated to electricity needed for the hydrogen production through electrolysis. Thus, improving the efficiency of electrolysis can be a key strategy for potential cost reduction.

For this purpose, the efficiency of the electrolysis process (AEL) is increased from 66%, the lowest efficiency reported for 2030 in the literature, to 76%. Simultaneously, the WACC is varied across values of 5%, 7%, and 9%, while considering the potential of selling O_2 for 20 $\$/t_{(O2)}$ and 50 $\$/t_{(O2)}$. To assess the competitiveness of e-diesel, estimated prices for marine diesel were incorporated, factoring in an increasing CO_2 price ranging from 0 to 400 $\$/t_{(O2)}$ in the Figure 13 below.

The results, based on a nominal power of 750 MW for AEL with full load hours of 8000 (h/a) and an 80% efficiency for the Fischer Tropsch plant, as well as a nominal power of approximately 180 MW with full load hours of 8000 (h/a), demonstrate that a combination of the considered factors (WACC reduction, O_2 price of 50 $\$/t_{(O2)}$, and increased AEL efficiency to 76%) can decrease the required carbon price in 2030 from around 360 $\$/t_{(O2)}$ to 260$\$/t_{(O2)}$ .However, it's important to note that this optimistic price projection contrasts with expected EU ETS prices of around 75.6-81 $\$/t_{(O2)}$ (EIA 2023). Implementing such a carbon price globally, especially in Europe, might pose challenges given current market conditions showing variable carbon prices from less than 10 $/t$_{(O2)}$ (Ukraine, Estonia..) to more than 120 $/t$_{(O2)}$ (Liechtenstein). Additionally, considering the international nature of the shipping sector, efficient measurements are more likely to be conducted on an international scale rather than on a localized basis in specific countries.

Figure 13: Comparison of e-diesel and conventional marine diesel prices in $/kg in Chilean Patagonia - 2030 Optimistic scenario: Exploring varied efficiencies and considerations



Source: Author's own calculation and illustration.

To summarize, the economic analysis of e-diesel production highlights the challenges and opportunities associated with this nascent technology. While potential cost reductions can be expected through efficiency gains and learning effects, the current high production costs combined with external factors favoring conventional marine diesel, pose significant hurdles. Notably, crucial catalysts for reshaping the economic landscape of e-fuels emerge in the form of external interventions, such as policy incentives and carbon taxes.

Conclusion

E-fuels, in particular e-diesel, will have to play a key role in replacing fossil fuels in shipping and thus promote climate change mitigation in this sector. However, at present, it remains uncertain whether e-diesel will indeed be utilized in the coming years, further adding to the challenge of predicting its availability and usage (Foreticha et al. 2021). Challenges such as inefficiency, high costs, and the absence of a clear policy framework impede its widespread adoption (Neuling and Berks 2023).

This research work explores the sustainability of e-diesel for the shipping sector, examining factors beyond CO_2 emissions, such as electricity requirements, carbon dioxide sourcing, resource utilization, and socio-economic impacts. It emphasizes the need for renewable energy sources, closed carbon cycles, and consideration of local demands to ensure the sustainability of e-diesel in mitigating the shipping industry's environmental footprint. However, many challenges, such as high land requirements, water scarcity and socio-economic considerations, underscore the complexity of transitioning to liquid e-fuels and the need for careful evaluation and international standards.

When focusing on countries characterized by the lowest and most competitive costs of photovoltaic (PV) and wind power plants worldwide, the estimated costs to produce e-diesel vary across the identified regions and over time, with the LCOE playing a crucial role. The model developed in this paper underscores the persistently high costs of e-diesel, with projected reductions until 2030 deemed insufficient. Factors such as lower LCOE, technological advancements, and economies of scale are anticipated to contribute to cost reductions, albeit not to a significant extent. Until 2050, costs are projected to remain relatively high, particularly in the pessimistic scenario, while the optimistic scenario presents more favorable outcomes.

Despite the current high production costs and competition from conventional marine diesel, potential catalysts for change, such as policy incentives, present opportunities to reshape the economic landscape of e-diesel. The overall findings emphasize the necessity of government intervention to ensure the economic viability of e-diesel production, advocating for prompt action to support its successful market entry.

However, the current regulatory framework for e-fuels in shipping faces numerous challenges, including uncertainty, inadequacy, and a lack of international coordination (Foreticha et al. 2021). Public skepticism and political obstacles in developing countries further complicate the regulatory landscape (Neuling and Berks 2023). It is essential to recognize that the political role and governmental responsibilities in the shipping sector are intricate, given its international scope. Policy adjustments in this sector carry not only direct but also indirect global repercussions, underscoring the formidable challenge posed by the complexity involved (Foreticha et al. 2021). Acknowledging and addressing these challenges are crucial steps towards fostering a supportive environment for the transition to sustainable marine fuels.

Appendix A.1: Model and formula

The total costs for the production of e-diesel are estimated using the annuity method. The annuity factor is calculated using formula (1):

$$A = \frac{1-\left(\frac{1}{(1+WACC)^{a}}\right)}{WACC} \quad (0)$$

With:

a = number of periods

WACC = Weighted Average Cost of Capital. For each technology, the total investment costs should be divided by the annuity factor to obtain the investment costs per year. The technology is assessed by analyzing the cost per kilogram of e-diesel produced.

i. Water desalination costs

The costs linked to seawater desalination plants are determined in dollars per kilowatt-hour (kWh) of hydrogen produced. The formulation (1)for these costs is expressed as follows:

$$\dot{C}^{D}_{Water,el(H2)} = CAP\dot{E}X^{D}_{el(H2)} + OP\dot{E}X^{D}_{el(H2)} + \dot{C}^{D}_{Electricity,\,D(H2)} \quad (1)$$

The total annual costs comprise the summation of annual Capital Expenditure ($CAP\dot{E}X^{D}_{el(H2)}$), annual fixed operating Expenditure ($OP\dot{E}X^{D}_{el(H2)}$) and variable Operating Expenditure which encompasses electricity costs ($\dot{C}^{D}_{Electricity,\,D(H2)}$). The fixed operating costs ($OP\dot{E}X^{D}_{el(H2)}$) are presumed to constitute a fixed percentage p_{OPEX} of the annual investment costs.

$$OP\dot{E}X^{D}_{el(H2)} = CAP\dot{E}X^{D}_{el(H2)} \cdot p_{OPEX} \quad (2)$$

The electricity costs ($\dot{C}^{D}_{Electricity,\,D(H2)}(3)$) of the plants, are determined by multiplying the annual electricity demand ($\dot{E}\left[\frac{kWh}{m^3}\right]$) by the Levelized Cost of Electricity ($LCOE\ [\frac{\$}{kWh_{el}}]$). The annual electricity demand ($\dot{E}$) is calculated by multiplying the electricity demand per cubic meter of water ($E_W\left[\frac{kWh}{m^3}\right]$) and the annual water consumption ($W\left[\frac{m^3}{y}\right]$) in cubic meters per year. The annual water consumption ($\dot{W}\left[\frac{m^3}{y}\right]$) is equivalent to the desalinated water amount per output unit ($B_{Water}[\frac{m^3}{kWh_{H2(el)}}]$) multiplied by the annual production of hydrogen in kilowatt-hours per year ($\dot{Q}\ [\frac{kWh_{H2(el)}}{y}]$).

$$\dot{C}_{Electricity,D} = \dot{E} \cdot LCOE \quad (3)$$

$$\dot{E} = E_W \cdot \dot{W} \quad (4)$$

$$W = B_{Water} \cdot \dot{Q} \quad (5)$$

ii. Hydrogen costs

The calculation of the cost of one kilowatt-hour (kWh) of hydrogen (k_{H2}) involves dividing the total annual production costs of hydrogen ($\dot{C}^{H2}[\$.y^{-1}]$) by the quantity of hydrogen produced in kilograms per year ($\dot{Q}^{H2}[\frac{kg}{y}]$). This result is then multiplied by the caloric value of hydrogen ($\Delta_{H2}[\frac{kWh}{kg}]$), set at 33.33 $kWh.kg^{-1}$:

$$k_{H2} = \frac{\dot{C}^{H2}}{\dot{Q}^{H2}} \cdot \Delta_{H2} \quad (6)$$

The formula for the annual hydrogen production equals the summation of investment costs ($\dot{CAPEX}^{H2}, [\frac{\$}{y}]$), fixed operating costs ($\dot{OPEX}_{f.H2}, [\frac{\$}{y}]$), electricity costs ($\dot{C}^{H2}_{Electricity}, [\frac{\$}{y}]$) and water costs ($\dot{C}^{H2}_{Water}, [\frac{\$}{y}]$). It is expressed as follows:

$$\dot{C}^{H2} = \dot{CAPEX}^{H2} + \dot{OPEX}_{f.H2} + \dot{C}^{H2}_{Electricity} + \dot{C}^{H2}_{Water} \quad (7)$$

The annual CAPEX ($\dot{CAPEX}^{H2}$) are calculated by multiplying the nominal capacity power of the plant ($P_N, [MW]$) by the specific power costs ($c_p, [\frac{\$}{MWh}]$), and subsequently utilizing the annuity method.

$$\dot{CAPEX}^{H2} = P_N \cdot c_p \cdot \frac{WACC}{1-(1+WACC)^{-a}} \quad (8)$$

The fixed operating costs ($\dot{OPEX}_{f.H2}$) are assumed to represent a fixed percentage p_{OPEX} of the annual investment costs, with a variable rate depending on the scenario ranging from 2% to 9% with a relevant decrease over time.

$$\dot{OPEX}_{f.H2} = p_{OPEX} \cdot \dot{CAPEX}^{H2} \quad (9)$$

The calculation of the electricity costs ($C^{H2}_{Electricity}$) involves multiplying the full load hours ($T, [h]$) by the nominal power ($P_N, [MW]$) and by the LCOE expressed in $\frac{\$}{MWh}$:

$$\dot{C}^{H2}_{Electricity} = T \cdot P_n \cdot LCOE \quad (10)$$

The water costs ($\dot{C}^{H2}_{Water}$) are derived straightforwardly from the desalinated water costs per kilowatt-hour of hydrogen output, multiplied by the quantity of hydrogen produced per year ($\dot{Q}^{H2}, [\frac{kWh}{y}]$):

$$\dot{C}^{H2}_{Water} = C^{D}_{Water,el(H2)} \cdot \dot{Q}^{H2} \quad (11)$$

The annual quantity of hydrogen produced ($\dot{Q}^{H2}$) is contingent upon the efficiency of the plant ($\eta, [\%]$), the full load hours ($T, [h]$), the nominal power of the plant ($P_n, [MW]$) and the number of electrolyzers in operation (n).

$$\dot{Q}^{H2} = \eta \cdot T \cdot P_n \cdot n \cdot 1000 \quad (12)$$

The efficiency of the plant ($\eta, [\%]$), the full load hours ($T, [h]$) as well as the nominal power of the plant ($P_n, [MW]$) are scenario-dependent, exhibiting notable advancements over time and contributing to the reduction of costs.

iii. Direct air capture costs

The aggregate costs of capturing one ton of CO_2 ($C^{DAC}_{CO2}, \left[\frac{\$}{t_{CO2}}\right]$) involve the summation of the CAPEX costs ($CAPEX^{DAC}_{tCO2}, [\frac{\$}{t_{CO2}}]$), fixed operating costs ($OPEX^{DAC}_{tCO2}, [\frac{\$}{t_{CO2}}]$), electricity costs ($C^{DAC}_{el,\,tCO2}, [\frac{\$}{t_{CO2}}]$), heat costs ($C^{DAC}_{Heat,\,tCO2}, [\frac{\$}{t_{CO2}}]$), and water costs ($C^{DAC}_{Water,\,tCO2}, [\frac{\$}{t_{CO2}}]$) per ton of CO_2 captured.

$$C^{DAC}_{CO2} = CAPEX^{DAC}_{tCO2} + OPEX^{DAC}_{tCO2} + C^{DAC}_{el,\,tCO2} + C^{DAC}_{Heat,\,tCO2} + C^{DAC}_{Water,\,tCO2} \quad (13)$$

The fixed operating costs ($O\dot{PEX}^{DAC}_{tCO2}$) are assumed to represent a fixed percentage p_{OPEX} of the annual investment costs, with a variable rate depending on the year decreasing from 6% to 4% until 2050.

$$OPEX^{DAC}_{tCO2} = CAP\dot{E}X^{DAC} \cdot p_{OPEX} \tag{14}$$

The electricity costs ($C^{DAC}_{el,tCO2}$) are determined by multiplying the electricity consumption per ton of CO_2 produced (E^{DAC}, $[\frac{kWh}{t_{CO2}}]$) with the $LCOE$:

$$C^{DAC}_{el,tCO2} = E^{DAC} \cdot LCOE \tag{15}$$

The heat costs ($C^{DAC}_{Heat,tCO2}(16)$) are computed by utilizing the $LCOE$ with a conversion efficiency of 90% from electricity to heat and a conversion ratio of 3.6 from GJ to kWh, taking into account the heat consumption of the plant per ton of CO_2 produced (H^{DAC}, $[\frac{GJ}{t_{CO2}}]$):

$$C^{DAC}_{Heat,tCO2} = H^{DAC} \cdot \frac{LCOE}{0.9 \cdot 3.6} \tag{16}$$

The water costs ($C^{DAC}_{Water,tCO2}$, (17)) are determined by multiplying the water consumption per ton of CO_2 (W^{DAC}, $[t_{H2O}.t^{-1}_{CO2}]$) with the water costs per ton (P^W, $[\frac{\$}{t_{H2O}}]$):

$$C^{DAC}_{Water,tCO2} = W^{DAC} \cdot P^W \tag{17}$$

iv. E-diesel production costs

The costs per kg e-diesel produced (c^{eD}, $\left[\frac{\$}{kg_{eD}}\right]$ (18)) are determined by dividing the total yearly costs ($\dot{C}^{eD}$, $[\frac{\$}{kg_{eD}}]$) by the total quantity of e-diesel produced per year ($\dot{M}_{e\_fuel}$, $[\frac{kg}{y}]$), and can be expressed as follows:

$$c^{eD} = \frac{\dot{C}^{eD}}{\dot{M}_{eD}} \tag{18}$$

The percentage (p_{eD}[%]) represents the highest proportion of e-diesel in the end product reported in the literature [Mah16]. Consequently, the yearly quantity of e-diesel produced ($\dot{M}_{eD}$) is determined by multiplying the factor (p_{eD}) with the total output of the fuel synthesis ($\dot{M}^{e\_fuel}$, $[\frac{kg}{y}]$).

The overall output of the fuel synthesis ($\dot{M}^{e\_fuel}$) is contingent upon the efficiency of the Fischer-Tropsch process (η_{FT}, [%]), the total load hours of the plant (T_{FT}, $[h]$), the nominal power of the plant (P_{FT}, $[MW]$), the caloric value of e-diesel (Δ_{FT}, $[\frac{kg}{kWh}]$) and the number of plants in operation (n_{FT}).

$$\dot{M}_{eD} = p_{eD} \cdot \dot{M}^{e\_fuel} \tag{19}$$

$$\dot{M}^{e\_fuel} = \frac{\eta_{FT}}{\Delta_{FT}} \cdot T_{FT} \cdot P_{FT} \cdot n_{FT} \tag{20}$$

The total yearly costs ($\dot{C}^{eD}$, $\left[\frac{\$}{y}\right]$) are the sum of the total CAPEX ($CAP\dot{E}X_{FT,f}$, $[\frac{\$}{y}]$), the annual fixed operating costs ($O\dot{P}EX_{FT,f}$, $[\frac{\$}{y}]$), the annual electricity costs ($\dot{C}_{El,FT,v}$, $[\frac{\$}{y}]$), the annual hydrogen costs ($\dot{C}_{H2}$, $[\frac{\$}{y}]$), the annual carbon dioxide costs ($\dot{C}_{CO2}$, $[\frac{\$}{y}]$) and the annual hydrogen storage costs ($\dot{C}_{H2,S}$, $[\frac{\$}{y}]$):

$$\dot{C}^{eD} = CAP\dot{E}X_{FT,f} + O\dot{P}EX_{FT,f} + \dot{C}_{El,FT,v} + \dot{C}_{H2} + \dot{C}_{CO2} + \dot{C}_{H2,S} \tag{21}$$

$$O\dot{P}EX_{FT,f} = p_{OPEX,FT} \cdot CA\dot{P}EX_{FT,f} \quad (22)$$

The electricity costs ($\dot{C}_{el,FT,v}$) are calculated by multiplying the annual electricity demand ($\dot{E}_{FT}$, $[\frac{kWh}{y}]$), derived from the required amount of electricity per ton of Fischer-Tropsch (FT) output and assumed to be constant as per literature, with the $LCOE$.

$$\dot{C}_{el,FT,v} = \dot{E}_{FT} \cdot LCOE \quad (23)$$

The annual hydrogen costs ($\dot{C}_{H2}$) depend on the hydrogen production costs (c_{H2}, $[\frac{\$}{kg_{H2}}]$) and the quantity of hydrogen required per kg of output ($\dot{M}_{e_{fuel}}$, $[\frac{kg}{y}]$). This is therefore influenced by the efficiency (η_{FT}, [%]) of the FT plant.

$$\dot{C}_{H2} = \frac{c_{H2} \cdot \dot{M}_{e_{fuel}}}{\eta_{FT}} \quad (24)$$

The annual carbon dioxide costs ($\dot{C}_{CO2}$) are determined by multiplying the total output of e-fuel synthesis ($\dot{M}_{e_{fuel}}$, $[\frac{kg}{y}]$) with the carbon dioxide demand per kilogram of output produced (B_{CO2}, $[\frac{kg_{CO2}}{kg_{efuel}}]$), and the carbon costs per kilogram of carbon dioxide (c_{CO2}, $[\frac{\$}{kg_{CO2}}]$).

$$\dot{C}_{CO2} = \dot{M}_{e\_fuel} \cdot B_{CO2} \cdot c_{CO2} \quad (25)$$

The annual stored quantity of hydrogen is calculated as the difference between the quantity of hydrogen produced ($\dot{Q}$, $[kg_{H2}. y^{-1}]$) and the amount required for the FT process with considering the remaining quantity of stored hydrogen from the previous years (I^{H2}, $[kg]$).

$$\dot{C}_{H2,S} = \; = (I^{H2} + \dot{Q} - \frac{\dot{M}_{e_{fuel}}}{\eta_{FT}}) \cdot \; c_S \quad (26)$$

With:

c_S = costs for storing one kg of hydrogen.

Appendix A.2

Table A.2: Selected worldwide PtX projects

Project name	Location	Products	Quantities in tons/y	Concerned sectors	Year
Arcadia e-fuels	Copenhagen	eKerosene and e-Diesel	75000	Shipping and aviation	2025
Bilbao Decarbonization Hub	Spain	E-fuels via FT	2337.5		2024
FlagshipONE	Sweden	eMethanol	50,000	Shipping sector	2023
INERATEC Pioneer Plant	Germany	Liquid e-fuels	3910	Aviation	2024
ReuZe Project	France	eKerosine and e-Diesel	More than 100,000	Shipping and Aviation	2026
Atmosfair Fairfuel	Germany	eKerosene	350	Aviation	2022
CAC Synfuel Plant	Germany	eGasoline und eKerosene	850		2030
Infinium Electrofuels Corpus Facility	United states	eKerosene and e-Diesel	11465	Shipping and Aviation	2023
Nordic Electrofuel - Plant 1	Norway	eKerosene	2025: 3.47, 2026: 8.93	Aviation	2024
Synhelion Solar Fuels	Germany	eKerosene, eGasoline, and e-Diesel	10000	Synhelion Solar Fuels	
Bell Bay Powerfuels Project	Tasmania, Australia	eMethanol	70.000		2024
Demonstration Plant Haru Oni	Chile	e-Methanol, e-gasoline	440.5 eGasoline and 350 eMethanol		2023
HIF Matagorda	United States	Green Hydrogen	300,000		2027
Norsk e-Fuel Alpha	Norway	FT liquid e-fuels	2024: 10.63 2026: 21.25		2024
Synhelion Solar Fuels Spain	Spain	eKerosene, eGasoline, and e-Diesel	425	Synhelion Solar Fuels Spain	

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