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The economics and greenhouse gas emissions of renewable hydrogen and e-fuels imported in the European Union

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INTRODUCTION

Under the European Climate Law, the European Union (EU) must reduce its greenhouse gas (GHG) emissions by 55% from 1990 levels by 2030 and reach climate neutrality by 2050. To reduce GHG emissions from certain transport sectors that will be hard to decarbonize, such as aviation and maritime, low-GHG alternative fuels will be critical. A 2023 ICCT paper described the policy support for these fuels in the European Union's "Fit for 55" energy and climate package (Baldino, 2023). Renewable hydrogen (i.e., hydrogen produced via electrolysis from 100% renewable electricity) and its derivatives, known as electrofuels (e-fuels), receive support in several EU fuels policies due to their high decarbonization potential and possible application in different sectors.

While renewable hydrogen and e-fuels can have close to zero GHG emissions if produced with 100% renewable electricity, there is a risk that this electricity could be diverted from decarbonizing the power sector. To mitigate such risks, the European Union has adopted rules to ensure that renewable fuels of non-biological origin (RFNBOs) used to meet EU fuels targets—whether sourced domestically or imported—are produced with renewable electricity that is additional to that needed for the renewable energy target for the power sector. Additionally, as RFNBO production requires a great amount of electricity and can thus burden the electricity grid, EU legislation also requires temporal and geographic matching requirements that aim to reduce the risk that demand for renewable hydrogen will be compensated by an increase in fossil electricity.

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This study assesses the economic costs and climate impacts of importing renewable hydrogen and e-fuels into the European Union. We focus on Brazil and Egypt, with which the European Union has recently expanded engagement in renewable hydrogen production and export. We estimate the cost of producing RFNBOs and exporting them from these countries to the European Union as compared with the cost of EU Member States producing these fuels domestically. Further, we assess the GHG emissions associated with the production of RFNBOs in Brazil and Egypt and their shipment to the European Union under two scenarios: one in which verification schemes ensure compliance with EU additionality and matching requirements, and one in which such requirements are not met.

POLICY CONTEXT

In EU transport policy, the revised Renewable Energy Directive (RED III), adopted in 2023, includes a target for 5.5% of the energy used in the transport sector to come from advanced biofuels or RFNBOs, which include renewable hydrogen and e-fuels (European Commission, 2023a). The RED III provides a 2x multiplier for RFNBOs and an additional 1.5x multiplier when such fuels are used in the maritime or aviation sector. The ReFuelEU Aviation regulation also sets a mandate for synthetic fuels in aviation, which include RFNBOs, starting in 2030. To help meet these targets, EU Member States have shown interest in importing renewable hydrogen and e-fuels from abroad. The REPowerEU plan sets a 10 million tonne target for renewable hydrogen imports by 2030 (European Commission, 2022b).

E-fuels can be produced by combining electrolysis hydrogen with carbon dioxide. Liquid e-fuels (e.g., e-diesel, e-gasoline, and e-kerosene) are drop-in fuels, meaning they are fully compatible with existing fueling infrastructure and internal combustion engines, avoiding the costs of retrofitting or building new infrastructure. However, to produce e-fuels, roughly half of the energy from electricity is lost during the conversion process. Thus, producing RFNBOs with even a small share of fossil fuels in the electricity mix can lead to significant GHG emissions, as the impacts of the fossil carbon intensity are amplified due to energy losses (Zhou et al., 2021; Zhou et al., 2022). Moreover, while renewable hydrogen and e-fuels can have close to zero GHG emissions if produced with 100% renewable electricity, there is a risk that this electricity could be diverted from decarbonizing the power sector and cause indirect GHG emissions.

To mitigate unwanted climate impacts of renewable hydrogen and e-fuels production, the European Union implements three basic rules for renewable electricity sourced over the electricity grid. A 2023 ICCT policy update (Baldino, 2023) discussed these rules. In summary:

1. **Additionality:** Producers of RFNBOs are required to have power purchase agreements with renewable power generators except when the grid-average electricity exceeds 90% renewable electricity. Starting in 2028, if the average GHG intensity of grid electricity in the bidding zone[1] is higher than 18 gCO_2e/MJ, then the producer must also demonstrate that the renewable energy facility does not receive state aid and does not go into operation earlier than 36 months before RFNBO production begins.
2. **Temporal matching:** Producers must demonstrate that RFNBOs were produced at the same time as the renewable electricity production. This matching is determined on a monthly basis up to 2030 and on an hourly basis after that year.

1 A bidding zone is the largest geographic area where electricity producers and consumers can submit bids and offers for electricity trading without allocating cross-zonal capacity.

3. **Geographic matching:** The site of RFNBO production and the renewable electricity installation must be in the same or in nearby bidding zones.

The additionality rule helps ensure that in regions without abundant renewable electricity, the renewable energy installation used to supply electricity for electrolysis would not have been built without the hydrogen production. The two matching rules connect hydrogen production to renewable energy generation in time and place, reducing the risk that high demand from the electrolyzer will lead to an increase in fossil electricity.

While these requirements are for RFNBOs produced with electricity sourced from the grid, RFNBOs can also be produced via a direct connection to a renewable generator. In this case, the EU legislation only requires the demonstration of additionality (i.e., that the renewable facility went into operation no earlier than 36 months before the RFNBO facility). Any renewable fuels, including RFNBOs, that are imported and counted towards the RED III target must comply with a certification scheme that verifies adherence to these requirements, and the RFNBO producer is audited for compliance with the scheme by an independent auditor.

The ICCT has published multiple studies evaluating the costs of renewable hydrogen and e-fuels produced domestically in the European Union (Zhou et al., 2022; Zhou & Searle, 2022), and the GHG emissions generated when the renewable electricity used in RFNBO production is not additional (Zhou et al., 2021). In this paper, we use the same methodology to assess the costs and climate impacts of importing renewable hydrogen and e-fuels to the European Union. Several EU Member States have identified North Africa and South America as regions with great potential for producing and exporting RFNBOs. We focus on Egypt and Brazil, which have attracted growing interest from the European Union for their high renewable resource production and export potential. Egypt and the European Union have announced a long-term partnership on renewable hydrogen (European Commission, 2022a), and Egypt is aiming to reach 5% to 8% of the global hydrogen market by 2040 (State Information Service, 2023). Brazil has signed agreements with multiple countries related to the export of renewable hydrogen (Uchôa, 2021), and the European Union has announced plans to invest €2 billion to support Brazil's renewable hydrogen production (European Commission, 2023b).

METHODOLOGY

In this study, we consider a direct connection for RFNBO production in both Brazil and Egypt, meaning it is directly connected to a renewable generator. Changes or additions to how renewable electricity is delivered over the grid in these countries might be needed to meet EU requirements for grid connection; however, the cost impact of these matching requirements is not considered in this assessment. We then estimate the GHG emissions associated with the production and shipment of the renewable hydrogen and e-fuels to the European Union if RFNBO production requirements were to be met, as well as if verification schemes did not properly ensure compliance with the requirements.

COST METHODOLOGY

The cost of importing hydrogen and e-fuels includes two main components: the cost of fuel production and the cost of shipment. We estimated renewable hydrogen and e-fuel production cost in Brazil and Egypt using a discounted cash flow model developed for previous ICCT analyses that estimates the levelized production cost of fuel in a region or country. The model considers the capital and operational costs of investing in a new facility and estimates the required selling price of the product for the investment to be economically viable.

For the cost of renewable hydrogen, electricity costs and capital costs of the electrolyzer system are the two main contributing factors. A previous ICCT study conducted a literature review on the uncertainties of capital costs and evaluated the impact of these expenditures on the production cost of renewable hydrogen, setting out three scenarios for the electrolyzer cost: Optimistic, Mid-level, and Pessimistic (Christensen, 2020). Past ICCT analyses have considered the Mid-level scenario as the representative case. However, more recent studies have reported higher capital costs than previously projected, especially in the European Union and the United States, due to interrupted supply chains, labor shortages, and inflation (Hydrogen Council, 2023; International Energy Agency, 2023a).

Therefore, in this study, we analyzed both the Mid-level and Pessimistic scenarios for estimating the capital cost of renewable hydrogen. Table 1 shows these costs by year, scenario, and electrolyzer type. These costs were adjusted for inflation and a 1.2x contingency factor that accounts for unforeseeable expenses based on the values from Christensen (2020).[2] The Pessimistic scenario would align with recent capital cost data ranging from €1,200 to €2,840 per kilowatt (Eble & Weeda, 2024).

Table 1

Electrolysis hydrogen capital cost by electrolyzer type under the Mid-level and Pessimistic scenarios

	Scenario	Alkaline electrolyzer (€/kW)	Proton exchange membrane (€/kW)	Solid oxide electrolyzer (€/kW)
2023	Mid-level	1,185	1,418	1,614
	Pessimistic	1,498	2,443	2,699
2030	Mid-level	1,029	1,231	1,402
	Pessimistic	1,255	2,046	2,261
2040	Mid-level	841	1,006	1,145
	Pessimistic	974	1,588	1,755
2050	Mid-level	687	822	936
	Pessimistic	756	1,233	1,362

Note: Values are in 2023 euros.

While most of the model inputs for renewable electricity, renewable hydrogen, and e-fuel cost estimation can be found in previous studies (Zhou et al., 2022; Zhou & Searle, 2022), we collected additional information on capacity factors and financial assumptions to project country-specific fuel costs for Brazil and Egypt.

The capacity factor determines how often a plant can run at full power and has a large impact on levelized fuel production costs. It is largely impacted by the local availability of renewable resources and technology. We collected current country-specific capacity factors for Brazil and Egypt and projected the increase of the factors over time due to technology improvements, as shown in Table 2 (International Renewable Energy Agency, 2018; Operador Nacional do Sistema Elétrico, 2022; The World Bank Group, 2023). These capacity factors reflect national-level assessments and do not consider regional differences within the country. To produce renewable hydrogen through a direct connection, it would be most cost efficient if the facility were located close to where renewable resources are most abundant, as the capacity factor of the hydrogen plant would be restrained by the capacity factor of the renewable generator.

2 The exchange rate assumed in this study is $1 = €0.9.

Table 2
Capacity factors of solar and wind in Brazil and Egypt

	Brazil		Egypt	
	Solar	Wind	Solar	Wind
2023	23.3%	44.8%	20.7%	31.3%
2030	24.4%	46.7%	22.5%	34%
2040	25.4%	48.6%	23.5%	35.4%
2050	26.4%	50.6%	24.4%	36.8%

Financial assumptions also affect the estimated levelized production cost of electricity and fuels. We collected debt, interest rate, and return rate information for renewable projects in Brazil and Africa from the International Energy Agency (2023b). As conditions were similar for the two regions, we chose middle values for these variables and applied them for both Brazil and Egypt, as shown in Table 3. We note that an interest rate of 9% is lower than typical market rates in Brazil, but the Brazilian government's Climate Fund Program provides financing for renewable energy projects, which can include loans at lower interest rates (Brazilian Development Bank, 2010). Since renewable hydrogen production is a new, emerging technology and can be riskier than renewable electricity projects, we assume a higher equity return required.

Both Egypt and Brazil recently adopted policies to provide incentives for renewable hydrogen projects. In Egypt, Law No. 2 of 2024, passed in January 2024, offers several tax and non-tax incentives for such projects, including a 33% to 55% income tax credit, a value-added tax exemption on necessary machines and raw materials, a value-added tax exemption on exports, and the rights to directly import materials and export products (Deloitte, 2024). In Brazil, Law No. 14,948/2024, passed in August 2024, establishes a regulatory framework for low-carbon hydrogen that includes incentives. For example, low-carbon hydrogen producers can access incentive debentures that are subject to lower taxation, indicating they probably could receive a lower interest rate, such as the one we assume in this study. Separately, Bill No. 3027/2024, now under consideration, would establish a refundable tax credit for hydrogen producers and set a cap on the total credit amount in the Union Budget, though details on how producers can benefit from such credits have not yet been released (Mattos Filho, 2024; Senado, 2024).

To understand the potential impact of incentives on RFNBO projects, we estimated fuel production costs for each country including and excluding these financial incentives. For Egypt, we estimated the costs for one scenario without any tax credits, and another with the maximum 55% tax credit (Table 3). For Brazil, due to the ambiguity of tax credit rules, we did not consider a tax credit but rather a reduction of the discount rate from 9.3% to 7%—the same assumed for the European Union in Zhou & Searle (2022)—to reflect incentive debentures. Other types of incentives that we did not include in this analysis might further reduce fuel production costs in the two countries.

Table 3

Financial assumptions for renewable electricity and hydrogen projects in Brazil and Egypt

	Renewable electricity	Renewable hydrogen and e-fuels
Debt-to-equity ratio	60%:40%	
Loan interest rate	9%	
Loan term	15 years	
Return on equity	13%	16%
Weighted average of capital cost (i.e., discount rate)	8%	Egypt: 9.3% Brazil: 9.3% or 7%
Corporate tax rate	22.5%	
Tax credit	0%	Egypt: 0% or 55% deduction Brazil: 0%

As many of the planned renewable hydrogen projects in Egypt and Brazil are located at ports (Uchôa, 2021; Matalucci, 2022), the fuel shipment cost would essentially be the shipping cost between the exporting and importing port. Assuming the port of Rotterdam as the importing port, the shipping distance from northern Egypt, near the Suez Canal, is 3,160 nautical miles (5,850 km) and from northeastern Brazil is 4,180 nautical miles (7,800 km; Sea-distances, 2023).

Hydrogen can be shipped in multiple forms. The three most discussed are liquid hydrogen, ammonia (NH_3), and liquid organic hydrogen carriers. Previous studies generally agree that shipping hydrogen in the form of ammonia is relatively cost efficient, especially over long distances (Al-Breiki & Bicer, 2020; Hank et al., 2020; International Energy Agency, 2019; International Renewable Energy Agency, 2022; Johnston et al., 2022). Moreover, both Egypt and Brazil are pursuing plans to export hydrogen as ammonia (Matalucci, 2022). For example, in July 2024, Germany awarded a contract to import green ammonia, which is produced using renewable energy sources, from Egypt into Germany (Amelang, 2024). Therefore, in this study, we assume ammonia as the hydrogen carrier for shipping.

We included the costs of converting the hydrogen into ammonia, shipping the ammonia, and reconverting the ammonia into hydrogen at the receiving port in the hydrogen shipment cost. Converting hydrogen into ammonia can be done through Haber-Bosch process, a mature technology applied widely in ammonia production that combines hydrogen with nitrogen that can be retrieved from the atmosphere through an air separation unit. We based the capital cost (€900/kW NH_3, including the air separation unit), energy efficiency (84%), and electricity demand (800 kWh/t NH_3) on previous studies and added these inputs to the renewable hydrogen discounted cash flow model (Nayak-Luke & Bañares-Alcántara, 2020; Fasihi et al., 2021; Arnaiz del Pozo & Cloete, 2022; Bose et al., 2022; International Renewable Energy Agency, 2022). We also included a levelized short-term hydrogen storage cost of €0.65/kg hydrogen at the ammonia plant (Christensen, 2020). The cost of storing ammonia is included in the shipping cost below.

Ammonia can be shipped in conventional tankers or ammonia-fueled ships. As the latter are still in development and are unlikely to be widely adopted in the next few years due to technological, economic, safety, and regulatory barriers, we assumed all shipping is via conventional tankers. We adopted an average levelized ammonia shipping cost of €0.058/kg hydrogen per 1,000 km from previous studies

(International Energy Agency, 2019; Fasihi et al., 2021; Salmon et al., 2021; Johnston et al., 2022). This cost includes the short-term storage of ammonia at the terminal, port cost, and vessel cost. The Port of Rotterdam is already equipped with ammonia terminals (Port of Rotterdam, 2021), and we therefore did not consider infrastructure retrofitting costs.

We assumed ammonia would be reconverted into hydrogen at the importing port via a process known as ammonia cracking. Based on cost information from previous studies, we assumed an average levelized cost of ammonia cracking of €1.4/kg hydrogen (International Energy Agency, 2019; International Renewable Energy Agency, 2022; Oxford Institute for Energy Studies, 2022). The capital cost of ammonia cracking could potentially decrease in the future with economies of scale; however, the costs of heat and electricity, which are energy inputs to the process, are likely to increase (International Renewable Energy Agency, 2022). Given these uncertainties, we assume constant ammonia cracking costs for all future years.

Table 4
Data assumptions of hydrogen derivatives production

<table>
<tr><th></th><th>Ammonia</th><th>E-fuels</th></tr>
<tr><td>Efficiency of converting from hydrogen</td><td>84%</td><td>73%</td></tr>
<tr><td>Capital costs (2023€/kW) until 2030</td><td rowspan="2">900[a]</td><td>900</td></tr>
<tr><td>Capital costs (2023€/kW) after 2030</td><td>405</td></tr>
<tr><td>Fixed operational costs</td><td colspan="2">4% of capital costs</td></tr>
<tr><td>Levelized hydrogen storage cost (€/kg H_2)</td><td colspan="2">0.65</td></tr>
<tr><td>Electricity demand (kWh/kg NH_3)</td><td>0.8</td><td></td></tr>
<tr><td>CO_2 demand (kg CO_2/kWh)</td><td></td><td>0.32</td></tr>
<tr><td>CO_2 price from point source (€/tonne)</td><td></td><td>36</td></tr>
</table>

[a] Includes the air separation unit that captures nitrogen from the atmosphere
Sources: Christensen & Petrenko (2017); Brynolf et al. (2018); Nayak-Luke & Bañares-Alcántara (2020); Fasihi et al. (2021); Arnaiz del Pozo & Cloete (2022); Bose et al. (2022); Brynolf et al. (2022); International Renewable Energy Agency (2022); Christensen (2020)

In contrast to ammonia production via the Haber-Bosch process, which is relatively mature, e-fuel production using the Fischer-Tropsch process is at an early stage, and we thus assume high capital cost in the near term and lower cost in the future (Brynolf et al., 2018). CO_2 cost can impact e-fuel production cost significantly. CO_2 can be captured and supplied from two types of sources: a concentrated point source, such as an industrial source (e.g., steel production), and direct air capture (DAC). The cost of CO_2 from a point source can be relatively low and tends to vary little. In contrast, the cost of CO_2 from DAC is highly uncertain, ranging from €100 to over €1,000 per tonne of CO_2 (Keith et al., 2018; Becattini et al., 2021; International Energy Agency, 2022a; Sievert et al., 2024). In this study, we consider an Optimistic and a Pessimistic scenario for DAC CO_2 cost based on projected ranges from previous studies, as shown in Table 5.

Table 5
Direct air capture cost assumptions

	CO_2 price from direct air capture (2023€/tonne)	
	Optimistic	Pessimistic
2023	880	
2030	230	753
2040	185	603
2050	140	480

We aligned our assessment of e-fuel cost with the rules for how to account for GHG emissions from point source and DAC in the European Commission Delegated Regulation, which is part of the RED II and the RED III. Under this Delegated Regulation, fossil-sourced CO_2 captured from power stations for use in e-fuel production is considered zero emissions until 2036, and CO_2 captured from all other fossil industrial sources is considered zero emissions until 2041, as long as the carbon has been subject to an effective carbon pricing system. Thereafter, DAC or biogenic point sources complying with specific requirements outlined in the rules for RFNBO GHG accounting must be used (Delegated Regulation [EU] 2023/1185). In December 2024, Brazil passed Law 15.042/2024, which establishes a carbon market in the country (Chamber of Deputies of Brazil, 2024), so we modeled e-fuels produced in Brazil using both point source CO_2 (biogenic after 2040) and DAC. Egypt does not have a carbon pricing system, so we only considered DAC for e-fuel production.

Since e-fuels are chemically similar to petroleum, we assumed the shipping of e-fuels to cost the same as shipping of petroleum products. Specifically, we assumed a shipping cost of €0.012 per kilogram of e-fuels per 1,000 kilometers (U.S. Environmental Protection Agency, 2016; UN Trade & Development, 2021). This levelized shipping cost includes the vessel fees and necessary surcharges, such as port costs and insurance.

For comparable results with our previous cost estimates of RFNBOs produced domestically in the European Union, we did not consider any further distribution and processing costs, such as hydrogen pipeline costs, for e-fuels and hydrogen beyond arriving at the port.

GREENHOUSE GAS EMISSIONS METHODOLOGY

As in a previous study that estimated well-to-wheel life-cycle GHG emissions from renewable hydrogen in the European Union (Zhou et al., 2021), we used the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model to estimate the GHG emissions from RFNBOs imported from Brazil and Egypt (Wang, et. al., 2021). The GREET model provides the flexibility to change assumptions and covers the system boundary of this study. To convert methane and nitrous oxide emissions into CO_2 equivalent, we used the same global warming potential as in the RED II, which is from the Intergovernmental Panel on Climate Change Fourth Assessment report (Directive [EU] 2018/2001). We considered emissions from the electricity, fuel production, fuel shipment to the European Union, and fuel combustion.

If the EU RFNBO production criteria are not met, the climate impacts from renewable hydrogen and e-fuels could be same as using grid mix electricity, if not higher. This is because the renewable energy is likely to be displaced from decarbonizing the power sector. In this study, we estimated emissions of hydrogen and e-fuels using grid mix electricity—known as the attributional emissions that result from direct consumption of grid electricity for hydrogen production—to represent the case when the RFNBO production requirements are not met. We illustrate this to show what would happen if a certification scheme did not properly ensure compliance with the EU production requirements. However, it is possible that emissions could be even higher than when using grid mix electricity, especially when considering long-term, system-wide emissions impacts from hydrogen production compared to the case where hydrogen production does not exist, known as the consequential emissions (Ricks et al., 2023). In this case, the marginal generation of electricity (i.e., the source of electricity that is ramped up to meet the additional electricity demand from hydrogen) is considered, which is highly likely to be fossil fuel due to its flexibility and cost. Therefore, we consider our estimate of GHG emissions when RFNBO production criteria are not met to be conservative.

We collected grid mix values for 2020 and the projected values for future years for Egypt and Brazil, shown in Table 5, and input them into GREET to reflect the country-specific carbon intensity of grid electricity. Egypt has a power generation target for different power sources for 2035, so we applied a linear interpolation to project the grid mix in 2030. For Brazil, the 2020 grid mix represents the actual electricity supply by source, including imported electricity; the 2030 grid mix represents the projected installed capacity by source in Brazil. We also updated the shipping distance in GREET using the distance values provided in the cost section. We did not change the default shipping fuel, which is diesel.

Table 5
2020 and future grid mix in Egypt and Brazil

	Egypt			Brazil	
	2020	2030	2035	2020	2030
Hydro	7.8%	4%	2%	65.2%	56.5%
Biomass				9.1%	7.9%
Wind	2.2%	10%	14%	8.8%	13.9%
Solar	2.3%	18%	26%	1.7%	4.2%
Natural gas	83.9%	63%	55%	8.3%	15.1%
Oil	3.7%	3%		1.6%	0.1%
Coal				3.1%	0.7%
Nuclear		2%	3%	2.2%	1.6%

Sources: Empresa de Pesquisa Energética (2022); International Energy Agency (2022b); Ministry of Mines and Energy (2022); Ministry of Electricity and Renewable Energy (2023).

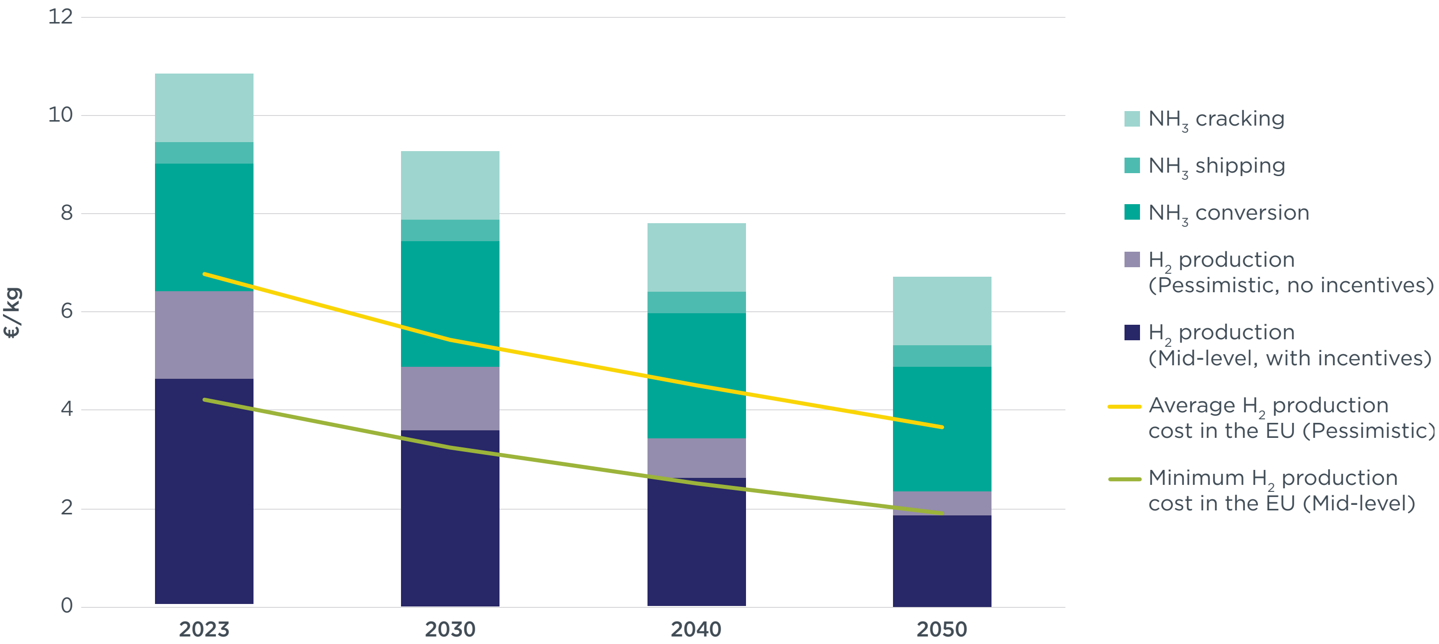
RESULTS

COST OF IMPORTING RENEWABLE HYDROGEN

We show the estimated renewable hydrogen cost delivered from Brazil and Egypt to a port in the European Union in Figures 1 and 2, respectively. All costs reported in this study are based on 2023 euro values, and future values are not adjusted for inflation. The costs of hydrogen compression and distribution after arrival to the European Union are also not considered. In both figures, the bars represent the breakdown of estimated costs in each year. We also consider two technology cost scenarios: a Mid-level and Pessimistic scenario, reflecting advancement (or not) in renewable electricity and electrolyzers. In the figures, two renewable hydrogen production costs are shown: one based on the Mid-level scenario with financial incentives provided in Brazil and Egypt, and one based on the Pessimistic scenario without financial incentives. The figures also show the estimated renewable hydrogen production costs in the European Union excluding any financial incentives, which we retrieved from previous analyses and adjusted by inflation (Zhou et al., 2022; Zhou & Searle, 2022). Specifically, the regional average costs under a Pessimistic scenario and the minimum hydrogen cost in the European Union assuming a Mid-level scenario are shown. Unlike Brazil and Egypt, where we only consider direct connection, in the European Union, we consider both direct and grid connection modes and present the lower cost, as in previous studies. These previous analyses were performed before the EU RFNBO production rules were finalized, so we did not assess the impact of these rules on the cost of grid-connected hydrogen produced in the European Union.

Figure 1

Cost of renewable hydrogen delivered from Brazil to the European Union



Notes: Hydrogen production costs are shown based on the Mid-level technology scenario with financial incentives, assuming direct connection, and the additional hydrogen production cost under the Pessimistic technology scenario without incentives in Brazil. For the European Union, both a grid connection scenario and direct connect scenario were assessed, and we illustrate the lowest cost outcome here. We do not consider the cost of implementing the EU's RFNBO production rules, which may increase the cost of hydrogen shown for the European Union.

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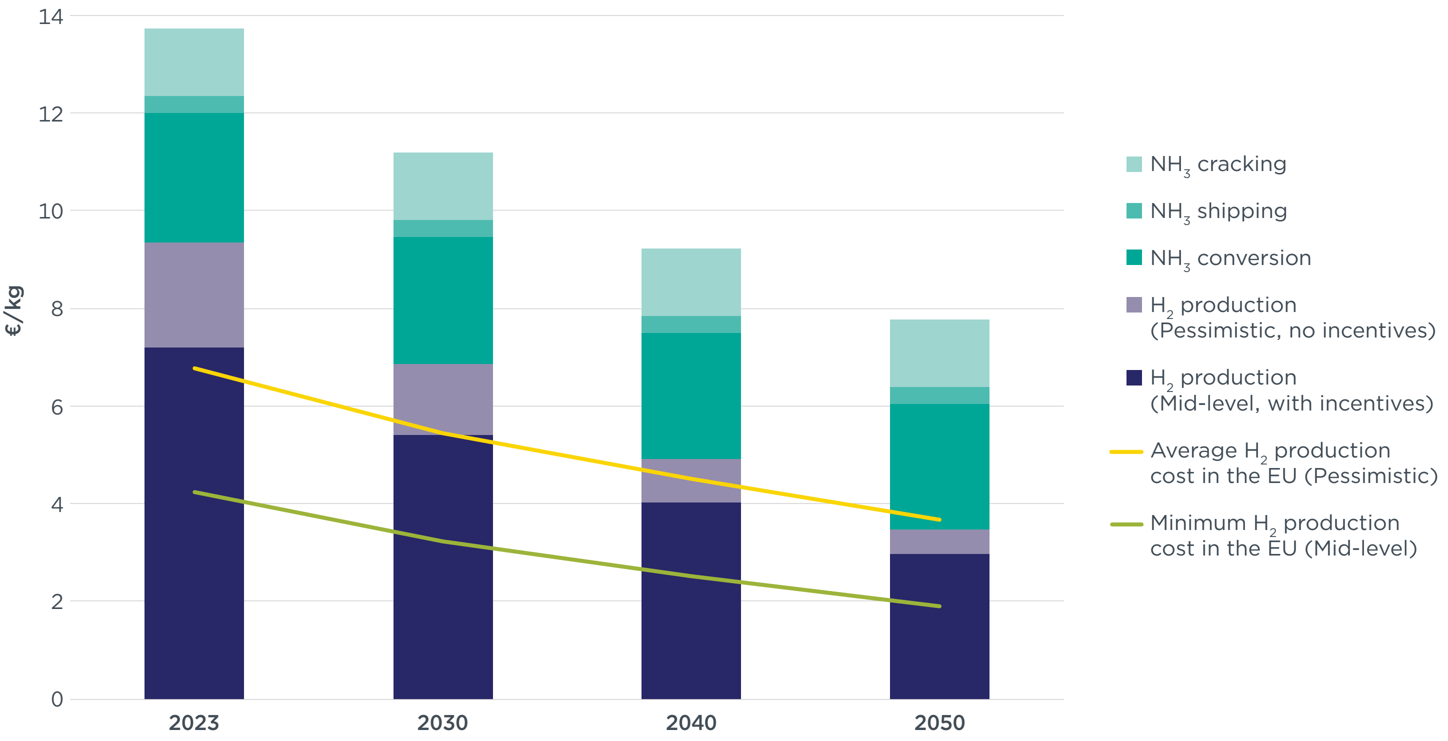
Figure 2

Cost of renewable hydrogen delivered from Egypt to the European Union



Notes: Hydrogen production costs are shown based on the Mid-level technology scenario with financial incentives, assuming direct connection, and the additional hydrogen production cost under the Pessimistic technology scenario without incentives in Egypt. For the European Union, both a grid connection scenario and direct connect scenario were assessed, and we illustrate the lowest cost outcome here. We do not consider the cost of implementing the EU's RFNBO production rules, which may increase the cost of hydrogen shown for the European Union.

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Notably, when considering the added costs of shipment, importing renewable hydrogen from Brazil and Egypt likely fails to provide a cost benefit relative to production in the European Union. We estimate the added shipping costs to be around €4.5 per kilogram hydrogen, roughly the same as it would cost to produce renewable hydrogen in Brazil. Even the best cost scenario for Brazil and Egypt in 2030, which assumes a Mid-level outlook with financial incentives, would result in a 50% higher cost in Brazil and a 80% higher cost in Egypt than the EU average assuming a Pessimistic outlook. Moreover, if Brazil and Egypt did not provide financial incentives for renewable hydrogen, the cost of importing hydrogen could be twice as high as producing the hydrogen in Europe. Because national averages for the wind and solar capacity factor are used in this analysis, hydrogen production costs may be lower in the windiest and sunniest regions in Egypt and Brazil. However, the cost of conversion, shipping, and cracking once in port would likely still negate any cost benefit provided by higher-than-average capacity factors.

In our analyses of the European Union, we found that over 90% of EU Member States would produce the lowest cost renewable hydrogen if connected to the grid, and these grid-connect production cost results are considered in Figures 1 and 2 (Zhou, et al., 2022; Zhou & Searle, 2022). However, the European Union's temporal matching requirements for grid connection might increase the cost of producing hydrogen via this mode. A study in the United States, for example, found that hourly matching might increase hydrogen cost by up to $1 per kilogram (Ricks et al., 2023). Therefore, it is possible that renewable hydrogen production costs in the European Union will be higher than shown in this study. However, even if both costs shown in the figures for production in the European Union increased by $1 per kilogram (€0.92 per kilogram), it would not change our interpretation of the results: that is, that it will be difficult to import renewable hydrogen from Brazil or Egypt at lower cost than producing it in the European Union.

We note that we assume the same electrolyzer costs in Brazil, Egypt, and the European Union, whereas this cost could vary by region. If Brazil and Egypt were to source cheaper electrolyzers, for instance, the renewable hydrogen production cost could be less than what this study estimates. We also consider lower discount rates for renewable electricity (3%) and renewable hydrogen (7%) in the European Union than in Brazil and Egypt (Table 3). The discount rates of real-world projects can be uncertain due to technological risks, financing challenges, and market fluctuations, especially for the new and emergent field of renewable hydrogen, with implications for the relative costs of production in these markets.

In the near term, the production of renewable hydrogen itself contributes the most to the final delivered costs from imports, indicating that lower electricity and electrolyzer costs are key to making imports cost competitive. Over time, as electricity and electrolyzer costs decrease, other components, led by ammonia conversion and cracking, gradually assume a greater share of the total cost of imports, though these costs are characterized by uncertainties. For instance, we assumed the capital cost of converting hydrogen into ammonia remains constant, as this is already a mature technology; therefore, the levelized cost of ammonia conversion only decreases slightly with declining renewable electricity cost. The cost of ammonia cracking is uncertain due to energy prices and economies of scale. Finally, the cost of shipping is unlikely to decrease unless there is a significant technology breakthrough in delivering hydrogen either as ammonia or in other forms, such as liquified hydrogen or liquid organic hydrogen carriers. As a result, in future years, the cost of producing renewable hydrogen is projected to decline as a share of the total cost of importing hydrogen relative to the costs of preparing hydrogen for shipping and use and of shipping it to the European Union.

However, other studies expect the cost of shipping hydrogen, including the relevant handling and processing costs, to decrease over time due to economies of scale. For example, the International Renewable Energy Agency (2022) projects the cost of shipping hydrogen in the form of ammonia will be €2.3–€4.1 per kilogram hydrogen in 2030; as the project size grows, this could decrease to €0.7–€1.4 per kilogram hydrogen in 2050, compared to €4.5 per kilogram in this study. If this significant cost reduction were to happen, it would make more economic sense for the European Union to import renewable hydrogen. However, these cost reductions would occur far in the future.

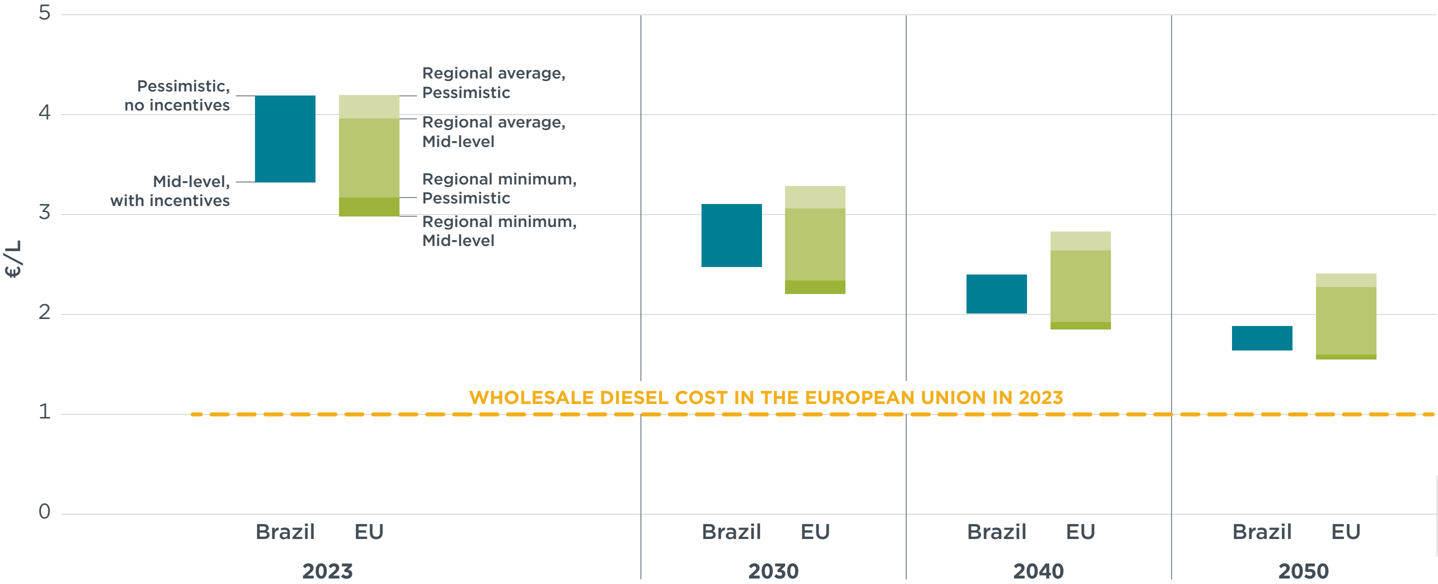
If the ammonia is not cracked into hydrogen upon delivery to the European Union, renewable ammonia could possibly be cost competitive, particularly for the case of Brazil. Based on Figure 1, the cost of importing renewable ammonia from Brazil (i.e., the bar without the NH_3 cracking portion) is similar to that of the EU average domestic production of renewable hydrogen, which would require the additional cost of converting hydrogen into ammonia. Renewable ammonia could be an attractive fuel for decarbonizing maritime vessels in the European Union, provided its safety risks are managed (European Maritime Safety Agency, 2023).

COST OF IMPORTING LIQUID E-FUELS

Figure 3 compares the estimated costs of renewable e-diesel produced using point source CO_2 when delivered from Brazil or produced in the European Union. (Egypt is not considered in this figure due to the country's lack of a carbon pricing system.) For Brazil, the bottom of each bar represents the cost assuming a Mid-level hydrogen cost outlook and financial incentives, while the top of the bar assumes a Pessimistic hydrogen cost without any incentive. For the European Union, we did not consider financial incentives in any of the cost results; shading in the bars represents the cost assuming different scenarios of hydrogen cost (regional average or minimum) and technology outlook (Mid-level or Pessimistic).

Figure 3

Cost of e-diesel produced using point source CO_2 delivered from Brazil to the European Union



Notes: For the European Union, both a grid connection scenario and direct connect scenario were assessed, and we illustrate the lowest cost outcome here. We note that we do not consider the cost of implementing the EU's RFNBO production rules for the EU results.

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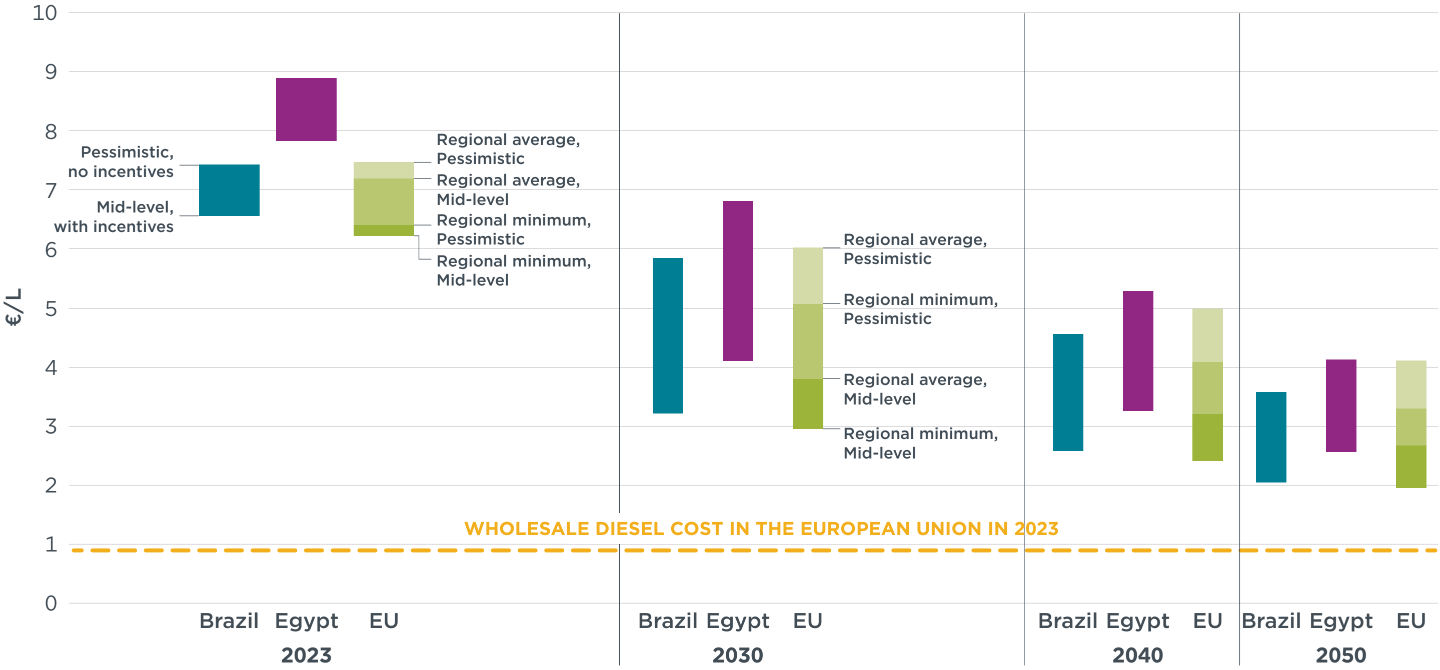
Figure 4 compares the estimated costs of renewable e-diesel produced from direct air capture when delivered from Brazil or Egypt or produced in the European Union. For Brazil and Egypt, the bottom of each bar indicates the cost assuming a Mid-level hydrogen cost outlook, an Optimistic DAC cost, and financial incentives, while the top of each bar indicates the cost assuming a Pessimistic hydrogen cost outlook, Pessimistic DAC cost, and no incentives. For the European Union, we again did not consider financial incentives in any of the cost results; shading in the bars represents the cost assuming different scenarios of hydrogen cost (regional average or minimum) and technology outlook (Mid-level or Pessimistic). From 2030 onwards, the order of the EU bar changes, such that the cost assuming a regional minimum hydrogen cost and a Pessimistic technology outlook is above the cost assuming a regional average hydrogen cost and Mid-level outlook.

Figure 4

Cost of e-diesel produced using CO_2 from direct air capture delivered from Brazil or Egypt to the European Union



Notes: For the European Union, both a grid connection scenario and direct connect scenario were assessed, and we illustrate the lowest cost outcome here. We note that we do not consider the cost of implementing the EU's RFNBO production rules for the EU results.

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Table A1, in the appendix, presents the estimated costs for e-kerosene imported from Brazil and Egypt or produced domestically in the European Union.

As shown in Figure 3 and Figure 4, e-diesel could be imported from Brazil, a renewables-rich country, at lower cost than it could be produced in the European Union, without considering any EU incentives. However, e-diesel produced in any country will be substantially more expensive than fossil diesel in the near term. Even in 2050, when costs are reduced due to technology improvements, e-diesel imported from Brazil still may not reach cost parity with fossil diesel in Europe. At the same time, this study includes assumptions about renewable electricity and electrolyzer costs consistent with our Mid-level scenario and Pessimistic scenario in previous analyses. Assuming an Optimistic scenario for renewable electricity and hydrogen costs would bring the cost of e-diesel slightly lower, but likely not enough to reach cost parity with fossil diesel. In our 2022 EU analysis, for example, we found that Optimistic assumptions led to an e-diesel cost about 15% to 20% lower than the Mid-level outlook, which we would expect to be similar here (Zhou & Searle, 2022). However, if the cost of fossil diesel increases and the costs of renewable electricity, electrolyzers, and DAC reduce further, the cost of e-diesel might be close to diesel in the long term, but likely beyond 2050.

GREENHOUSE GAS EMISSIONS

We next show the GHG emissions from importing renewable hydrogen (Figure 5) and e-fuels, including e-gasoline, e-kerosene, and e-diesel (Figure 6) from Egypt and Brazil to the European Union. Emissions from electricity, fuel production and processing, shipping, and combustion are included. The transport fossil fuel comparator of 94 g CO_2e/MJ in the RED III is shown in both figures. The renewable electricity bars represent GHG emissions when 100% additional renewable electricity is used for hydrogen production and ammonia conversion and cracking, in compliance with RFNBO production requirements. In this case, hydrogen and e-fuels would be nearly zero carbon and the GHG emissions from imports are from burning fossil fuels during shipping, as long as renewable electricity is also used for ammonia cracking in the European Union.

Figure 5

Attributional greenhouse gas emissions from delivered renewable hydrogen, should the EU RFNBO production rules be met or not

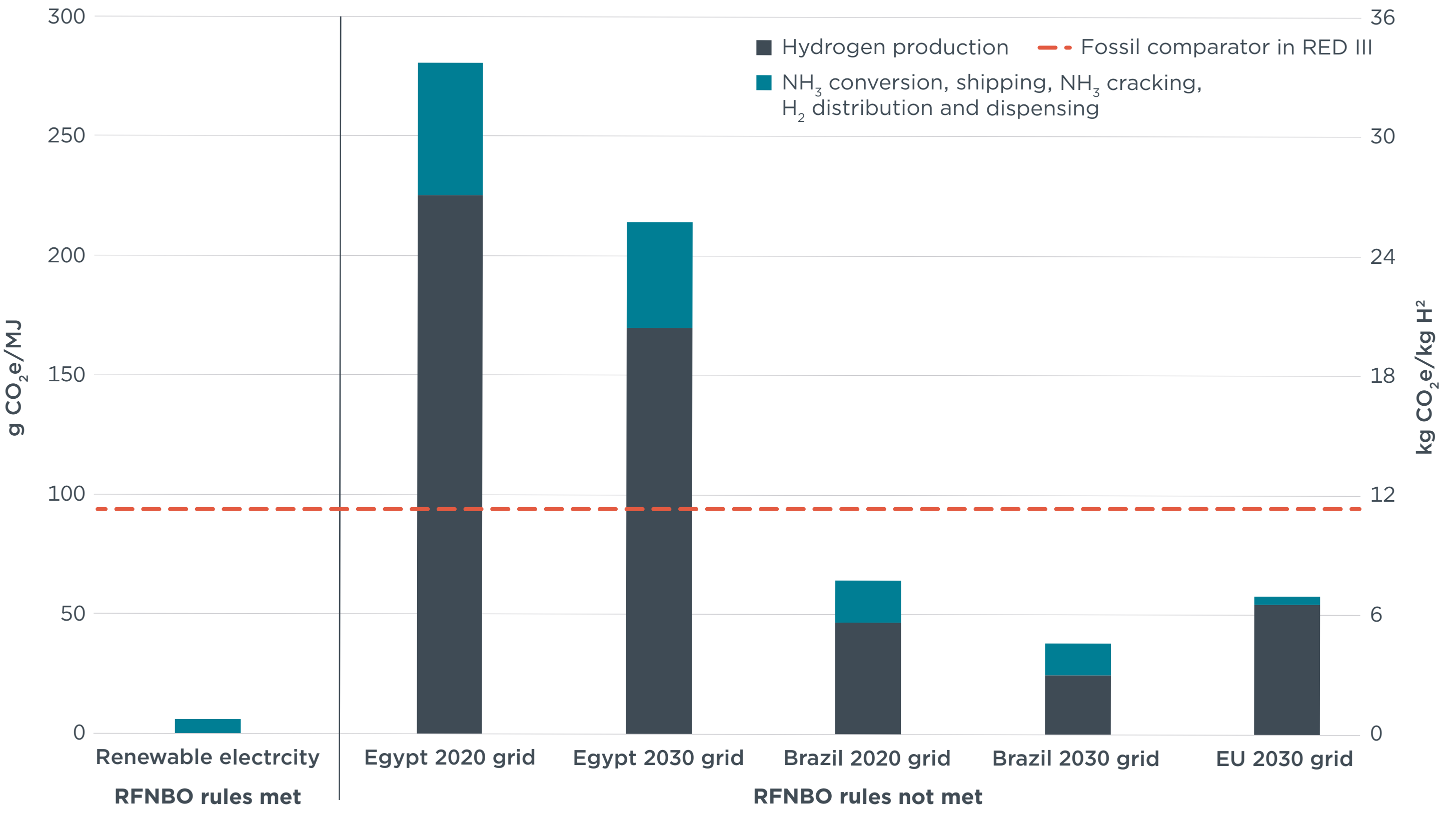

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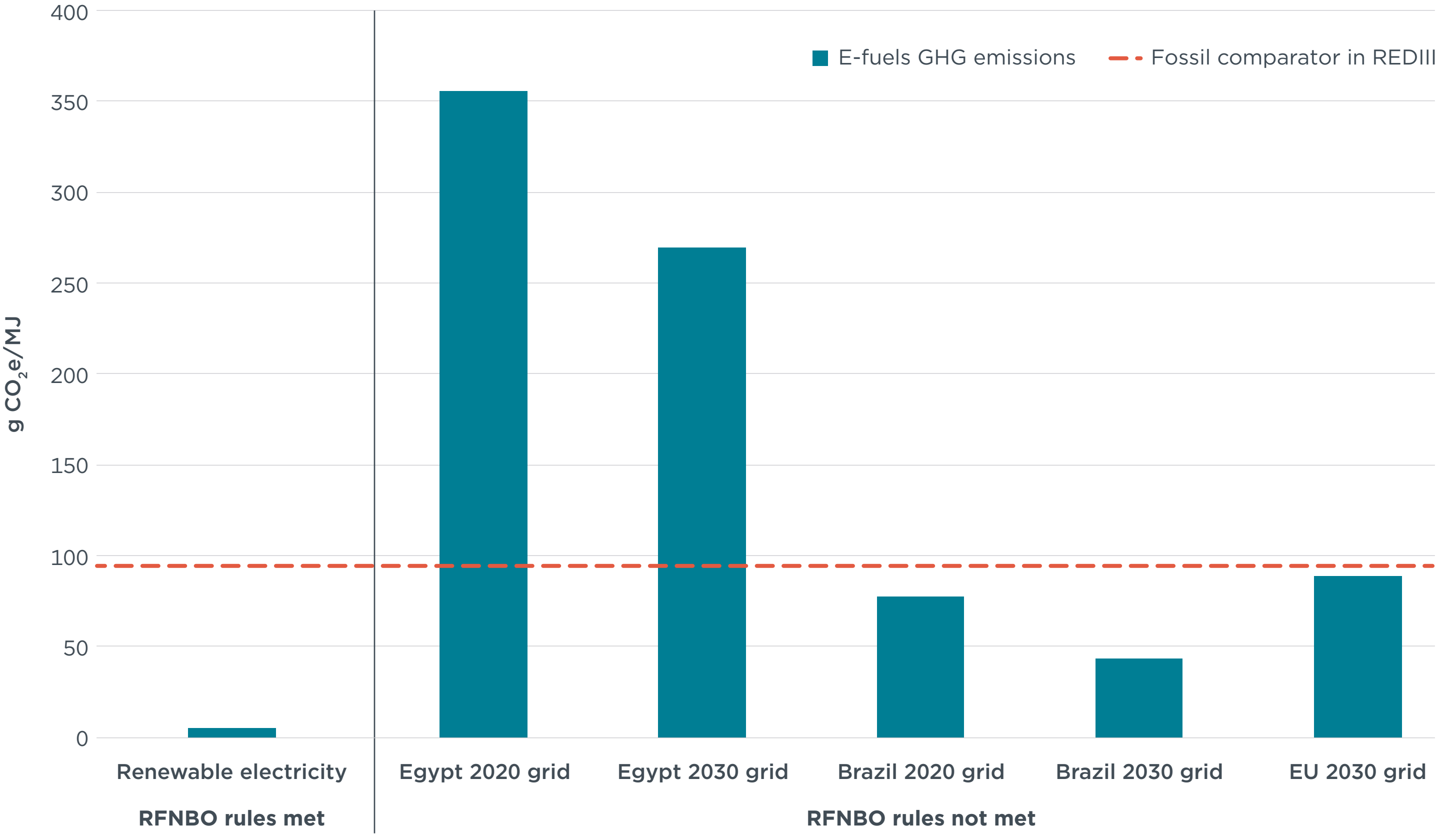
Figure 6
Attributional greenhouse gas emissions from delivered renewable e-fuels, should the EU RFNBO production rules be met or not



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The figures also show the approximate emissions impacts if compliance with the certification scheme is not adequately verified and RFNBO production requirements are not met. In this case, emissions could be as high as if grid mix electricity were used for RFNBO production from an attributional emissions standpoint. However, as noted in the methodology section, emissions from improperly implementing the EU RFNBO production rules could be even higher than from grid electricity when considering consequential emissions. This is because fossil fuels are likely to be the marginal energy used to serve the additional demand from hydrogen production when EU matching requirements are not met (Ricks et al., 2023).

For a country like Egypt, where fossil fuels make up a majority of the grid, the GHG emissions when EU RFNBO production requirements are not met could be more than double the emissions from fossil fuels. In Brazil, where renewables account for over 80% of the grid, not meeting RFNBO production requirements would have a considerably smaller impact on the GHG emissions released from hydrogen production, depending on the type of marginal electricity source used to meet the additional electrolyzer energy demand. In this case, the GHG impact could be lower than the fossil comparator in the RED but would still fail to meet the 70% GHG reduction threshold of 28.2 g CO_2e/MJ fuel for RFNBOs in the RED III.

CONCLUSIONS

The European Union aims to import 10 million tonnes of renewable hydrogen by 2030. Considering Brazil and Egypt as case studies, we estimate that importing renewable hydrogen as ammonia from countries with abundant renewable resources could be more expensive than producing it domestically in the European Union. Renewable-abundant countries such as Brazil may produce RFNBOs at a lower cost than the European Union, especially when financial incentives are provided in those countries. However, the additional cost of shipping, including the cost of converting the hydrogen to ammonia, transporting it over a long distance, and then re-converting the ammonia back into hydrogen, can be as high as the production cost itself. For example, an optimistic cost estimate of hydrogen imported from Brazil in 2030, assuming mid-level technology costs and financial incentives, is around €8/kg hydrogen. This is 50% higher than a pessimistic estimate of EU domestic renewable hydrogen production. The cost and challenge of shipping hydrogen long distances could undermine the intended benefit of producing it in cheaper locations.

On the other hand, we find that the cost of importing renewable e-fuel could be lower than producing it domestically in the European Union. However, using our primary modeling assumptions, we estimate that it is unlikely for imported e-fuel to reach cost parity with fossil diesel unless the cost of fossil diesel increases while renewable electricity, electrolyzers, and DAC all have significant technology breakthroughs that enable deep cost reductions for e-fuels.

To ensure RFNBOs effectively decarbonize transport in the European Union, the requirements for additionality and geographic and temporal matching, which help ensure that renewable electricity is not diverted from the power sector when used to produce hydrogen, could be properly certified and verified by third parties. Otherwise, the GHG emissions from RFNBOs could be significantly higher than those of fossil fuels.

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APPENDIX

E-kerosene and e-diesel are co-products of Fischer-Tropsch synthesis. Table A1 shows the estimated e-kerosene import cost from Brazil and Egypt, as well as the average production cost of e-kerosene in the European Union. We assumed e-diesel and e-kerosene have the same share of Fischer-Tropsch product slate, meaning they have the same production cost on an energy basis but different cost on a volumetric basis due to different heating values.

Given the RED II and RED III requirements on the CO_2 source for e-fuel production, we provide both point source CO_2 and DAC scenarios for Brazil and the European Union, and only a DAC scenario for Egypt. The range represents the four scenarios we analyzed in this study for each region. For Brazil and Egypt, the scenarios are Mid-level hydrogen cost with Optimistic DAC cost (with financial incentives) and Pessimistic hydrogen cost with Pessimistic DAC cost (without financial incentives). For the European Union, the lower range represents the EU minimum cost based on a Mid-level renewable electricity and hydrogen outlook combined with an Optimistic DAC outlook, and the higher end represents the EU average cost based on a Pessimistic renewable electricity and hydrogen outlook with Pessimistic DAC technology assumptions. No financial incentives were considered in the European Union.

Table A1
Estimated cost of e-kerosene imported from Brazil and Egypt and e-kerosene produced domestically in the European Union for comparison

Year	From Brazil		From Egypt	European Union	
	Point source CO_2 (€/L)	DAC (€/L)	DAC (€/L)	Point source CO_2 (€/L)	DAC (€/L)
2023	3.2–4.1	6.4–7.2	7.6–8.6	2.9–4.1	6–7.2
2030	2.4–3	3.1–5.7	4–6.6	2.1–3.2	2.9–5.8
2040	1.9–2.3	2.5–4.4	3.2–5.1	1.8–2.7	2.3–4.8
2050	1.6–1.8	2–3.5	2.5–4	1.5–2.3	1.9–4

Note: Values are in 2023 euros.

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