Article

Environmental Impact of e-Fuels via the Solid Oxide Electrolyzer Cell (SOEC) and Fischer–Tropsch Synthesis (FTS) Route for Use in Germany

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Abstract: This paper examines the current and prospective greenhouse gas (GHG) emissions of e-fuels produced via electrolysis and Fischer–Tropsch synthesis (FTS) for the years 2021, 2030, and 2050 for use in Germany. The GHG emissions are determined by a scenario approach as a combination of a literature-based top-down and bottom-up approach. Considered process steps are the provision of feedstocks, electrolysis (via solid oxide co-electrolysis; SOEC), synthesis (via Fischer–Tropsch synthesis; FTS), e-crude refining, eventual transport to, and use in Germany. The results indicate that the current GHG emissions for e-fuel production in the exemplary export countries Saudi Arabia and Chile are above those of conventional fuels. Scenarios for the production in Germany lead to current GHG emissions of 2.78–3.47 $kgCO_2$-eq/L e-fuel in 2021 as the reference year and 0.064–0.082 $kgCO_2$-eq/L e-fuel in 2050. With a share of 58–96%, according to the respective scenario, the electrolysis is the main determinant of the GHG emissions in the production process. The use of additional renewable energy during the production process in combination with direct air capture (DAC) are the main leverages to reduce GHG emissions.

1. Introduction

In mid-2021, the German government tightened its climate targets with the goal of greenhouse gas neutrality by 2045 [1]. E-fuels (synthetic fuels derived from power, carbon dioxide and water) will probably make a decisive contribution to achieving these climate targets, particularly in the transport sector as there are certain areas that are difficult or impossible to decarbonize by electrification such as aviation and deep-sea shipping. In these cases, e-fuels can contribute to reducing the use of fossil fuels and thus the level of greenhouse gas (GHG) emissions. Political decision makers in Germany and the European Union already claim e-fuels to be a sustainable alternative to conventional fossil fuels and designate the prospective use of e-fuels in the mobility sector [2]. Due to the high political interest in e-fuels, the question of their environmental impact and their contribution potential to reducing GHG emissions arises.

Therefore, this paper evaluates the GHG emissions of e-fuels used in Germany. While the focus lies on domestic production, for the purpose of comparison, Saudi Arabia and Chile are considered as two exemplary countries to represent possible export regions with existing or planned economic relations. Different production routes exist, using carbon dioxide, water, and electricity as resources. The conversion efficiency from electricity to fuel is currently still low at approximately 44% [3]. Solid oxide fuel cells (SOFCs) as a technology on the verge of commercial use offer great potential for improvement in electrolysis due to

their comparatively high theoretical efficiency and the possibility to generate synthesis gas from carbon dioxide and water in a single process step. In [4], the conversion efficiency from electricity to hydrogen, based on the lower heating value, is quantified as 76.8%, compared to a maximum of 70% for alkaline electrolysis and a maximum of 72% for proton exchange membrane (PEM) electrolysis until 2030. For co-electrolysis in solid oxide electrolyzer cells (SOECs), due to the continuous development, a longer time horizon of 2050 instead of 2030 was chosen.

In this paper, an innovative system configuration combining SOECs for synthesis gas production and Fischer–Tropsch synthesis (FTS) for the conversion to crude fuel is studied, leading to the research question: "What are the potential GHG emissions of e-fuels produced via the SOEC and FTS route for use in Germany?"

For the assessment of the environmental impacts, data from the literature can hardly be referred to, since to date, only a few life cycle analyses exist on the production of liquid hydrocarbons from carbon dioxide via the Fischer–Tropsch route [5]. To the authors' knowledge, no study has previously examined the environmental impacts of precisely the system configuration at hand with the combination of Co-SOEC and FTS, although [6–8] have examined its technical performance. Another relevant aspect is the distribution of environmental impacts among the individual process steps in order to identify the levers (other than electrolysis) for increasing overall efficiency. In the existing literature, however, merely the overall process is usually considered. This paper, therefore, aims to break down the evaluated GHG emissions of e-fuels by process step wherever possible.

2. Materials and Methods

As described above, there have been few studies to date on the environmental impact of the production of synthetic fuels from electricity and CO_2 via the FTS route. Existing studies also differ in their structure and results. For this reason, a combination of two methods was intentionally chosen to categorize the literature data and validate own calculation results. The methodology used in this work is a combination of literature-based top-down and bottom-up analyses. In a top-down analysis using a comprehensive review of the existing literature, the range and average values of overall GHG emissions were quantified in absolute terms and their distribution to the main process steps was determined in relative figures. In a complementary approach, the bottom-up analysis calculated GHG emissions in absolute terms by multiplying the necessary energy usage, provided that it was known for the respective process step, with the corresponding emission factor. Where data were missing, as was the case with the Fischer–Tropsch synthesis step, the determined relative value from the top-down analysis was used for approximation. The absolute values of the overall GHG emissions resulting from the two different approaches were finally cross-checked.

For solid oxide co-electrolysis as a technology under continuous development and due to the innovative combination with Fischer–Tropsch synthesis, a bottom-up approach was used. Fischer–Tropsch synthesis, as a well-established technology (using fossil fuels as ground stock), on the other hand, has been the subject of numerous studies, of which [9,10] are to be mentioned primarily, though not in combination with SOECs. Here, a literature-based top-down analysis is at an advantage and also served to cross-check the results from the bottom-up approach. As an indicator of the environmental impact along the process chain of e-fuel production and use, the potential GHG emissions, measured in CO_2 equivalents (CO_2-eq), were assessed. The considered process steps were the provision of feedstocks including direct air capture (DAC), electrolysis (via SOEC), synthesis (via FTS), e-crude refining, and transport and use. A scenario-based approach was applied in order to estimate and compare future emissions. In this context, the emissions (CO_2-eq) were determined for the years 2021 (as a reference), 2030, and 2050 for production sites in Germany, Saudi Arabia, and Chile. The latter countries were chosen for reasons of data availability as well as existing trade relations [11,12] and are supposed to be representative of the regions Middle East and South America.

The input for the production of each kilogram of synthesis gas (syngas; a mixture of CO and H_2) as feedstock of the FTS, was found to be 4.87 kWh of electricity, 0.77 kg H_2O, and 0.7 kg CO_2 in 2021 [13]. According to [13], the demand of H_2O and CO_2 remains constant for prospective syngas production. Owing to productivity increases, the electricity demand is expected to be reduced to 4.26 kWh/kg of syngas by 2050. Based on an interpolation, an electricity demand of 4.66 kWh/kg of syngas can be assumed by 2030. Furthermore, 0.77 kg H_2O and 0.7 kg CO_2 are required. The GHG emissions per kg e-fuel were determined by multiplying the input demand with the corresponding emission factor (in CO_2-eq). Regarding electricity, the current country-specific electricity mix was applied. For estimating future emission factors, the self-imposed targets for the electricity mix of the respective countries were used. Taking into account the upstream chain emissions, this leads to a current (2021) emission factor of 485 gCO_2-eq/kWh in Germany (220 gCO_2-eq/kWh in 2030; 14 gCO_2-eq/kWh in 2050) [14,15]. In Chile, the use of electricity from the public grid (Sistema Eléctrico Nacional) leads to 636 gCO_2-eq/kWh [14,16,17]. For 2030, 338 gCO_2-eq/kWh and 14 gCO_2-eq/kWh for 2050 will be emitted [15,18]. In Saudi Arabia, 676 gCO_2-eq/kWh are emitted (338 gCO_2-eq/kWh in 2030; 122 gCO_2-eq/kWh in 2050) [19,20]. The calculation of the future CO_2-eq emissions is based on the share of renewable energy in the grid according to the self-proclaimed targets of the respective country and their current composition of the electricity mix. In Table 1, the described feedstock demand per kg synthesis gas and the CO2-eq/kWh are displayed.

Table 1. Feedstock demand of synthesis gas and CO_2-eq/kWh.

	Feedstock Demand (for 1 kg Synthesis Gas)			CO_2-eq/kWh		
	Electricity	H_2O	CO_2	Germany	Chile	Saudi Arabia
2021	4.87	0.77	0.7	485	636	676
2030	4.66 *	0.77	0.7	220	338	338
2050	4.26	0.77	0.7	14	14	122

* Interpolation.

For the provision of H_2O as a feedstock, firstly, the local availability of freshwater and saltwater was determined. Secondly, the electricity demand of freshwater (ground- and surface water) treatment and the desalination of salt water was reviewed. The considered technologies for freshwater treatment are 1. conventional pre-treatment (process steps: iron removal, chemical softening, and filtration) in combination with reverse osmosis (R.O.), 2. conventional pre-treatment in combination with ion exchange technology, 3. combined treatment. For the salt water treatment, R.O. as the dominating technology on the market according to [21,22] was chosen. Based on [14], the respective energy demands (in kWh/m^3) are 1. 2.9 kWh/m^3 in 2021, 1.9 kWh/m^3 in 2030, 0.9 kWh/m^3 in 2050; 2. 0.7 kWh/m^3 in 2021, 0.6 kWh/m^3 in 2030, 0.5 kWh/m^3 in 2050; 3. 3.3 kWh/m^3 in 2021, 2.3 kWh/m^3 in 2030, 1.3 kWh/m^3 in 2050. R.O. technology has an expected energy demand of 2.35 kWh/m^3 up to 2030 and 2 kWh/m^3 in 2050 (see Table 2).

Table 2. Electricity demand for water treatment.

	Freshwater			Saltwater
	1.	2.	3.	R.O.
2021	2.9	0.7	3.3	2.35
2030	1.9	0.6	2.3	2.35
2050	0.9	0.5	1.3	2

The technologies included in this analysis for the provision of CO_2 are 1. DAC, 2. Biomass (organic waste), 3. CO_2 capture from cement production. The electricity

demand of DAC technologies varies between 1.4 and 2.8 kWh/kg CO_2 according to data from the literature [23,24]. In the following, an average of 2.1 kWh/kg CO_2 was used. According to [25], 0.46 kWh/kg CO_2 is necessary while using a pressure swing absorption process. For the CO_2 capture during the cement production by means of Selexol© scrubbing, 0.31 kWh/kg CO_2 are required [14]. The Selexol© process involves the utilization of a liquid physical solvent to extract acidic gases from both synthetic and natural gas streams [26]. A total of eight scenarios of the above-mentioned alternatives for the provision of feedstock for the electrolysis was considered (see Appendix A).

To identify the environmental impacts of Fischer–Tropsch synthesis in particular, initially, literature research was carried out, mainly using the metadata service Google Scholar as the biggest academic database and search terms both in English and German. The search terms were then entered into other minor databases, both open-access and commercial, in order to cross-check the search results. Search terms were "Fischer Tropsch synthetic fuels", "LCA Fischer Tropsch", "LCA solar fuels", "LCA wind fuels", "Fischer Tropsch fuels renewable energy"/"Fischer Tropsch Kraftstoffe erneuerbare Energien". Based on the abstracts, all relevant articles from the first five pages of the respective search results i.e., those works focusing on Fischer–Tropsch fuels produced from electricity, were then reviewed in detail. Subsequently, the references cited in these papers were included to broaden the literature review. This step was used as an indicator to reveal a too-narrow choice of search terms eventually. Since only one of the eleven studies evaluated in the final loop was included in the literature search as a reference of another study, the choice of search terms can be deemed sufficiently diversified and therefore comprehensive.

In [27], the GHG emissions over the entire life cycle of an aviation fuel and naphtha production plant using solar energy are investigated. Water and carbon dioxide are captured from air and converted to syngas in a thermochemical reactor before being converted to jet fuel via Fischer–Tropsch synthesis. Specific life cycle GHG emissions are calculated to 14.7 gCO_2-eq/MJ jet fuel and 17.7 gCO_2-eq/MJ naphtha in the solar stand-alone solution design case, with different values due to the different energy densities and emission factors during combustion. Fischer–Tropsch synthesis accounts for 16% of the emissions, i.e., 2.3 gCO_2-eq/MJ jet fuel and 2.8 gCO_2-eq/MJ naphtha, which are largely composed of the syngas leakage and the combustion of the light hydrocarbons in the cogeneration plant. The plant construction for the FT reactor including follow-up treatment plays a minor role and is not mentioned separately in this analysis. Using solar energy (instead of the CHP plant) also for post-treatment of the FT hydrocarbons leads to a reduction in emission levels.

Also, in [5], a life cycle analysis of GHG emissions from the production of liquid fuels by Fischer–Tropsch synthesis is performed. The investigated system consists of a direct air capture plant (for CO_2), coupled with a Fischer–Tropsch synthesis plant, designed for diesel production. Syngas is obtained from the reverse water gas shift reaction using the captured CO_2 and water as inputs. In the design case, the required electrical energy is supplied from the power grid with a comparatively very low assumed emission factor of 13 gCO_2-eq/kWh, and an oxygen-fueled calciner is considered as an alternative to an electrically powered one. The greenhouse gas emissions over the entire life cycle for Fischer–Tropsch synthesis and electrolysis are calculated in the design case to be 7.3 gCO_2-eq/MJ, based on the calorific value of the synthetic diesel fuel and for both types of calciner. There is no direct comparability to the values from [27], because of the combined assessment of electrolysis and synthesis as well as the different product, requiring different process control.

The greenhouse gas emissions as well as the cumulative energy demands of different production routes of liquid hydrocarbons from CO_2, water, and electrical energy are also calculated and compared in [28]. In this study, the three carbon dioxide sources, natural gas, biomass, or ambient air, and three electricity sources (natural gas, biomass combustion, or photovoltaic) are combined into nine conceivable production options, five of which are further evaluated. Hydrogen is obtained via alkaline electrolysis and fed to the reverse water gas shift reaction for syngas production. Included in the comparison are the gas-to-liquid and biomass-to-liquid processes as reference technologies. GHG emissions for DAC

of CO_2 and electricity generation from photovoltaic are calculated to 30 gCO_2-eq/MJ of fuel and the cumulative energy demand (CED) (also called 'primary energy consumption') is 2.90 MJ_{Prim}. per MJ fuel.

In [29], the focus of the study is on the influence of electrolysis and the choice of system boundary. The considered stand-alone solution uses wind or solar energy for electricity generation. Hydrogen is produced by low-temperature electrolysis, without further specification, and syngas is generated via reverse water gas shift reaction, where the CO_2 stems from any (non-defined) source. This solution causes greenhouse gas emissions of only 3.8 gCO_2-eq/MJ of fuel if the hydrogen is separated and recycled from the exhaust gas of the FT reactor. Without hydrogen recycling, the production route actually represents an emission sink with a value of −8.3 gCO_2-eq/MJ of fuel, since the combustion of the hydrogen-containing off-gas generates additional electricity that replaces grid electricity with a higher emission factor. However, the GHG emissions associated with the upstream chains of CO_2 input are not taken into account, so these values can in no way be used for a direct comparison. Rather, this production route should be seen as an add-on to other processes serving as a point source for CO_2. One example of such an integrated system is a plant for the production of ethanol from corn combined with Fischer–Tropsch synthesis, which provides the carbon dioxide for fuel production. Its life cycle greenhouse gas emissions are 37.6 gCO_2-eq/MJ fuel with hydrogen recycling and 35.3 gCO_2-eq/MJ fuel without, which is equivalent to savings of about 60% compared to petroleum-based fuels. This order of magnitude is also given in [30]. The importance of the choice of system boundary for the results is emphasized in the study to draw attention to possible implications for allowance trading regulations. The lack of uniform and binding specifications for LCAs on synthetic fuels also makes it difficult to compare results among the different analyzed studies and research groups.

In [13], the individual process steps for the production of synthetic fuels via the Fischer–Tropsch route are investigated and evaluated separately with regard to their sustainability potentials. The system includes hydrogen electrolysis by proton exchange membrane electrolysis cell (PEMEC), DAC, reverse water gas shift reaction and Fischer–Tropsch synthesis for diesel and kerosene production. The combustion of the fuels is not considered in the life cycle analysis. As power sources, the German electricity mix from 2020 and an onshore wind farm for the year 2050 are compared. The greenhouse gas emissions using the 2020 electricity mix are 314.1 gCO_2-eq/MJ fuel (assumed calorific value of 44.7 MJ/kg), whereby the share of hydrogen supply is about six times as large as that of the other process steps (supply of CO_2 and electricity as well as FT plant construction). The relative shares of catalysts appear almost negligible; they are at best guessed at in the visual representation of the results. In the projection for wind power and technological advances in 2050, the relative importance of the respective shares has shifted significantly; hydrogen supply now accounts for about half of the emissions, while CO_2 supply contributes more than 30% and FT plant construction more than 12%. Taking into account the carbon dioxide credit, a negative value of −39.8 gCO_2-eq/MJ fuel is calculated overall.

In [14], the production of e-fuels via FT synthesis is structured into technical modules that form different combinations with each other to be systematically compared in terms of environmental impacts. Also in this study, the construction and operation of the synthesis plant itself is found to account for only a small proportion of the GHG emissions in each of the different generic pathways considered. For the pathways using DAC and renewable energy sources, the respective shares in emissions attributed to synthesis range from 9% to 15% at present, prospectively decreasing to between 3% and 4% in 2050. If the synthesis plant is utilized to a theoretical maximum of 8000 operation hours per year, the shares in emissions even decrease to 4–10% at present and to 1–2% in 2050, respectively. The overall greenhouse gas emissions of most pathways remain below the averaged reference value of 89 gCO_2-eq/MJ for fossil gasoline and diesel, many even between 8 and 20 gCO_2-eq/MJ of fuel. For pathways with CO_2 from fossil point sources, however, this is only true as long as the environmental burdens of the upstream chains are attributed to the

source (memorandum fossil CO_2). Otherwise, their GHG emissions exceed that of the fossil reference.

In [31], the state of the art and the prospects for a future supply of alternative aviation fuels is discussed, including e-fuels. In this context, the results of [32,33], considering the greenhouse gas emissions for production, transport, distribution, and dispensing of e-fuels from renewable electricity, are summarized. No emissions are attributed to the production when renewable energy and direct air capture are used. Transport, distribution, and dispensing cause overall emissions of approximately 1 gCO_2-eq per MJ of final fuel. In [32], it is argued that emissions from the construction of power generation facilities and production sites, as well as the combustion process, are often excluded from life cycle analyses.

In [34], the GHG emissions range between a minimum of 32 gCO_2-eq/MJ (with electricity input from hydropower) and a maximum of 301 gCO_2-eq/MJ (with electricity purchased from the grid) for an assumed plant efficiency of 65%, or between 31.5 gCO_2-eq/MJ and 282.1 gCO_2-eq/MJ at 70% efficiency, respectively. The combination with wind power results in GHG emissions of about 40 gCO_2-eq/MJ, while photovoltaics achieve 50 gCO_2-eq/MJ. If the heat required for DAC is provided by waste heat instead of burning natural gas, the GHG emissions drop to a minimum of 8.4 gCO_2-eq/MJ for use of hydropower, 11 gCO_2-eq per MJ for wind power, 28 gCO_2-eq per MJ for photovoltaics, and to a maximum of 259.1 gCO_2-eq/MJ for grid electricity. Emissions from the construction of power generation plants and production sites, all located in Germany, are taken into account. The study considers high-temperature electrolysis and DAC in combination with FTS and subsequently upgrading to final fuel.

Considering the latter part, the upgrading of the synthesis product, the majority of the literature sources evaluated do not provide precise information on the refining of e-crude, although either referring to end products such as diesel or explicitly assuming the end product to correspond to diesel [13,14,28,32–34]. Only in [27], the energy demand for the post-treatment of the FT product is quantified with the equivalent of 5 kJ electrical and 31 kJ thermal energy per MJ product (LHV), and there, it is provided in-process by the combustion of the light hydrocarbon fractions (C1–C4) in a cogeneration plant, since the direct recycling of the light hydrocarbons into the synthesis process contradicts common practice in existing GtL plants.

A qualitative comparison between the refining of fossil crude oil and e-crude as a product of Fischer–Tropsch synthesis is provided in [35], concluding that the energy requirement for refining the synthetic fuel is lower than in the conventional case as several process steps with relatively high energy demand can be eliminated while others are modified or new ones added. The available data vary by a power of ten and range from 0.036 MJ per MJ product (LHV) in [27] to an upper limit of 0.13 MJ per MJ (LHV) in [36], which again is consistent with data in [37,38], or 0.43 MJ per MJ (LHV) in [35], respectively. Curiously enough, a comparison of the data used in the older studies for the crude oil throughput in U.S. refineries in the mid 1970s and the required energy demand with the more recent studies shows that the values quoted can still be seen as up to date.

The system designs from the selected literature were compared in the next step with regard to their components, process steps, and system boundaries in order to obtain information on the comparability of the results for the environmental impacts. Finally, the extent to which the studies provided information on the distribution of environmental impacts among the individual process steps was examined and the assumptions found were compared. It was assumed that if the process design is sufficiently similar, a comparison with regard to the derived GHG emissions between individual pathways from [14] and other literature sources is permissible. The process design must include direct air capture of CO_2, hydrogen from electrolysis, synthesis via the Fischer–Tropsch route, and consideration of plant construction, refining, and combustion of the fuel. The supply pathways 10 to 19 from [14], as well as three other literature sources [13,28,34], met the similarity criteria defined above and consequently were included in the comparison.

In a next step, it was assumed that processes with similar enough designs and GHG emissions in a comparable order of magnitude also have a similar distribution of the respective environmental impacts among the individual process steps. From [14], where a systematic comparison between different generic supply pathways is conducted on the basis of uniform assumptions, an arithmetic mean value for the proportional contributions of the individual process steps to the specific GHG emissions of the fuel was calculated. As the data showed wide variation, an interval was then defined for the Fischer–Tropsch synthesis's share, which comprised at least 70% of the supply pathways. That interval of the share was, in accordance with the available data, defined for the years 2015, 2030, and 2050 and subsequently used in the bottom-up analysis as a basis for the assumptions on the Fischer–Tropsch synthesis's contribution to the emissions, where the year 2015 served as a reference for the current status.

In order to determine the GHG emissions of the transport of e-crude, nine transport routes and means were examined. Specifically, the production of e-crude in Chile or Saudi Arabia was considered. For the transport route within Germany, it was assumed that the electrolysis and FTS plants are located in the immediate vicinity of refineries. The entire transport route was divided into two sections. The first section describes the transport of e-crude via ocean-going tankers to Europe. In the second section, the e-crude is further transported within Europe to the refineries via pipelines or barges. An overview of the transport routes can be found in Appendix C.

For the first section of the transport route, a distinction was made between the route from Saudi Arabia to Europe and Chile to Europe. The calculation of the GHG emissions for the first transport section is based on [39], which has worked out the specific GHG emissions for different transport routes based on a sample in the scope of 70,000 oil shipments. The transport route from Saudi Arabia to Europe using the trade route from the Arabian gulf to Europe was estimated at 5126 km. The specific GHG emissions for the route from Chile to Europe were extrapolated using a transport distance of 14,000 km.

The pipeline routes as the second transport section include the Wilhelmshaven–Hamburg (NDO), Wilhelmshaven–Wesseling (NWO), Rotterdam–Wesel (RRP–Wesel), Rotterdam–Wesseling (RRP–Wesseling), and Trieste–Karlsruhe (TAL) connections. Regarding the GHG emissions of the transport of e-fuel, only consumption at pumping stations was taken into account on the basis of the available literature i.e., any differences in altitude along the route were omitted due to the limited availability of consumption data. Furthermore, with regard to pipeline transport, only the German electricity mix was used as a general basis for the calculations of energy consumption. The GHG emissions for pipeline transportation are based on [40], which states that pumping stations along the pipeline route require about 0.5% of the transported energy for their operation. Based on the length of the route, the associated number of pumping stations, the density of the e-crude, and the average amount of crude oil transported each year, the GHG emissions were determined. Since this approximate procedure is prone to a certain inaccuracy in the determined GHG emissions, an overall average value of the transport routes was added to the total GHG emissions of the e-fuel use in Germany to account for the emissions linked to the crude and fuel transport.

3. Results

The results found in the literature study were checked for comparability according to the previously explained specification. The calculated GHG emissions over the entire life cycle for supply paths 10 to 19 from [14] as well as for the similar system designs from [13,28,34] were deemed comparable accordingly and are illustrated in Figure 1.
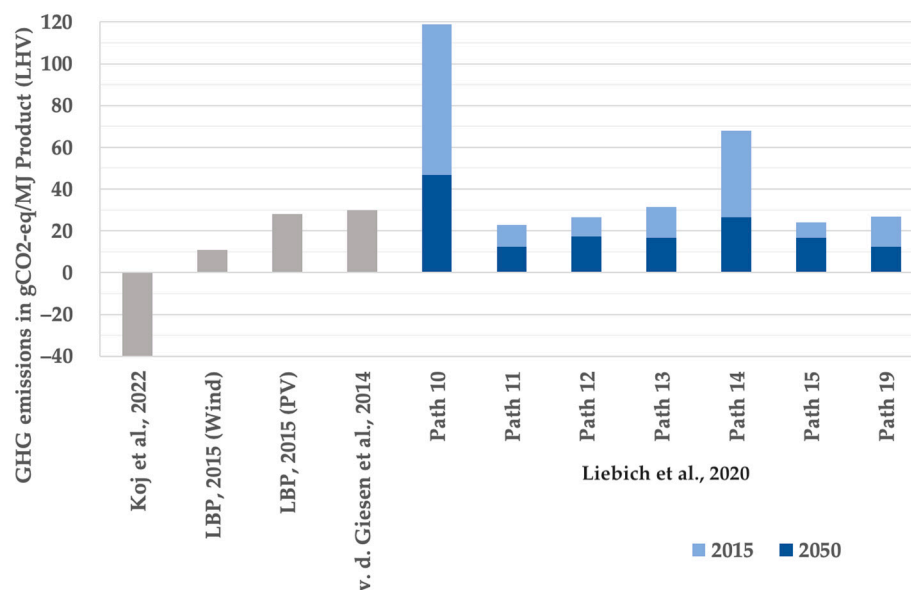
Figure 1. GHG emissions in gCO$_2$-eq per MJ product (LHV) of Fischer–Tropsch fuels from literature review, pathways 10 to 19 at full load operation of the electricity source [13,14,28,34].

The technical specifications of the system designs from Figure 1 are detailed in Table 3.

Table 3. System details for the studies on the horizontal axis label in Figure 1.

Literature Reference	CO$_2$-Source	Power Supply	Type of Electrolysis
Koj et al., 2022 [13]	DAC	Wind power 2050	Proton exchange membrane electrolysis
LBP, 2015 [34]	DAC	Wind/PV	High-temperature electrolysis
v. d. Giesen et al., 2014 [28]	DAC	PV	Alkaline electrolysis
Liebich et al., 2020 [14]	DAC	Renewables (diverse)	Alkaline electrolysis and high-temperature electrolysis

From Figure 1, as a first approximation, GHG emissions of 20 to 30 gCO$_2$-eq per MJ product (LHV) of Fischer–Tropsch fuels can be derived. At the same time, the great variety in the results is apparent, ranging from −40 gCO$_2$-eq to 119 gCO$_2$-eq per MJ, the latter even exceeding the refence value for fossil fuels of 89 gCO$_2$-eq per MJ from [14].

One of the aims of this work was to break down the distribution of GHG emissions between the individual process steps wherever possible. However, only source [14] in the literature study provided information on the environmental impacts of the synthesis step. For own calculations in the bottom-up analysis, a relative share of the synthesis in the total GHG emissions was therefore used, which was determined as an arithmetic mean value of a fluctuation interval. For this purpose, the percentage shares of the synthesis plant in the GHG emissions of the electricity-based power-to-liquid pathways from [14] utilizing both DAC as a CO$_2$ source and renewable electricity sources i.e., pathways 10–19, were calculated. In the reference year 2015, the share of synthesis in the GHG emissions for the majority (over 70%) of these pathways is between 9% and 15% for full utilization of the electricity source, with 12% as an arithmetic mean value. The same value is used in the bottom-up analysis for the reference year 2021. By 2030, this share falls below 5%, with an arithmetic mean value of the fluctuation interval of 4%; another 1% of decline can be witnessed up to 2050. The derivation of relative shares from [14] served as an intermediate step in order to ultimately calculate absolute GHG emissions. As it can be assumed that the synthesis step is performed at the same efficiency in the three considered countries, the

absolute GHG emissions are independent of the location. Accordingly, the relative shares presented in Table 4 differ between the countries, while for Germany, they correspond to the mean value derived from [14] in the intermediate step.

Table 4. Relative contribution of the three main e-fuel production steps to CO_2-eq emissions.

	Process	**Germany**	**Saudi Arabia**	**Chile**
2021	Electrolysis	88%	87%	87%
	FT	12%	11%	11%
	Transport	0%	1%	2%
2030	Electrolysis	96%	94%	94%
	FT	4%	4%	4%
	Transport	0%	2%	3%
2050	Electrolysis	97%	92%	58%
	FT	3%	3%	2%
	Transport	0%	5%	40%

From the bottom-up approach, it can be seen that freshwater availability is a crucial limiting factor for e-fuel production. The analysis of the AQUASTAT database on water resources of the Food and Agriculture Organization (FAO) of the United Nations shows that in Germany and Chile, further extraction of freshwater would be possible. In contrast, Saudi Arabia faces critical water stress and can therefore not provide further groundwater or surface freshwater. Consequently, the production of e-fuels in Saudi Arabia needs to be based on desalinated saltwater.

Figure 2 illustrates the CO_2-eq emissions of e-fuels while including all considered scenarios for the provision of feedstocks and puts them in comparison with conventional fuel. Taking into account the upstream chain emissions, 2.73 kgCO_2-eq/L gasoline and 3.08 kgCO_2-eq/L diesel are emitted [41], leading to an average of 2.91 kgCO_2-eq/L for conventional fuel. The red line illustrates the CO_2-eq of conventional fuel, serving as a benchmark against which the considered scenario of e-fuel consumption in Germany is compared. It delineates the threshold beyond which the CO_2-eq of e-fuels surpass the CO_2-eq of conventional fuel.
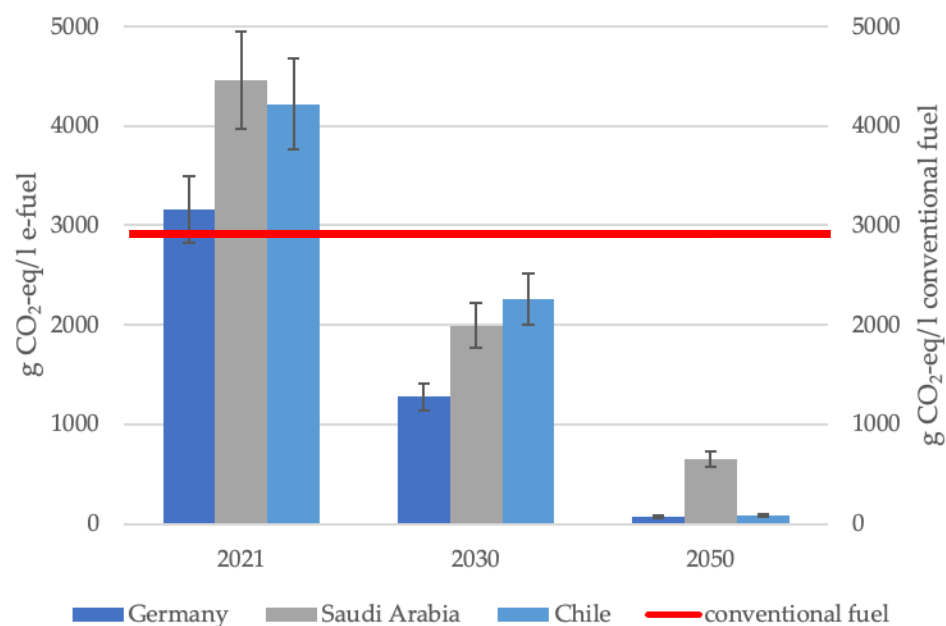
Figure 2. CO_2-eq emissions per liter e-fuel compared with conventional fuel.

Figure 2 contains the average of eight considered scenarios for the respective country and year. Additionally, the variation in scenarios is mapped by the error bars.

The comparison of the specific GHG emissions of e-fuels and conventional fuels shows the following:

- In every scenario for e-fuel production in the reference year 2021, the GHG emissions for production in Saudi Arabia and Chile are still higher than those of conventional fuels.
- For production in Germany, four out of eight scenarios lead to higher GHG emissions in the reference year 2021, while the remaining four scenarios lead to marginal CO_2-eq savings already in 2021 (see Appendix B).
- For all countries, the scenarios from 2030 and beyond lead to less CO_2-eq/L compared to conventional fuels.

As shown in Table 4, the process step contributing the most to GHG emissions is electrolysis.

The energy mix used for feedstock production is therefore the major factor for GHG emissions during the production of e-fuels. Due to the efforts of the considered countries to increase the share of renewable energies in their energy mix, the specific CO_2-eq emissions will decrease over time. Moreover, increased efficiency in the production process will reduce the energy demand for the provision of feedstocks and electrolysis.

4. Discussion

The objective of this article was to answer the following research question: "What are the GHG emissions of e-fuels produced via the SOEC and FTS route for use in Germany?" The scenarios considered in this context show that currently (2021), the emissions for e-fuel production using grid electricity still mostly exceed those of fossil fuels, which is in line with the findings in [13,14,27,30,34]. The exceptions are four scenarios for production in Germany, which show slightly reduced CO_2-eq emissions already in 2021. Although the GHG emissions from the use of e-fuels in Germany decrease drastically in the considered scenarios for 2050, it cannot be concluded that e-fuels should be a direct substitute for fossil fuels allowing for a continuation of current consumption patterns. The usage of e-fuels in motorized individual transportation in particular has major disadvantages. Firstly, as shown above, in most scenarios, the current GHG emissions of e-fuels still exceed those of conventional fuels. Secondly, the costs of e-fuels are not yet economically feasible. Current prices are estimated at 3.4 EUR/L and are predicted to reach 2 EUR/L in 2030 [42]. On the contrary, private companies' claims of reaching final prices of 1.2 EUR/L in 2030 exist [43]. Yet, no scientific studies or real-life experiences can back this claim. Thirdly, the energy conversion efficiency at 10–35% is much below that of direct or battery electric vehicles [44]. Fourthly, the production of e-fuels is at present only available in R&D facilities and first smaller-scale production sites. Norsk e-fuel as the currently largest manufacturer is aiming for a capacity of 50 mio·l/year (corresponding to 40,000 tons/year) after completion of their first plant in 2026 and a supply of over 250 mio·l/year from a total of three plants in 2030 [45]. Therefore, broad application of e-fuels is not yet secured. In conclusion, a broad substitution of fossil fuels by e-fuels is so far neither applicable, economically feasible, nor energy efficient compared to direct electricity usage. Nevertheless, e-fuels offer an important option for defossilization in areas that cannot be electrified and are therefore difficult to decarbonize, and where, in addition, energy carriers with high energy density are needed, as pointed out in a similar way in [28]. These are, in particular, heavy non-road machinery such as rescue vehicles used in natural disaster areas, military vehicles, aviation, and deep-sea shipping. The exclusive usage of e-fuels in niche areas is likewise discussed in [28].

Regarding the determined GHG emissions, this study is also based on the assumption that the considered countries (Germany, Saudi Arabia, Chile) meet their self-defined targets for the expansion of renewable energies. On the basis of historical data, however, this would require a much greater effort on the part of the countries concerned than in the past. If the respective shares of renewable energies in the national grid remain below the targets aspired

to, the GHG emissions increase compared to the presented results. Furthermore, in order to effectively reduce the GHG emissions, additional renewable energy is required for e-fuel production as is also emphasized in [34]. The additionality is essential to avoid CO_2-eq balance shifts within a country. On the one hand, the redistributed use of renewable energy would lead to a reduction in e-fuel emissions if considered individually. On the other hand, without additional (newly built) renewable energy in the electricity grid, the renewable energy demand allocated to all other consumers would simply be substituted with fossil energy, which would actually lead to an increase in the overall GHG emissions of a country due to the increased overall energy demand. Therefore, the importance of mandatory requirements for the determination of the system boundary against the background of emission allowance trading is also emphasized in [29], supporting our findings.

In the scope of this article, solely the current water availability in the three analyzed countries has been taken into account for the use of ground/surface water. However, according to [46], the future water availability in Germany and Chile might also differ e.g., as a consequence of climate change. Hence, the availability, cost of freshwater and the social acceptance of freshwater use for e-fuel production can lead to future challenges and have to be further evaluated. The alternative use of salt water desalination does not lead to a supply issue. Yet, this energy-intensive process also requires additional renewable energy [14]. Lastly, other potential environmental impacts (such as on marine ecosystems due to the brine disposal) must also be further investigated for desalination processes.

It was assumed that if the system designs of the investigated processes are similar enough, the calculated GHG emissions for the individual supply paths from [14] are comparable with the data from the other literature sources [13,28,34]. This assumption was used to check the consistency of the various literature values and see if the distribution of the environmental impacts among the individual process steps from [14] could be used for orientation. In this next step, it was assumed that similar enough process designs also result in similar shares of the respective process steps in the environmental impacts, and that the average share of synthesis for the supply paths from [14] could therefore be transferred to our bottom-up calculation. As the synthesis step is of minor importance in terms of environmental impact compared to the electrolysis and CO_2 capture, this assumption was not considered to lead to a significant miscalculation. Furthermore, the results of our calculation are consistent with the conclusion in [13], according to which the share of electrolysis accounts for about six times the environmental impact of the other process steps. The findings of this study also correspond with other studies that focus on e-fuel production even though deviating production processes have been examined [28,29,47].

One aspect that often is excluded from LCA studies but also deserves some attention is the refining of e-crude. As outlined above, it is difficult to quantify the required energy demand and even more, the associated emissions. However, as soon as e-crude is more than just a blend in existing refineries, a different infrastructure will be required, resulting in emissions not only for operation, but also for the construction of the corresponding plants [35].

Overall, in recent studies, the environmental impacts of high-temperature electrolysis are estimated to still be higher compared to other types of electrolysis [14]. This results from the assumed significantly lower stack lifetime of a technology still under development, which cannot be fully compensated for by the efficiency advantage at this stage. However, it should also be noted that a service life of 10,000 operating hours as assumed in [14] may now no longer correspond to the actual state of the art due to the technical progress. Furthermore, while effects of variation in location, CO_2 source, power source for electrolysis, electrolysis type, and transport route are directly compared in [14], the synthesis type remains constant. In order to find the most efficient production route, a further comparison with a system combining high-temperature co-electrolysis and methanol synthesis would therefore be interesting for future work.

In our study, we focused exclusively on the greenhouse gas emissions of e-fuels produced by high-temperature electrolysis in combination with Fischer–Tropsch synthesis.

We thereby excluded other aspects, yet not for lack of importance. In particular, the social aspects and other impacts of a global e-fuel production and trade network must be considered separately. Research in this field is absolutely necessary in order to avert negative side effects, especially in the producing countries, and not to drift into a new energy colonialism [48–50].

5. Conclusions

Overall, e-fuels can be an environmentally beneficial alternative to conventional fuels. Nevertheless, it is crucial that additional renewable energy be used along the whole production chain, which must be designed as efficiently as possible. Otherwise, as shown in this study, the GHG emissions may even exceed those of conventional fossil fuels. Finally, the application should be prioritized and limited to use cases that are hard to decarbonize. In the ecological dimension, aspects other than a sole reduction in GHG emissions have to be investigated further, such as the disposal of brine stemming from sea water desalination plants or land use due to power generation plants. More research is also needed on other aspects from the social sustainability dimension especially, which have so far tended to be left out of many debates on e-fuels [48–50].

Appendix A

Table A1. Overview of the scenarios considered for the provision of feedstocks for the electrolysis.

Scenario	Electricity Source	Water Treatment *	CO2 Source
1	Grid	Conventional pre-treatment and reverse osmosis	Direct air capture
2	Grid	Conventional pre-treatment and ion exchange	Biomass (organic waste)
3	Grid	Combined treatment	Direct air capture
4	Grid	Reverse osmosis	Direct air capture
5	Grid	Conventional pre-treatment and reverse osmosis	Biomass (organic waste)
6	Grid	Conventional pre-treatment and reverse osmosis	Cement production
7	Grid	Reverse osmosis	Biomass (organic waste)
8	Grid	Reverse osmosis	Cement Production

* For Saudi Arabia, the water treatment is restricted to reverse osmosis of salt water.

Appendix B

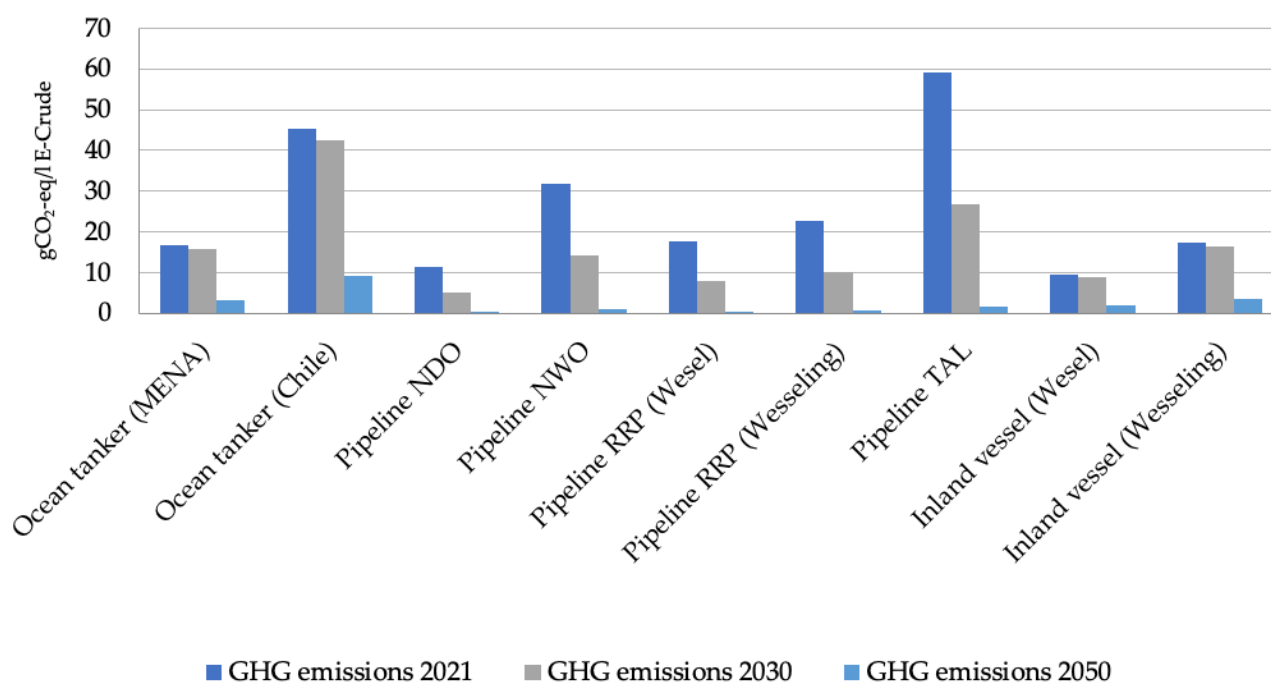**Table A2.** GHG emissions of the considered scenarios according to country and year.

	Gramm CO_2-eq Emissions/L e-Fuel								
	2021			**2030**			**2050**		
Scenario	**Germany**	**Saudi Arabia**	**Chile**	**Germany**	**Saudi Arabia**	**Chile**	**Germany**	**Saudi Arabia**	**Chile**
1	3476	4923	4654	1403	2202	2498	82	726	92
2	3475	4922	4652	1403	2201	2497	82	726	92
3	3476	4924	4654	1403	2202	2498	82	726	92
4	3476	4923	4653	1403	2202	2498	82	726	92
5	2902	4044	3829	1195	1797	2042	66	582	75
6	2789	3966	3753	1116	1761	2000	64	569	74
7	2902	4046	3828	1195	1798	2042	66	582	75
8	2789	3966	3752	1116	1762	2000	64	569	74

Appendix C

Table A3. Overview of the transport routes and means.

	Route	Transportation	Distance in km	Pumping Stations
1	Saudi Arabia–Europe	Ocean tanker	5126	-
2	Chile–Europe	Ocean tanker	14,000	-
3	Wilhelmshaven–Hamburg	Pipeline	142	1
4	Wilhelmshaven–Wesseling	Pipeline	391	3
5	Europoort–Wesel	Pipeline	220	2
6	Europoort–Wesseling	Pipeline	280	2
7	Triest–Karlsruhe	Pipeline	731	10
8	Europoort–Wesel	Inland vessel	365	-
9	Europoort–Wesseling	Inland vessel	666	-

Appendix D

Figure A1. GHG emissions of the considered transport routes and means at the different points of time analyzed.

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