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Life Cycle Assessment and Uncertainty Analysis of German Import Strategies for Hydrogen and Ammonia

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ABSTRACT

Green hydrogen, produced via renewable electricity and water electrolysis, is a cornerstone in Germany's net zero strategy. Since renewable electricity is not always available where needed, Germany plans to import hydrogen from regions with high renewable resources. However, hydrogen's low volumetric density makes transport difficult, thus, importing ammonia instead is a promising alternative. We present a comprehensive Life Cycle Assessment of hydrogen and ammonia imports to Germany from 13 exporting countries. We evaluate 16 environmental impact categories across multiple scenarios and uncertain input parameters. For ammonia, we evaluate both its role as fuel for direct utilization and as hydrogen carrier. The domestic renewable and fossil production of hydrogen and ammonia in Germany serve as benchmarks. We quantify uncertainties using Monte Carlo Analysis and conduct a Global Sensitivity Analysis to identify the most sensitive input parameters. Our comprehensive assessment including uncertainties enables robust recommendations: Ammonia imports via ship and hydrogen imports via pipeline are environmentally favorable strategies across all scenarios. Ammonia imports should be prioritized to meet the domestic ammonia demand in Germany before using ammonia as hydrogen carrier. Shipping hydrogen can achieve low environmental impacts if hydrogen is used as shipping fuel. Compared to the domestic fossil production in Germany, a diversified import portfolio can achieve greenhouse gas emission reductions of 74 % and 85 % in a 2030 and 2045 scenario, respectively. However, increased material demands due to high electricity demands cause environmental burden-shift in at least six categories, for which we propose mitigation strategies for future work.

1. Introduction

The mitigation of climate change requires the decarbonization of different sectors, such as the heat, power, chemicals, steel and mobility sector. In many cases, electrification via renewable energy sources (RES) such as wind and solar energy offers a viable pathway [1]. However, electrification faces two major limitations. First, some sectors (e.g. steel and chemicals) are hard to electrify and require fuels with high energy densities [1]. Second, countries with limited renewable resources, such as Germany and Japan, are unable to generate sufficient renewable energy locally [2]. These limitations can be overcome through the import of low-carbon fuels from regions with high availability of RES [2].

One of the most discussed low-carbon fuels is green hydrogen, which

List of abbreviations: RES, Renewable energy sources; HB, Haber-Bosch; CO_2, Carbon dioxide; IRENA, International Renewable Energy Agency; LCA, Life Cycle Assessment; GHG, Greenhouse gas emissions; MCA, Monte Carlo Analysis; LOHC, Liquid organic hydrogen carriers; JRC, Joint Research Center; GSA, Global Sensitivity Analysis; GWI, Global Warming Impact; GWP, Global Warming Potential; UA, Uncertainty Analysis; LHS, Latin Hypercube Sampling; LCIA, Life Cycle Impact Assessment; FU, Functional Unit; LCI, Life Cycle Inventory; DE, Germany; MO, Morocco; NO, Norway; ICE, Iceland; CAN, Canada; CHL, Chile; AUS, Australia; BRA, Brazil; SAU, Saudi-Arabia; NAM, Namibia; ESP, Spain; DEN, Denmark; IN, India; EGY, Egypt; SMR, Steam Methane Reforming; ASU, Cryogenic air separation unit; LH2, Liquid hydrogen; HFO, Heavy fuel oil; BOG, Boil-off gas; EF, Environmental Footprint; CI, 95% Confidence Interval; A_{tfw}, Acidification; ET_{FW}, Ecotoxicity of freshwater; E_{FW}, Eutrophication of freshwater; RD_{mm}, Resource depletion of metals and minerals; RD_e, Resource depletion of energy resources; PM, Particulate matter formation; IR, Ionising radiation; LU, Land use; WS, Water use; E_m, Eutrophication marine; E_t, Eutrophication terrestrial; HT_c, Human toxicity carcinogenic; HT_{nc}, Human toxicity non-carcinogenic; OD, Ozone depletion; PCOF, Photochemical oxidant formation; H_2-S, Liquid hydrogen transport via ships; H_2-P, Compressed hydrogen transport via pipelines; H_2-NH_3-S, Ship transport of ammonia as hydrogen carrier; H_2– NH_3-P, Pipeline transport of ammonia as hydrogen carrier; NH_3-S, Ship transport of ammonia; NH_3-P, Pipeline transport of ammonia.

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is produced via water electrolysis powered by renewable electricity [3]. Green hydrogen offers a wide range of promising use-cases, such as storing volatile renewable electricity, providing low-carbon heat and power through combustion and supporting low-carbon steel production as reduction agent [4]. However, hydrogen's low volumetric density poses challenges for storage and transport [5,6]. To increase hydrogen's volumetric density, it needs to be compressed or liquefied before storage and transport, requiring high amounts of energy [7].

Ammonia is a promising alternative as its high volumetric energy density addresses the drawbacks associated with hydrogen transport and storage [8,9]. Additionally, ammonia's low storage and shipping costs make it an attractive alternative to hydrogen [10]. Furthermore, a well-established global infrastructure for ammonia transport already exists due to its critical role in fertilizer production [11,12]. Ammonia also has flexible applications: It can be used directly or reconverted into hydrogen [13]. Currently, over 96 % of ammonia is produced via the fossil Haber-Bosch (HB) process [14], which accounts for 1.2 % of the global carbon dioxide (CO_2) emissions [15]. Green ammonia can be produced using an electrified HB process, which emits significantly less CO_2 emissions if powered by renewable electricity [16].

Germany is expected to become a major importer of hydrogen and ammonia [17–19]. Germany's current annual hydrogen demand is 55 TWh [18], while its annual ammonia demand is 12 TWh [12]. According to Germany's National Hydrogen Strategy, demand for hydrogen and its derivatives is projected to reach 95–130 TWh by 2030 [18], and could rise as high as 420–887 TWh by 2045 [20]. Several studies emphasize that imports are necessary for Germany to meet the high demand [20–22]. Thus, the National Hydrogen Strategy projects hydrogen and hydrogen-derivative imports of 45–90 TWh by 2030. By 2045, the International Renewable Energy Agency (IRENA) projects 206 TWh of ammonia and 238 TWh of hydrogen imports for Germany [23]. In fact, the German government even published a separate import strategy for hydrogen and hydrogen-based derivatives due to its importance [19]. Despite these ambitious targets, few studies provide a comprehensive environmental assessment of renewable hydrogen and ammonia import pathways to Germany.

Previous studies have evaluated the environmental impacts of hydrogen and ammonia supply chains. Alghool et al. [24] find that compressed hydrogen transport achieves the lowest Global Warming Impact (GWI). Lilonfe et al. [25] emphasize that supply chains delivering compressed or liquid hydrogen achieve lower GWI than supply chains delivering hydrogen via ammonia or methanol. Ishimoto et al. [26] and Son et al. [27] also state that if hydrogen is the desired end product, importing liquid hydrogen can have a lower GWI than using ammonia as hydrogen carrier due to the energy-intensive ammonia splitting process. Al-Breiki et al. [28] show that PV-based liquid hydrogen imports achieve a lower GWI than importing PV-based ammonia. On the other hand, Kwak et al. [29] point out that if ammonia is the desired end product, the import of ammonia can have a lower GWI. Furthermore, Noh et al. argue that ammonia imports via ships are more promising than liquid hydrogen because of existing infrastructure for ammonia [30]. Coppitters et al. [31] and Ishimoto et al. [26] also show that ammonia imports should be preferred over hydrogen for long distances. While the environmental impacts of hydrogen and ammonia supply chains have been studied in previous literature, the environmental trade-offs between ammonia's role as fuel for direct utilization and as hydrogen carrier have not yet been systematically addressed.

Moreover, none of the mentioned studies focus on Germany as an importing country, nor do they conduct a detailed Uncertainty Analysis (UA). Recently, the Joint Research Center (JRC) of the European Commission conducted an LCA of different hydrogen supply chains within Europe [32]. The study highlights that data on hydrogen supply chains are subject to uncertainties due to ongoing technological development. To address these uncertainties, the authors conducted one-at-a-time sensitivity analyses of selected parameters [33]. However, since there are many parameters which are uncertain, varying one parameter at a time can be misleading in LCA studies [34]. A detailed consideration of uncertainties in LCA studies can be achieved by combining Monte Carlo Analysis (MCA) and Global Sensitivity Analysis (GSA) [35]. The MCA quantifies the uncertainties of the environmental impacts, while the GSA identifies the most sensitive uncertain input parameters.

To the best of our knowledge, only three studies consider uncertainties in the environmental impacts of hydrogen supply chains [36–38]. Ozawa et al. assess the uncertainties in the GWI of hydrogen supply chains using MCA, however, the authors do not include ammonia as hydrogen carrier or conduct a GSA [37]. De Kleijne et al. determine the GWI of green hydrogen production facilities and assess transport via pipelines and ships for both hydrogen and ammonia, while accounting for uncertainties [36]. However, De Kleijne et al. also omit a GSA, thus, providing limited insights on uncertainties. While Bennett et al. apply both MCA and GSA, the study focuses on hydrogen production pathways for the United Kingdom (UK), not considering import scenarios [38]. Furthermore, none of the three studies focuses on Germany as importing country.

Several studies have assessed the environmental impacts of hydrogen imports to Germany, however, several shortcomings remain. Kanz et al. evaluate the GWI of producing and transporting PV-hydrogen from Africa to Germany via pipelines [39] and ships [40]. Hermesmann et al. compare the GWI of renewable hydrogen imports via pipelines to the hydrogen production in Germany [41], while Kolb et al. assess the environmental impacts for liquid hydrogen imports via ship [42]. Kockel et al. determine the environmental impacts of hydrogen imports to Germany via ships, pipelines and ammonia as hydrogen carrier from eight promising countries [43]. Scheffler et al. evaluate the costs and GWI of four hydrogen carriers via ships, including ammonia and liquid hydrogen [44]. The studies consistently find that importing renewable hydrogen to Germany – whether via pipelines, ships or via ammonia as hydrogen carrier – can result in a lower GWI than the local fossil or renewable hydrogen production, particularly when imports originate from regions with significantly higher renewable full load hours.

In summary, while previous studies have evaluated the environmental impacts of hydrogen and ammonia supply chains, none have comprehensively assessed these impacts for Germany as an importing country, particularly with a detailed analysis of uncertainties using both MCA and GSA. Moreover, previous studies have primarily focused on ammonia's role as a hydrogen carrier, neglecting its role as fuel for direct utilization, which could be more environmentally favorable due to the emission-intensive ammonia splitting process [45].

To address the identified research gaps, we conduct a comprehensive LCA considering multiple scenarios and uncertainties to evaluate import strategies and derive robust recommendations for Germany to meet its energy demand for renewable hydrogen and ammonia. Specifically, we assess the environmental impacts of renewable hydrogen and ammonia imports from 13 exporting countries. Our assessment includes both pipeline and ship transport as import options. For ammonia, we evaluate both its role as fuel for direct utilization and as a hydrogen carrier. To assess potential environmental burden-shifts from fuel imports, we analyze 16 different impact categories as recommended by the JRC [46]. Since the primary motivation for hydrogen and ammonia imports is the mitigation of climate change, we address uncertainties in the climate change impacts of hydrogen and ammonia supply chains by quantifying these uncertainties using a Monte Carlo Analysis (MCA) and conducting a Global Sensitivity Analysis (GSA) to identify the most sensitive input parameters. To provide further insights into the environmental burden-shift, we apply the MCA and GSA to another selected impact category besides climate change. We benchmark all import options against the renewable and fossil hydrogen and ammonia production in Germany. Ultimately, our study determines, when, from where and how Germany should import hydrogen and/or ammonia, and the circumstances when local production is preferable, while incorporating uncertainties and various scenarios.

2. Data and methods

This study follows the four steps illustrated in Fig. 1. First, the environmental impacts of the supply chains are modeled using Life Cycle Assessment (LCA). Next, it is distinguished between uncertainties in fore- and background data [35]. In the third step, uncertainties are propagated within the LCA model by sampling the uncertain parameters along assigned probability distributions and conducting a Monte Carlo Analysis, resulting in a distribution that reflects the overall uncertainties in the model output [47]. In the final step, a Global Sensitivity Analysis (GSA) is conducted to determine the most sensitive uncertain input parameters [48–50].

2.1. Life cycle assessment

The environmental assessment is conducted through an LCA as defined in the ISO 14040/44 standards [52]. An LCA study follows 4 steps: 1) Goal and scope definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA) and 4) Interpretation [52,53].

2.1.1. Goal and scope definition

This study compares the environmental impacts of importing hydrogen and ammonia to Germany with those of green and fossil fuel production in Germany. Therefore, the imported or locally produced energy quantity is chosen as functional unit (FU), i.e., *"1 MWh based on the lower heating value of imported or locally produced hydrogen or ammonia at 84 bar and 10 bar, respectively"*. For hydrogen, an end pressure of 84 bar at ambient temperature [54] is assumed, making it suitable for distribution via pipeline. For ammonia, an end pressure of 10 bar and ambient temperature is assumed, corresponding to liquid ammonia that is ready for distribution either via pipeline or trucks [8].

A cradle-to-gate system boundary is chosen, which includes the fuel production and transport but excludes the use-phase and end-of-life of the fuels (see Fig. 2). The port of Hamburg in Germany (DE) is defined as the common destination. This analysis considers 13 promising exporting countries: Morocco, Norway, Iceland, Canada, Chile, Australia, Brazil, Saudi-Arabia, Namibia, Spain, Denmark, India and Egypt. These countries are mentioned as potential exporting countries in Germany's import strategy [19] and have been identified as promising in other studies as well [55–58]. Explicit bilateral cooperations for hydrogen already exist with most of these countries [19]. For each exporting country, one representative existing or planned production site is chosen for solar PV and onshore wind electricity in regions with high capacity factors. Hydrogen or ammonia is produced at these sites and exported to Germany. The selection was based on publicly available project databases and literature sources identifying promising renewable export locations. Table 1 of the Supporting Information (SI) summarizes the country-specific data.

To capture a broad spectrum of potential environmental impacts, three scenarios are considered, which differ in both technological assumptions (e.g. energetic efficiencies, boil-off, shipping fuel) and the electricity source along the supply chain. The first scenario is the base case, which represents conservative current or near-future assumptions. In the base case, only the production of hydrogen and ammonia is powered by renewable electricity, while the remaining supply chain relies on grid electricity. The second scenario has the same technological assumptions as the base case, however, the supply chain is powered with renewable electricity (base case with renewable supply chain). The third scenario reflects an optimistic case, which assumes improved future technological assumptions and renewable electricity to power the supply chain. Across all scenarios, the transport routes supply 1 MWh hydrogen or ammonia as defined in the FU. All specific technological assumptions for each scenario are given in Section 2.1.2 and Section 1 and 2 of the SI.

Given 13 exporting countries, the local production in Germany and both base and optimistic case for each of the 14 countries, to improve the interpretability of the results, the number of routes are reduced and clustered. Firstly, all countries are categorized based on the transport distance: Close proximity (<500 km); short distance (500–5,000 km); middle distance (5,000–10,000 km) and long distance (>10,000 km). Six fuel transport routes are evaluated for each exporting country within short distance: Transport of liquid hydrogen via ships (**H_2-S**), compressed hydrogen via pipelines (**H_2-P**), liquid ammonia via ships or pipelines with subsequent splitting back into hydrogen (**H_2-NH_3-S** and **H_2-NH_3-P**) and two direct ammonia routes where liquid ammonia is transported via ships or pipelines (**NH_3-S** and **NH_3-P**). For the other countries, certain fuel routes are eliminated: For export locations in close proximity, only the pipeline routes (**H_2-P** and **NH_3-P**) are considered, while for export locations at medium and long distances, only consider shipping routes (**H_2-S**, **H_2-NH_3-S** and **NH_3-S**) are considered since long distance pipelines have too high investment costs [59]. The transport routes are depicted in Fig. 2.

2.1.2. Life cycle inventory

In the following, the main processes of the Life Cycle Inventory (LCI) are presented. Ecoinvent v3.9.1 is used to model all background processes [60]. The complete LCI can be found in Section 1.2 of the SI.

2.1.3. Electricity production

For each exporting country, excluding Iceland and Norway, a location for the production of photovoltaic (PV) and onshore wind electricity is selected. Locations with hybrid PV-/wind-electricity are not considered. For Iceland and Norway, it is assumed that the entire supply chain, including fuel production, is powered by grid electricity in both base and optimistic case, given that their electricity grids are 100 % renewable [23].

The environmental impact of the renewable energy sources depends on the location-specific capacity factor. To determine the location-specific capacity factor, Renewables.ninja [61–63] is used to export the average annual capacity factor for 2013–2022 for all considered locations. These average annual capacity factors are then averaged to one capacity factor per location. For onshore wind electricity, a Vestas V80 2000 wind turbine with a hub height of 80 m is assumed, while for PV electricity, a free-field PV plant with 10 % system loss, no tracking, a tilt angle of 35° and an azimuth of 180° is assumed. The construction impacts of the wind turbine and PV plant are modeled using ecoinvent

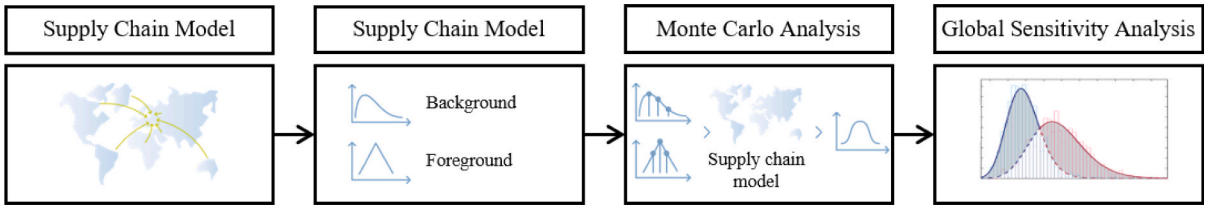


Fig. 1. Method overview, adapted from [33,35,51]. First, the supply chain model is set up to perform an environmental assessment using Life Cycle Assessment. Next, uncertain input parameters are identified and probability distributions are assigned. The uncertainties are propagated in the model using Monte Carlo Analysis. Finally a Global Sensitivity Analysis is conducted to determine the most sensitive input parameters.

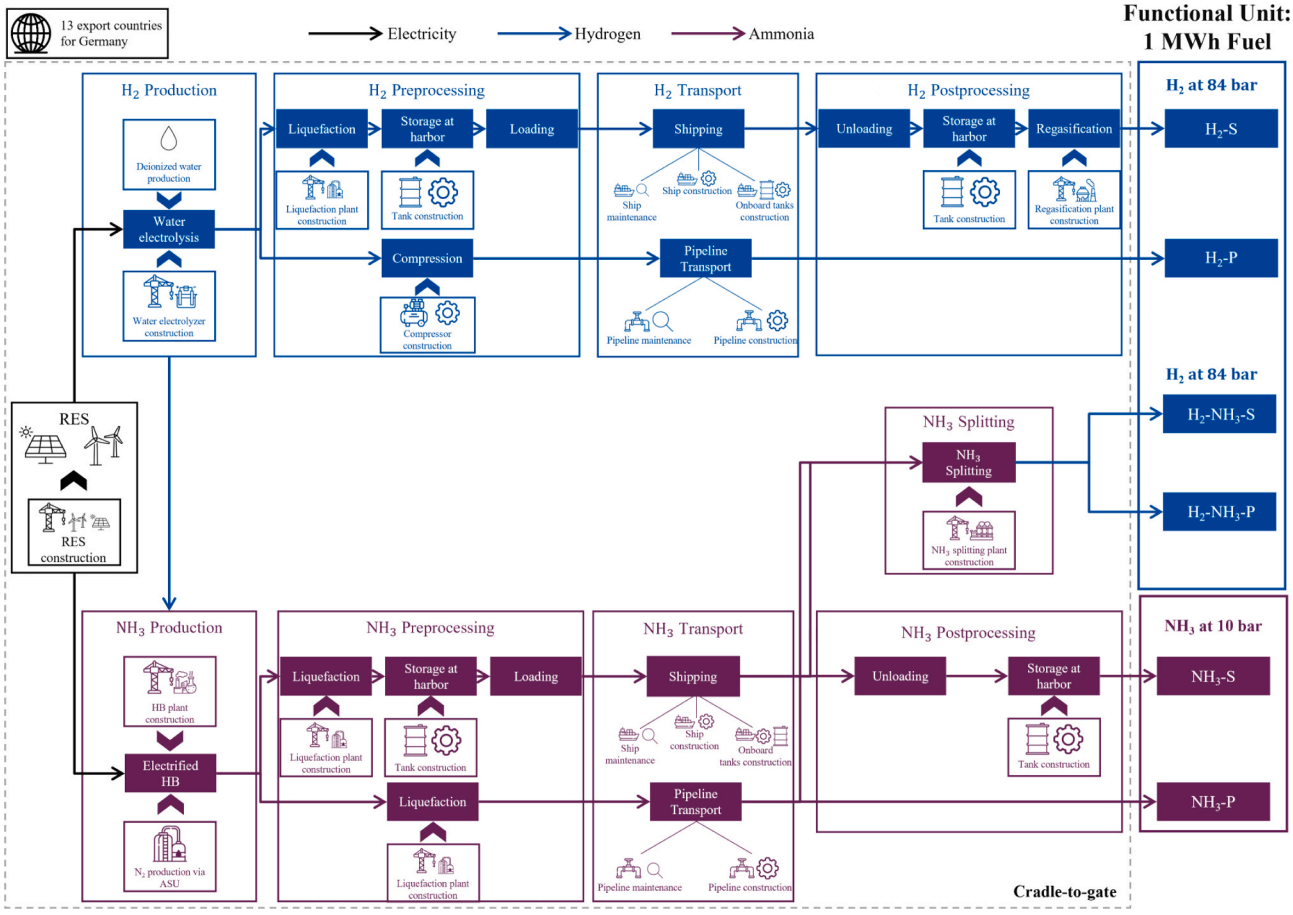


Fig. 2. Overview of the considered fuel transport routes with the cradle-to-gate system boundary. H_2-S and H_2-P describe the transport of liquid hydrogen via ships and the transport of compressed hydrogen via pipelines, respectively; H_2-NH_3-S and H_2-NH_3-P are the transport routes where ammonia is used as hydrogen carrier and transported via ships and pipelines, respectively; NH_3-S and NH_3-P describe the transport of 1 MWh ammonia via pipeline and ship, respectively. H_2: Hydrogen, NH_3: Ammonia, RES: Renewable energy sources, HB: Haber-Bosch, ASU: Air Separation Unit, N_2: Nitrogen.

processes [60]. Given the differing impacts of PV- and wind-based electricity, an important assumption is the ratio of PV- to wind-based fuel production for each exporting country. In the base case, the ratio of wind- and PV-based fuels corresponds to the ratio of wind- and PV-electricity generated by the exporting country [23]. In the optimistic case, projections for electricity generation and installed capacities forecasted for 2050 are utilized. However, increased wind generation is assumed, thus, half of the projected installed PV capacity up to 2050 is replaced by wind turbines. The data on the considered sites is summarized in Table 1 of the SI.

2.1.4. Hydrogen production

Green hydrogen production is modeled via proton exchange membrane (PEM) electrolysis, where deionized water is split into hydrogen and oxygen by using renewable electricity. Hydrogen is assumed to exit the PEM electrolysis at 20 bar and 80 °C [64]. For the materials consumed in the construction of the electrolyzer, the base and optimistic inventory models from Bareiß et al. [64] and Sharma et al. [65] are assumed. As a benchmark, a fossil hydrogen production via steam methane reforming (SMR) is assumed, adapting the LCI from Antonini et al. [66].

2.1.5. Ammonia production

Ammonia is produced via hydrogen and nitrogen in the Haber-Bosch (HB) process [15]. In the conventional HB, hydrogen and nitrogen are produced by SMR of natural gas. Green ammonia, on the other hand, is produced via an electrified HB process, which utilizes hydrogen produced through water electrolysis and nitrogen produced through a cryogenic Air Separation Unit (ASU) [67]. The HB process is assumed to operate isobar at 200 bar [60]. The inlet temperature of the feed is assumed to be 300 °C, while the outlet temperature of ammonia is assumed to be 420 °C [15]. The construction of the HB process is modeled using a chemical factory dataset in ecoinvent [60]. Due to the absence of SMR in the electrified HB process, it is assumed that additional electricity is required for the ASU as well as pre-heating and compressing hydrogen and nitrogen [32]. The conventional HB process is modelled according to D'Angelo et al. [15].

2.1.6. Pre- and postprocessing

Both ammonia and hydrogen require pre- and postprocessing before and after transport. For pipeline transport, preprocessing includes the compression of hydrogen [39] and the liquefaction of ammonia [32], while no additional postprocessing steps are required. However, for hydrogen and ammonia ship transport, additional pre- and post-processing steps include the liquefaction, loading and unloading and storage at the departure and receiving harbor (see Fig. 2) [68,69]. For hydrogen, additional regasification is required to meet distribution requirements.

2.1.7. Pipeline transport

The construction of hydrogen pipelines is modeled in accordance with two technical reports of the JRC [32,56], adapting the ecoinvent dataset for long distance natural gas pipelines to account for the required amount of steel and the hydrogen flow rate. For the

construction of the ammonia pipeline, a dataset for liquid petroleum pipelines from the ecoinvent database is assumed. This assumption is supported by Scott et al. [70], who demonstrate that ammonia can be transported in petroleum pipelines as a solution in a liquid hydrocarbon.

Recompression stations are required every 100 km along the hydrogen and ammonia pipelines to maintain operation. The recompression stations are powered entirely by electricity. The electricity impact is the average of the importing and respective exporting countries. The construction of the hydrogen compressor stations is modeled after Kanz et al. [39]. The construction of the ammonia pumping stations is modeled after an ecoinvent dataset for air compressors [60]. The leakage rates of hydrogen and ammonia pipelines have been modeled in accordance to Kanz et al. [39] and Galimova et al. [11], respectively.

2.1.8. Ship transport

Hydrogen and ammonia are shipped in liquid form. The model of a large liquid hydrogen (LH_2) ship, designed by Alkhaledi el al. based on an existing natural gas tanker is adapted in this work [71]. To ensure a fair comparison, the LH_2 and ammonia ship are assumed to have the same total ship weight and ship hull weight (total ship minus fuel and tank weight). The onboard tanks are modeled separately in accordance to Alkhaledi et al. [71] for hydrogen and Bartels et al. [72] for ammonia to account for their additional weight. The empty transfer runs are included in the calculation. Furthermore, an average load factor is included to consider the remaining gas that cannot be pumped out of the tanks, i.e., the ratio of transferred fuel to the maximum payload capacity [73].

In the base case, heavy fuel oil (HFO) is assumed as the shipping fuel, while in the optimistic case, it is assumed that ships are fueled with hydrogen or ammonia, respectively. The fuel consumption for the unloaded return is scaled according to Gorski et al. [74]. One of the main challenges of LH_2 storage is boil-off gas (BOG), which can lead to significant losses [28,69]. In the base case, BOG is emitted into the atmosphere as biosphere flow, but in the optimistic case, 99.9 % recovery is assumed and hydrogen and ammonia BOG can be used as auxiliary fuel [71].

2.1.9. Ammonia splitting

Ammonia splitting via thermal ammonia decomposition is the inverse endothermic reaction to ammonia synthesis [75–77]. The required energy demand can be met through electrical heating and the combustion of a fraction of the ammonia or unrecovered hydrogen [26,32]. The unrecovered hydrogen is combusted in a boiler, while the remaining heating demand is provided via electric heating. The construction impact is modeled using a dataset for chemical factories from ecoinvent [60].

2.1.10. Life cycle impact assessment

The method Environmental Footprint (EF) v3.1 [46] is used to translate the biosphere flows into environmental impacts. The main purpose of this study is to assess the environmental impacts of hydrogen and ammonia imports for Germany. The EF method is selected to ensure comparability with other EU- and Germany-focused LCA studies and to align with the European Commission's recommended LCIA framework for harmonized environmental assessments [46]. However, according to EF v3.1, the *GWP100* characterization factor of hydrogen is 0, whereas recent studies show that hydrogen could form methane or other greenhouse gases in the atmosphere and therefore also has a characterization factor [78]. A *GWP100* characterization factor of 11.6 for hydrogen has been assumed in this work [78].

As recommended by the JRC, 16 impact categories are included in this study to assess the risk of environmental burden-shifting.

2.2. Uncertainty analysis

To quantify the uncertainty of an impact category, a Monte Carlo Analysis (MCA) is conducted by repeatedly sampling uncertain input parameters and calculating the environmental impacts for each set of sampled inputs. After a large number of calculations, a distribution of the environmental impacts is obtained, which represents the uncertainty due to input variability. All input parameters are assumed statistically independent. For each transport scenario, 20,000 samples are generated using Latin Hypercube Sampling [79]. The key performance indicators to evaluate the uncertainties are included in Section 2.2 of the SI.

To conduct the MCA, probability distributions need to be assigned to the uncertain input parameters. The uncertainty in the input parameters can arise from three sources: Foreground system, background system and impact assessment methods [35]. The focus of this study is to quantify and analyze uncertainties within the supply chains, specifically targeting the fore- and background system. Background uncertainties arise from uncertainties in databases such as ecoinvent and foreground uncertainties pertain to the supply chain model developed in this study. Background uncertainties are assessed using uncertainty information for both techno- and biosphere flows from ecoinvent [60]. To reduce the number of uncertain parameters in the background system, the uncertainty distribution of an environmental impact category for each aggregated ecoinvent process is determined. To this end, an MCA of the aggregated ecoinvent process including its uncertain techno- and biosphere flows as input parameters is conducted. For the considered aggregated ecoinvent processes in this study, the resulting uncertainty distributions of the impact categories are found to follow a lognormal distribution.

For foreground uncertainties, probability distributions need to be assigned. Although some studies report empirical ranges for certain parameters, the underlying frequency data required to fit specific probability distributions are not available. Therefore, triangular probability distributions are assigned to the uncertain foreground parameters by determining the parameter range from literature. The mode of the triangular distribution is assumed to lie in the middle of the determined range. We further differentiate in the distributions for the base and optimistic case. In the base case, the range between the minimum and maximum value as well as the mode of the triangular distribution is assumed to be higher for some uncertain parameters. For example, the range of possible hydrogen emissions in the supply chain are assumed to be higher in the base case than in the optimistic case.

For the *GWP100* characterization factor of hydrogen, a triangular distribution with a deviation of 2.8 from the deterministic value is assumed [78]. For further details, the reader is referred to Section 2 in the SI.

2.3. Global sensitivity analysis

The primary objective of a sensitivity analysis is to investigate how various sources of uncertainty in model inputs influence the uncertainty of the model output [80]. According to Saltelli, a sensitivity analysis method needs to be global, quantitative and model-free [81]. Global means that the technique allows to consider the entire input distribution and model-free means that no assumptions on the functional relationship to the inputs is necessary to provide accurate results [49]. Saltelli further shows that variance-based methods meet the three requirements [81]. Among the variance-based methods, Sobol indices are commonly used sensitivity indicators [82].

The drawback of variance-based methods is that they implicitly assume that a statistical moment such as the variance is sufficient to describe output variability. However, according to Helton and Davis, any statistical moment (including the variance) only provides a summary of the probability distribution with inevitable loss of resolution [83]. Thus, Borgonovo adds a fourth feature to Saltelli's three requirements, namely moment-independence and propose a moment-independent Global Sensitivity Analysis (GSA) indicator named δ [49].

The key advantage of δ is that instead of relying on the variance, it evaluates how the entire output distribution changes in response to

variations in the input variables. This change is evaluated by calculating the expected shift between the unconditional probability distribution of the output and the conditional probability distribution of the output if one of the input parameters is fixed at a certain value [49]. The moment-independent property of δ can be advantageous when combining different types of input distributions. The mathematical formulation of δ can be found in Section 2.3 of the SI. Borgonovo further shows that the values of the sensitivity indicator δ lie between 0 and 1, with a value of 0 meaning that the model output is independent of the input parameter. Furthermore, Borgonovo proves that δ can be formulated in the presence of correlations among the input parameters. We calculate the δ-indicators using the Python library SALib [84,85].

3. Results

In Section 3.1-3.5, detailed results for Morocco, Saudi-Arabia and Chile (representative short, middle and long distance countries) are provided, while in Section 3.6, an overview of the Global Warming Impact (GWI) for hydrogen and ammonia imports from all 13 considered countries is provided. All further results can be found in Section 3 of the

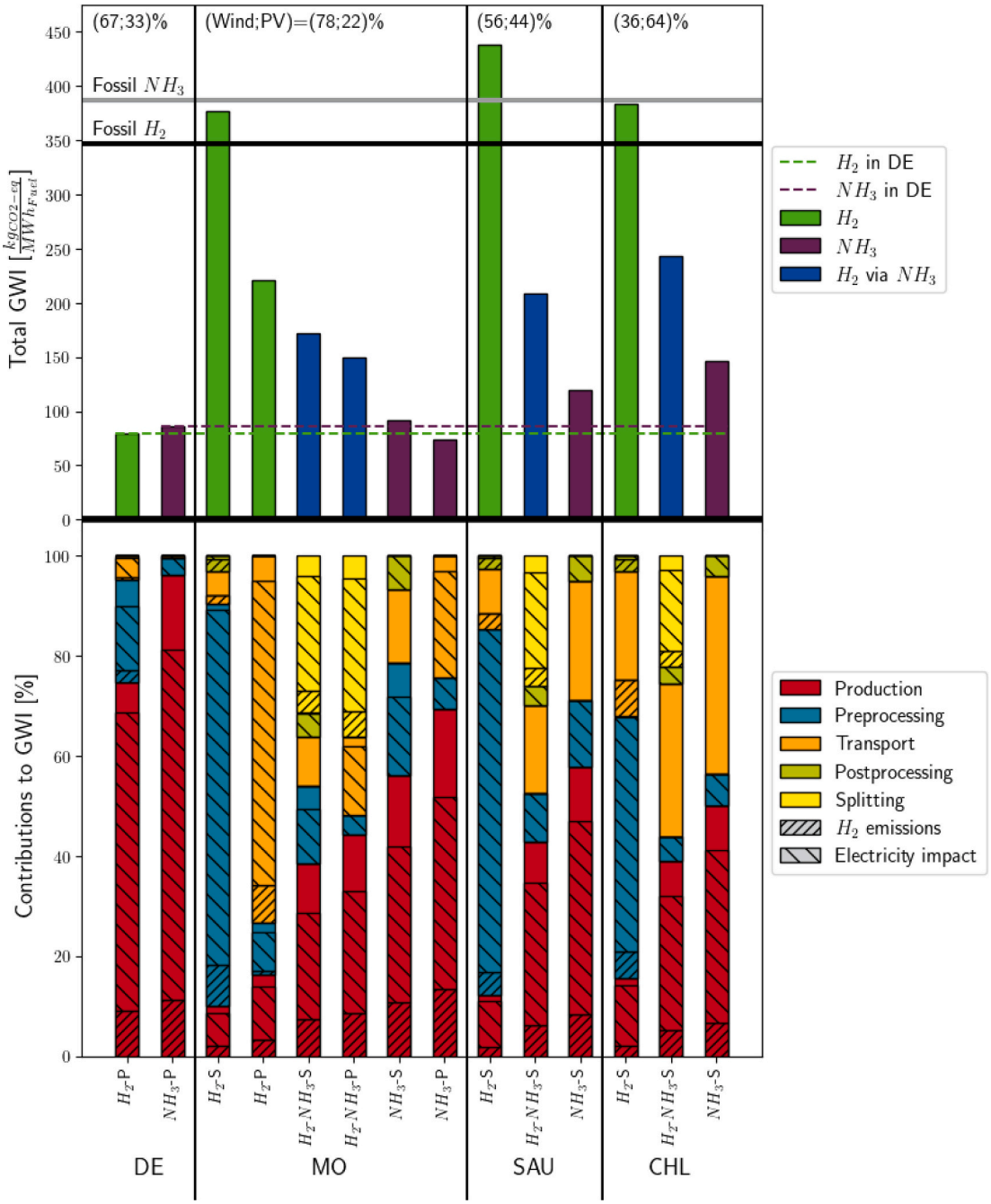


Fig. 3. Contribution analysis base case. Hydrogen and ammonia are produced using renewable electricity, while the transport, pre- and postprocessing operations rely on grid electricity (see Section 2.1.2). The percentages in the brackets denote the wind- and PV- percentages in the electricity mix for fuel production in the respective countries. The top subplot shows the overall GWI for all transport routes and the bottom subplot shows the contribution analysis. H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2– NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia, GWI: Global warming impact. DE: Germany, MO: Morocco, SAU: Saudi-Arabia, CHL: Chile.

SI and the Excel-sheet in the SI.

3.1. Base case

This section is divided into two subsections, which contain a contribution analysis and a sensitivity analysis of the GWI for the

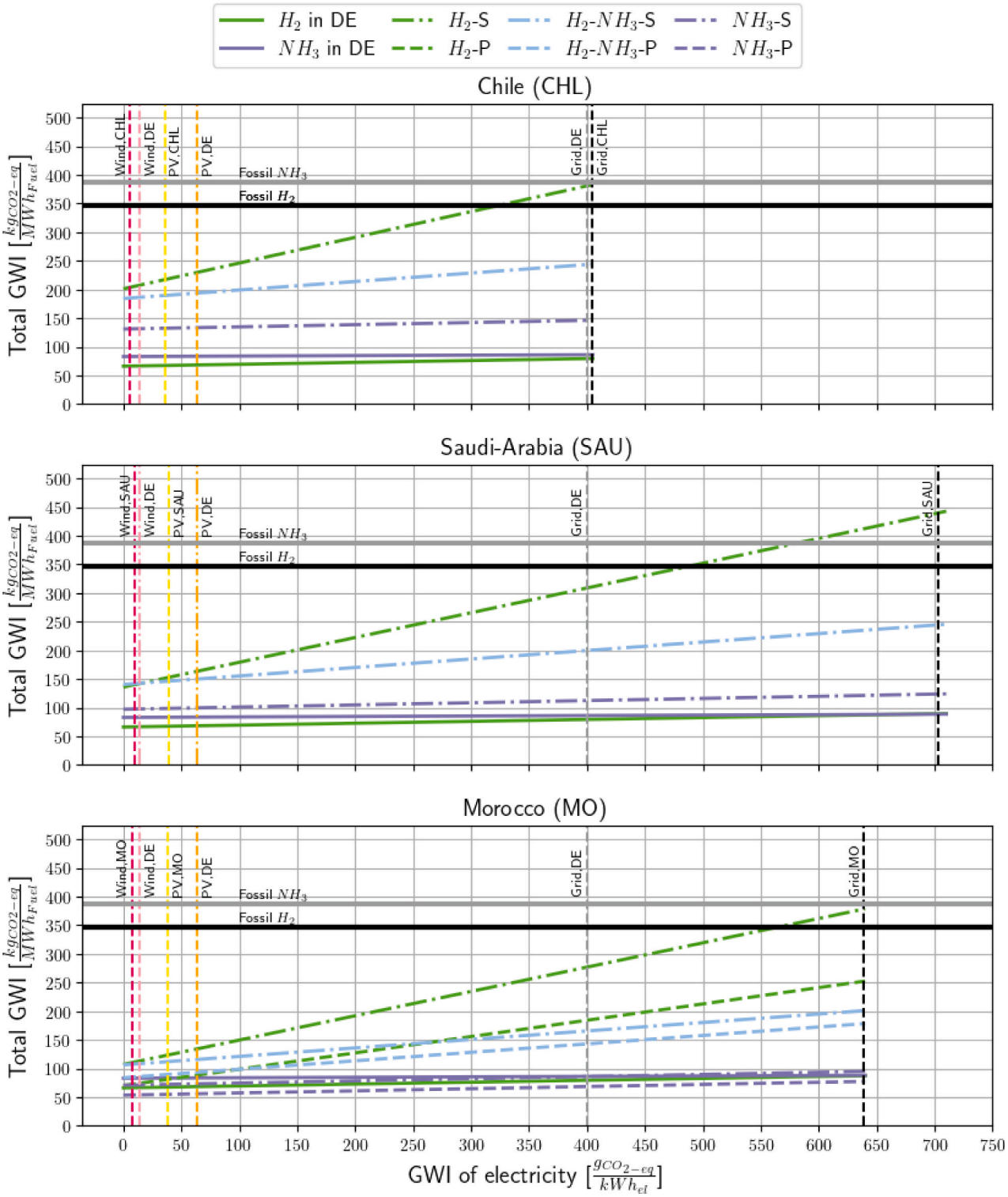


Fig. 4. Sensitivity analysis of the GWI for the electricity used during transport, pre- and postprocessing of the fuels. The electricity during fuel production remains the same as in Fig. 3. The top subplot shows the total GWI for Chile (CHL) compared to the local production in Germany (DE), the middle subplot shows the total GWI for Saudi-Arabia (SAU) compared to the local production in Germany (DE), the bottom subplot shows the total GWI for Morocco (MO) compared to local production in Germany (DE). H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia, GWI: Global warming impact.

electricity in all supply chain operations except the fuel production.

3.1.1. Contribution analysis

Fig. 3 contains the contribution analysis for hydrogen and ammonia imports from the three representative countries in the base case. In the base case, renewable electricity is used for the fuel production, while all remaining supply chain operations (transport, pre- and postprocessing) rely on grid electricity. The results in Fig. 3 highlight that imports have a higher GWI than the local production in Germany in almost all cases.

There are three main reasons for the high GWI of hydrogen imports in the base case: The usage of grid electricity to power the energy-intensive supply chain operations, direct hydrogen emissions and the usage of heavy fuel oil as shipping fuel. If powered with grid electricity, the preprocessing stage – particularly hydrogen liquefaction – accounts for 80 %, 73 %, and 52 % of the total GWI of hydrogen ship imports from Morocco, Saudi-Arabia, and Chile, respectively (compare Fig. 3). Thus, hydrogen imports via ship even have a higher GWI than the fossil production. While pipeline imports from Morocco have a lower GWI than ship imports, the use of grid electricity for pipeline recompression leads to a higher GWI than green hydrogen production in Germany. The second dominant driver in the base case are direct hydrogen emissions. The high GWI contribution of direct hydrogen emissions are caused by assuming conservative hydrogen emission rates and that hydrogen emissions are not reliquefied during storage and transport. Emitting hydrogen to the atmosphere not only decreases efficiency of the supply chain, but also increases the GWI due to the GWP of hydrogen. The third dominant driver in the base case is the usage of heavy fuel oil as shipping fuel, which further increases the GWI, especially for long distance imports from Chile.

Contrary to hydrogen supply chains, ammonia supply chains exhibit a much lower energy demand during preprocessing and transport in the base case. Thus, ship and pipeline imports of ammonia from Morocco achieve 75 % and 67 % lower GWI than hydrogen imports via ships and pipeline, respectively. Similar trends are observed for Chile and Saudi-Arabia. Notably, ammonia imports via ships from Morocco are comparable to the green ammonia production in Germany, and ammonia imports via pipeline have an even lower GWI (compare Fig. 3). While ammonia production causes higher GWI than hydrogen production, the overall GWI of ammonia imports is lower than hydrogen imports in the base case because the preprocessing and transport of ammonia is less energy-intensive.

In the base case, using ammonia as hydrogen-carrier yields a lower GWI than hydrogen imports despite the energy-intensive ammonia splitting process. However, importing 1 MWh ammonia always results in a lower GWI than importing 1 MWh hydrogen via ammonia as hydrogen-carrier because the latter requires the additional ammonia splitting process.

3.1.2. Sensitivity analysis electricity impact

To assess the impact of electricity on the GWI of the supply chains, we conduct a sensitivity analysis of the GWI for the electricity in all supply chain operations except the fuel production (compare Fig. 4). The sensitivity analysis reveals that with a lower GWI for electricity, a significant decrease in the GWI of hydrogen imports across all countries is achieved, emphasizing the high electricity demand of hydrogen supply chains (see Fig. 4).

For Morocco, hydrogen imports via ships have a higher GWI than importing ammonia as hydrogen carrier, regardless of the GWI for electricity. However, hydrogen imports via pipeline from Morocco are comparable to the local hydrogen production in Germany if powered by wind electricity. Ammonia imports from Morocco via ship or pipeline consistently outperform the local ammonia production in Germany, even with emission-intensive grid electricity (see Fig. 4).

Imports from Chile and Saudi-Arabia exhibit a higher GWI than the local production (compare Fig. 4), primarily due to the longer transport distances and higher photovoltaic (PV) shares in the production mix compared to Morocco (see Fig. 3). However, imports from Saudi-Arabia or Chile have a lower GWI than the fossil production if the electricity has a GWI below 485 $g_{CO2\text{-}eq}$/kWh or 347 $g_{CO2\text{-}eq}$/kWh, respectively (see Fig. 4). For Saudi-Arabia, a shift in the preferred transport form is observed: When electricity with a GWI below 16 $g_{CO2\text{-}eq}$/kWh is used, hydrogen imports via ships result in a lower GWI than importing ammonia via ships as hydrogen carrier. In contrast, for Chile, importing ammonia via ships as hydrogen carrier remains the more favorable option regardless of the GWI for electricity.

Even though the impact of electricity on the GWI of hydrogen supply chains is reduced through the sensitivity analysis, middle and long distance hydrogen imports still have higher GWI than the local production in Germany. This is because the other two dominant drivers of hydrogen supply chains identified in Section 3.1.1, namely direct hydrogen emissions and the use of heavy fuel oil as shipping fuel, remain unchanged. Consequently, even in the base case with renewable electricity in the supply chain, ammonia imports have a lower GWI than hydrogen imports in almost all cases, especially for imports from middle or long distance countries. A contribution analysis of the base case with renewable supply chain is given in Section 3.2 of the SI.

3.2. Contribution analysis of the optimistic case

In the optimistic case, we assume lower direct hydrogen emissions throughout the supply chain, reliquefaction of hydrogen boil-off during storage and transport and that hydrogen and ammonia can be used as shipping fuel (compare Section 2.1.2). The optimistic case in Fig. 5 reveals significant reductions in the GWI of all import routes across all countries. Compared to the base case in Section 3.1.1, all import routes are dominated by the GWI contribution of hydrogen and ammonia production, which in turn are almost entirely dominated by the electricity impacts. Consequently, the impacts of all supply chain stages are reduced in the optimistic case.

In the optimistic case, hydrogen imports via ship have lower GWI than hydrogen imports via pipeline, as hydrogen pipeline transport remains electricity-intensive. Hydrogen imports from Morocco via ships even have a lower GWI than green hydrogen production in Germany. In the optimistic case, using ammonia as a hydrogen carrier results in a higher GWI than direct hydrogen imports, consistent with findings from previous studies [36].

Ammonia imports via ships and pipelines from all countries consistently outperform the green ammonia production in Germany, benefiting from superior renewable conditions in exporting countries. The remaining supply chain impacts for the ammonia routes are negligible compared to ammonia production (compare Fig. 5). However, in the optimistic case, the GWI of ammonia imports exceeds the GWI of hydrogen imports via ships. Additionally, using ammonia as hydrogen-carrier has the highest GWI among the import routes because of the additional ammonia splitting process.

Given the assumed PV-wind ratio for electricity (see Fig. 5), hydrogen production in Germany is competitive to imports since we assume that 87 % of the produced hydrogen in Germany is wind-based. Even then, hydrogen imports from Morocco, Chile or Saudi-Arabia via ships have a comparable or lower GWI than the green hydrogen production in Germany. If PV-based green hydrogen production is taken as reference, all hydrogen import routes, even hydrogen import via ammonia, from the considered countries show a lower GWI.

3.3. Environmental burden-shift

In Fig. 6, we compare the environmental impacts of hydrogen and ammonia imports in 16 environmental impact categories to the fossil production. For hydrogen import via pipelines or ships, the environmental impacts are lower than fossil hydrogen production in 4–5 out of 16 categories (compare Fig. 6). For imports via ammonia as hydrogen carrier, the environmental impacts are lower than the fossil hydrogen

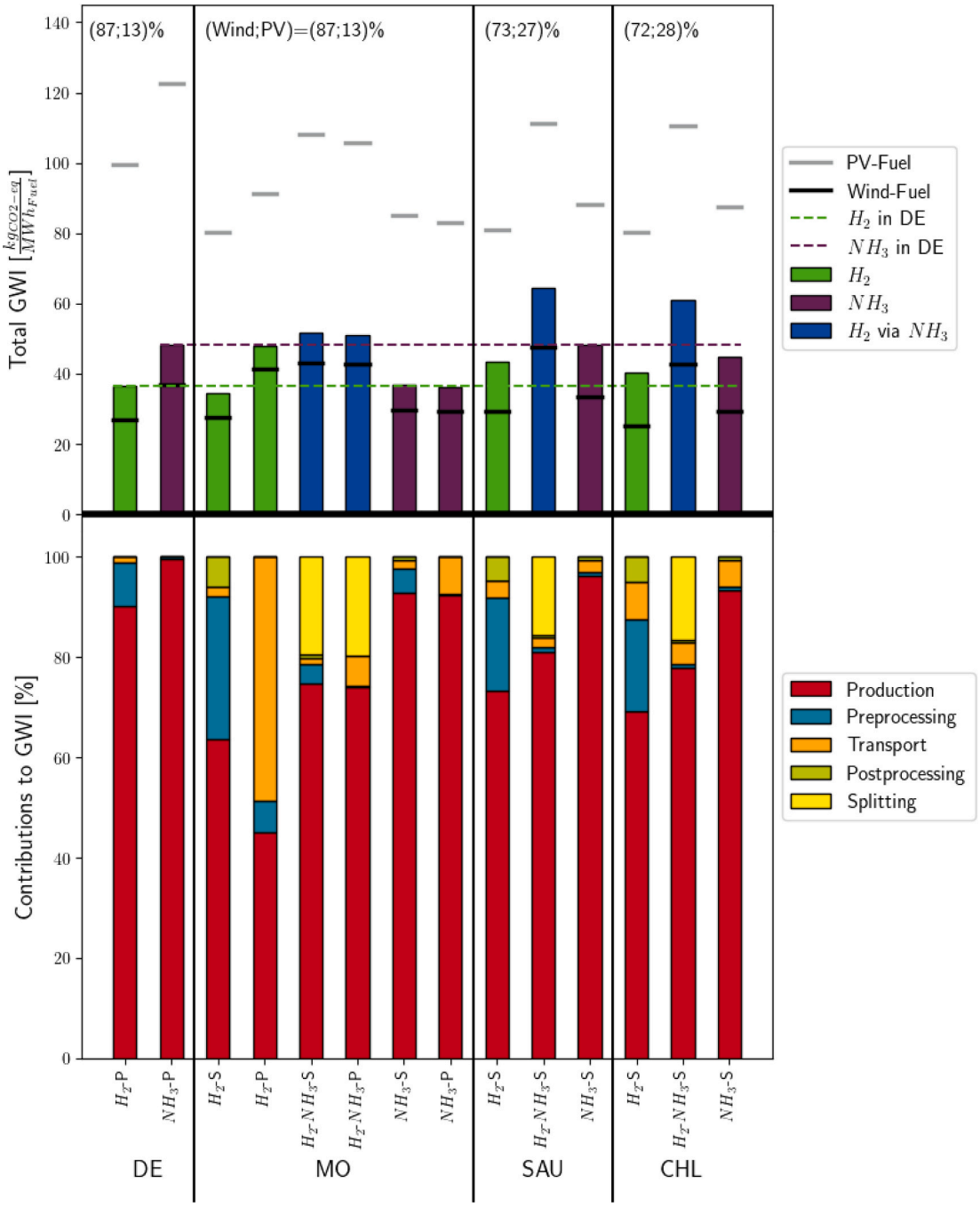


Fig. 5. Contribution analysis optimistic case. The top subplot shows the overall GWI for all transport routes and the bottom subplot shows the contribution analysis. The percentages in the brackets denote the wind- and PV- percentages in the electricity mix for fuel production in the respective countries. The floating grey reference line (PV-Fuel) marks the GWI if 100 % PV-electricity is used in the supply chain, while the floating black reference line (Wind-Fuel) marks the GWI if 100 % Wind-electricity is used in the supply chain. H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia, GWI: Global warming impact. DE: Germany, MO: Morocco, SAU: Saudi-Arabia, CHL: Chile.

production in 3 out of 16 categories (compare Fig. 6). For ammonia imports via ships or pipelines, the environmental impacts are lower than the fossil ammonia production in 7–10 categories (compare Fig. 6). The better performance of ammonia import routes stems from the higher environmental impacts of the fossil ammonia production compared to fossil hydrogen production. Accordingly, our results show that the decrease in climate change impacts through ammonia and hydrogen imports is accompanied with an increase of environmental impacts on at least 6 other categories, so-called environmental burden-shift.

Fig. 6 also shows that environmental burden-shift occurs in 5 categories across all considered transport routes: Ecotoxicity of freshwater (ET_{FW}), eutrophication freshwater (E_{FW}), ionising radiation (IR), land use (LU) and water use (WU). For each of these five impact categories (compare Fig. 34–43 in Section 3.5.3 of the SI), the main driver for the increased impacts are the construction impacts in the production stage, even when using wind and PV electricity. The large amounts of steel for the construction of the wind turbines as well as the construction of the PV panels contribute substantially to the increase in all of the aforementioned impact categories except LU. Similarly, the deionized water demand during hydrogen and ammonia production is by far the

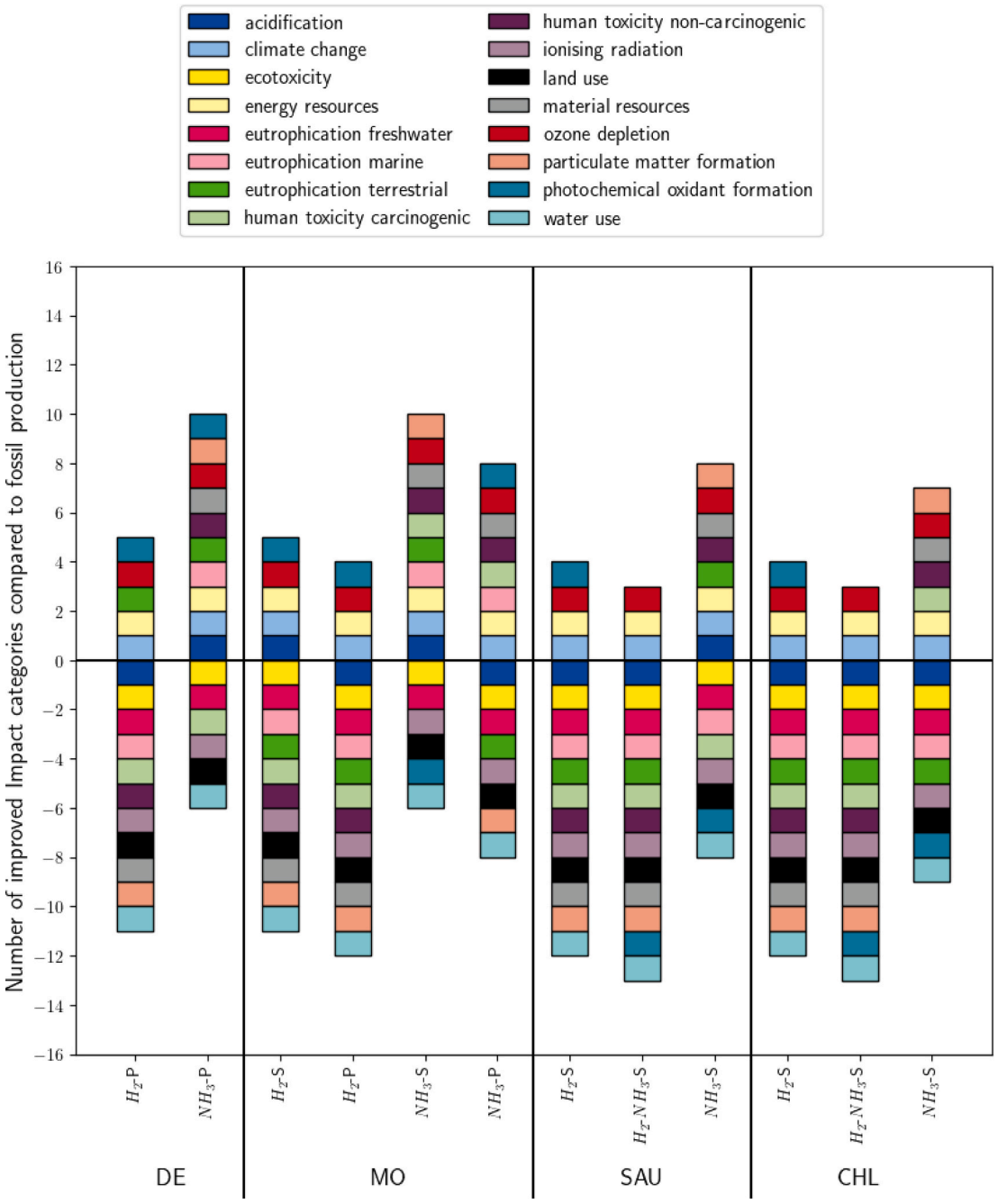


Fig. 6. Overview of environmental burden-shift in 16 environmental impact categories compared to fossil production in the optimistic case. Positive values indicate the number of impact categories where the import route has lower environmental impacts than the fossil reference and negative values indicate the number of impact categories where the import route has higher environmental impacts.

largest contributor to E_{FW}, while also impacting the increase in ET_{FW}, IR and WU. ET_{FW} and E_{FW} are further increased by the copper demand for the wind turbines, while WU is also increased by the glass demand for the wind turbines. The increase in LU is caused by the large land area required for the wind turbines and PV plant. While the construction of the electrolyser system contributes to the IR impacts, the construction has negligible contributions in the other four impact categories compared to the electricity and deionized water demands. Even though the production stage is the main driver for the environmental burden-shift, the high steel demand throughout the supply chain, i.e., for the storage, pipeline and ship construction and the nickel catalyst used in ammonia splitting also increases the impacts in ET_{FW}, IR and WU. For the ammonia routes, direct ammonia emissions during storage and transport contribute to the higher environmental impacts in ET_{FW} due to ammonia's high characterization factor in ET_{FW} [46].

For hydrogen-based import routes, there is burden-shift in up to 7 additional categories: eutrophication marine (E_m), eutrophication terrestrial (E_t), human toxicity carcinogenic (HT_c) and non-carcinogenic (HT_{nc}), resource depletion of metals and minerals (RD_{mm}), particulate matter formation (PM) and acidification (A_{tfw}). The increase in these 7 impact categories is also mainly caused by the increased demand for electricity. Furthermore, nitrogen oxide emissions during ship transport contribute to the increase in E_m, E_t, PM and A_{tfw}. The material demands for the electrolyser system (steel demand for balance of plants and catalyst materials for the stack) contribute to the increase in RD_{mm} impacts. We refer to Section 3.6 of the SI for further results.

Our results show that the reduction of climate change impact through the employment of green hydrogen and ammonia shifts environmental burdens to other impact categories. However, our work does not quantify the magnitude of this burden-shift. Future work should therefore evaluate the severity of environmental burden-shift, e.g., by performing an absolute environmental sustainability assessment [86]. Although wind and PV electricity is assumed as the electricity source, the associated environmental impacts remain substantial, mainly due to the material demands for the wind turbines and PV panel production. These environmental impacts could decrease with future material supply chains, such as hydrogen-based steelmaking. To estimate such potential improvements, we recommend performing a prospective LCA of the material supply chains. Additionally, the overall environmental impacts of the material supply chains can be further reduced by lowering the necessary amount of virgin materials. The reduction of virgin materials can be achieved by increasing recycling rates and implementing circular design strategies for materials.

3.4. Uncertainty analysis

The Uncertainty Analysis (UA) results (compare Fig. 7) show that the difference between minimum and maximum values of the GWI in each

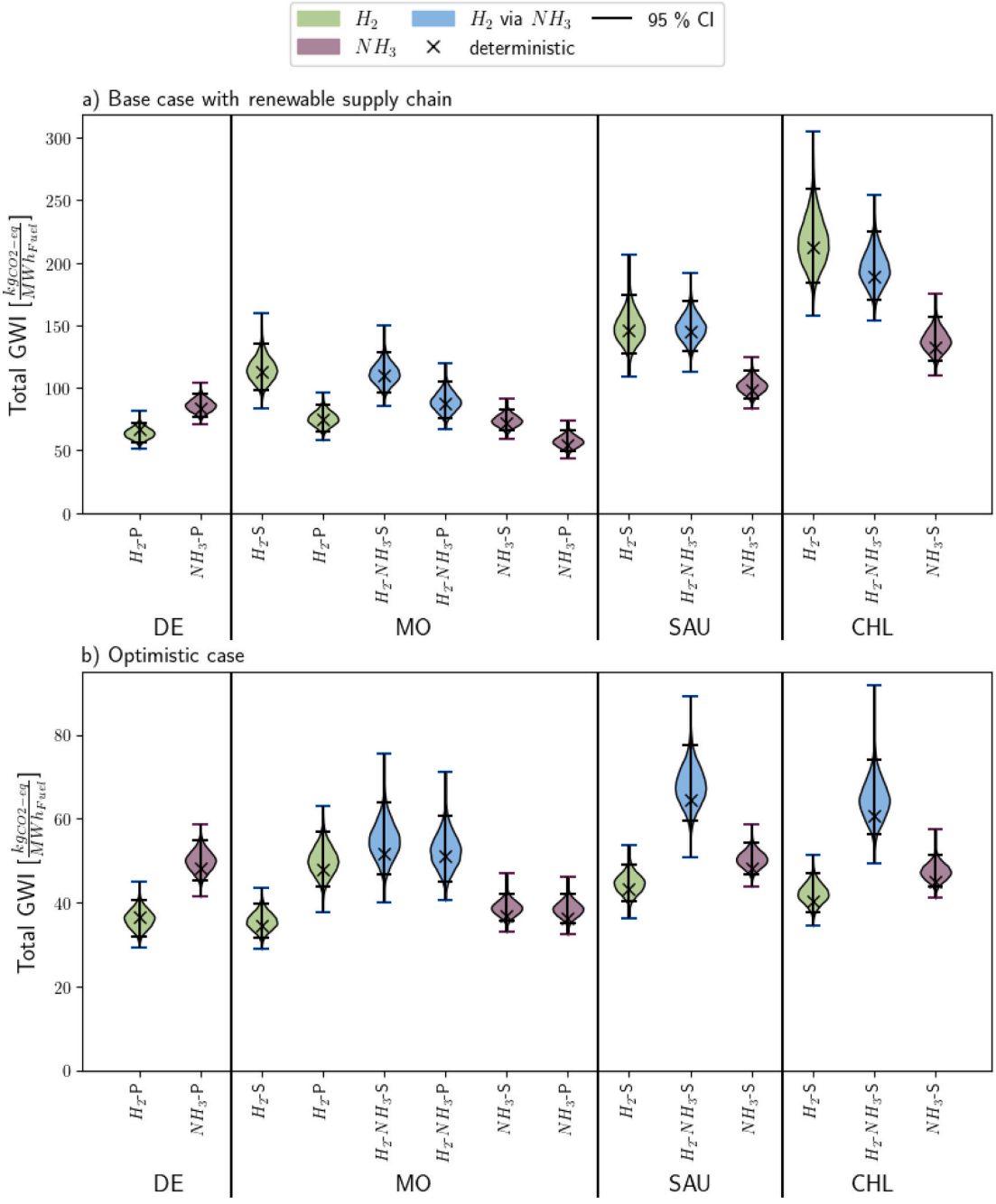


Fig. 7. Violin plots showing the results from the Uncertainty analysis. The subplot a) compares the base case with renewable electricity in the supply chain to the deterministic results (Section 3.1.2). The subplot b) compares the optimistic case to the deterministic results (Section 3.2). H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia, DE: Germany, MO: Morocco, SAU: Saudi-Arabia, CHL: Chile. 95 % CI: 95 % Confidence interval. GWI: Global warming impact.

import route is higher in the base than the optimistic case. The higher difference in the base case is because we assume that some input parameters such as hydrogen emissions in the supply chain have a higher parametric uncertainty compared to the optimistic case (compare Section 2.1 of the SI). Additionally, in the base case, we assume that the hydrogen emissions during storage and transport are not reliquefied, leading to a higher uncertainty of the GWI. Thus, in the base case, the uncertainty of the GWI increases with increasing transport distance, with hydrogen imports via ships showing the highest uncertainty among all transport routes (see Fig. 7a). In the optimistic case, the difference between minimum and maximum values of the GWI across the import routes is smaller, with the hydrogen and ammonia imports via ships exhibiting smaller uncertainty than the import of hydrogen via ammonia (compare Fig. 7b).

The UA for the optimistic case also highlights that there is an overlap in the 95 % Confidence Interval (CI) of the green hydrogen production in Germany and hydrogen imports via ships from Chile (see Fig. 7b). This suggests that imports from Chile could have a lower GWI than the local hydrogen production, even for the assumed PV/wind ratio for electricity. Conversely, the UA indicates that the CI of other import routes

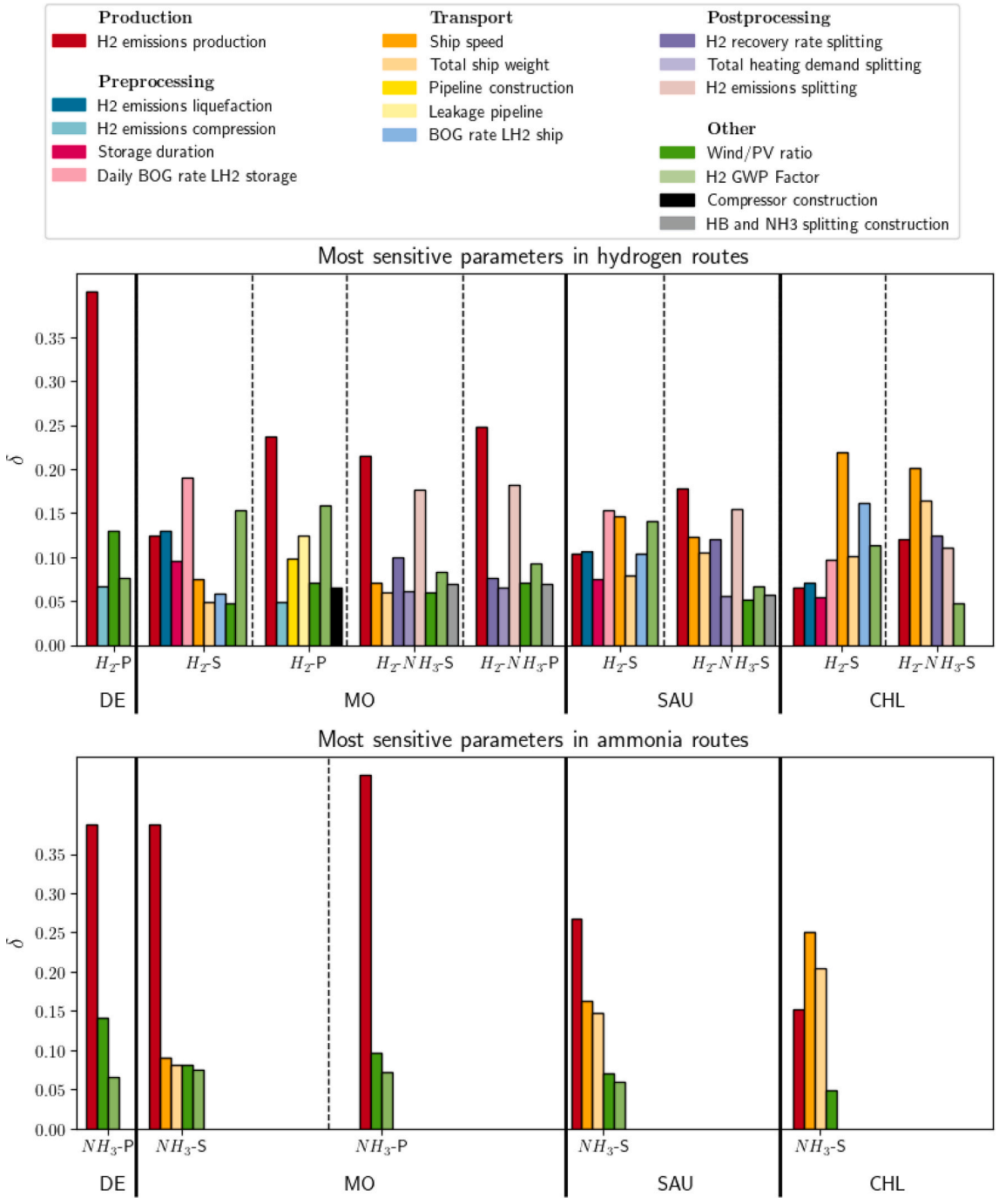


Fig. 8. Sensitivity indices δ for most sensitive parameters in hydrogen and ammonia transport routes in the base case with renewable electricity in the supply chain for the impact category Global Warming Impact (compare Fig. 7). H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia. DE: Germany, MO: Morocco, SAU: Saudi-Arabia, CHL: Chile, H_2: Hydrogen, NH_3: Ammonia, HB: Haber-Bosch process, GWP: Global Warming Potential.

(such as hydrogen imports via ships from Saudi-Arabia or via pipeline from Morocco) do not overlap with the local production, making green hydrogen production in Germany the more favorable option even when accounting for parametric uncertainty.

Import routes with ammonia as a hydrogen carrier show the highest uncertainty range in the optimistic case, but its CI does not overlap with the green hydrogen production in Germany, making the local production more favorable (see Fig. 7). Ammonia imports via ship from Morocco show lower GWI compared to the green ammonia production in Germany, even when considering parametric uncertainty. For ammonia imports from Saudi-Arabia or Chile, the overlap of the CI with the green ammonia production in Germany suggests that the local production may have a lower GWI when accounting for parametric uncertainty.

In summary, the UA reveals that, contrary to what the results in Section 3.1 and 3.2 suggest, imports might have lower or higher GWIs than the production in Germany, depending on the import route and uncertain parameters. Consequently, the UA results highlight the competitiveness of imports to the local production in the optimistic case.

Additionally, we conducted the UA and GSA for one of the critical impact categories identified in Section 3.3, namely Ecotoxicity of freshwater (ET_{FW}). The results of the UA for the optimistic case are given

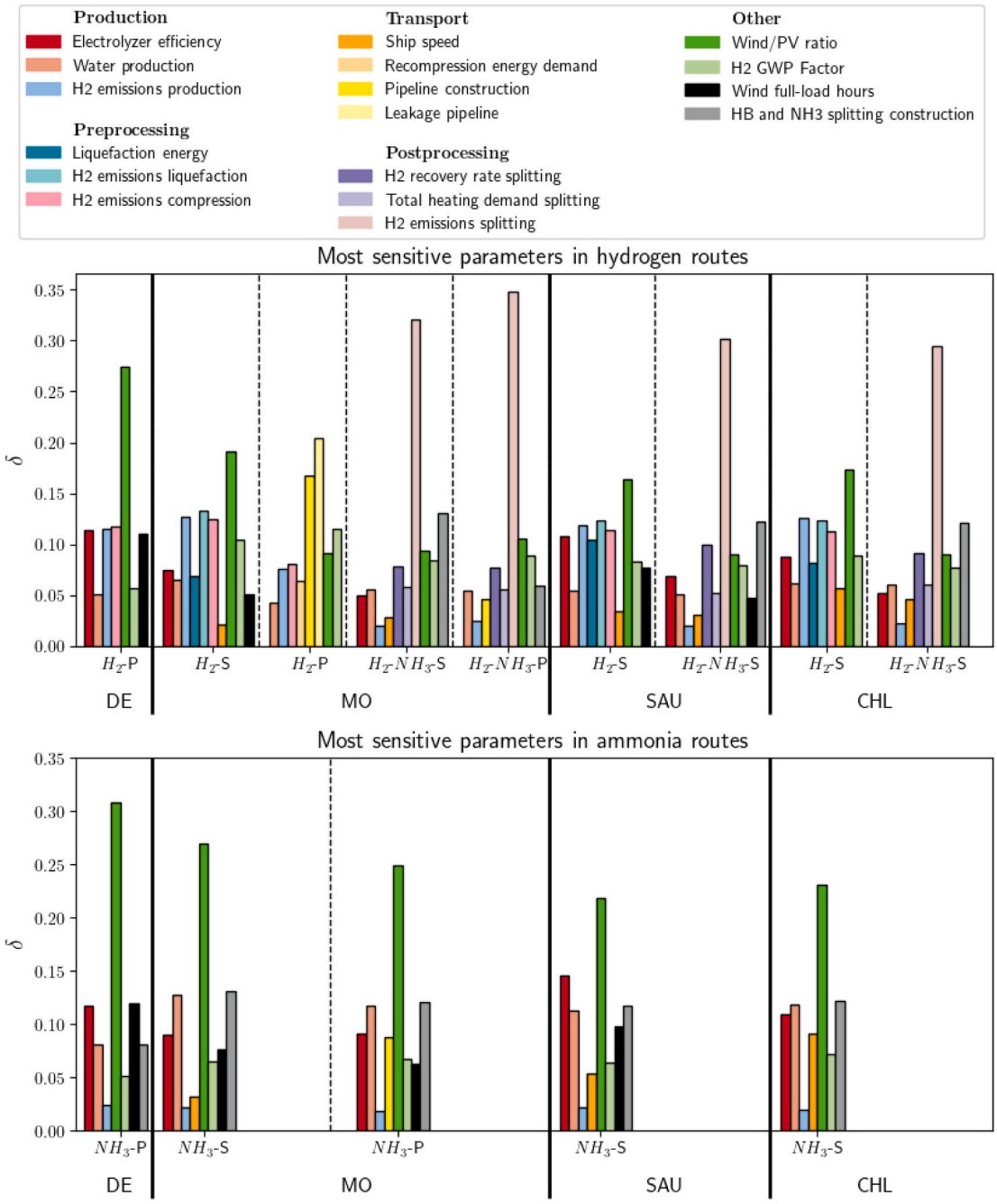


Fig. 9. Sensitivity indices δ for the most sensitive parameters across the supply chain in hydrogen and ammonia transport routes in the optimistic case for the impact category Global Warming Impact (compare Fig. 7). H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia. DE: Germany, MO: Morocco, SAU: Saudi-Arabia, CHL: Chile, H_2: Hydrogen, NH_3: Hydrogen, HB: Haber-Bosch process, GWP: Global Warming Potential.

in Fig. 44 in Section 3.5.4 of the SI and show that the deterministic results are at the lower end of the CI. The resulting uncertainty in ET_{FW} is much larger compared to GWI even in the optimistic case. However, the UA for ETFW shows that despite the wider uncertainty range, the fossil reference is exceeded in all routes. Therefore, environmental burden-shift occurs even when considering uncertainties.

3.5. Global sensitivity analysis

The Uncertainty Analysis shows that the base case with a renewable supply chain exhibits a higher uncertainty range than the optimistic case. The Global Sensitivity Analysis (GSA) reveals to which uncertain input parameters the GWI of each transport route is most sensitive to. The most sensitive parameters are summarized in Fig. 8 and Fig. 9, while the remaining parameters have $\delta \leq 0.05$, indicating negligible sensitivity importance. The GSA highlights that all transport routes in the base case are sensitive to storage parameters like storage duration, the daily boil-off gas (BOG)-rate or transport parameters like ship speed and BOG-rate during shipping since they have high δ estimates (see Fig. 8). This can be attributed to the assumption that BOG is not reliquefied in the base case, leading to fuel losses and in the case of hydrogen emissions to an increased GWI. In the optimistic case, storage and transport parameters are less sensitive because the BOG is reliquefied (see Fig. 8 and Fig. 9). In both base and optimistic case, hydrogen emissions throughout the supply chain are among the most sensitive parameters.

The overall GWI of hydrogen and direct ammonia imports in the optimistic case is most sensitive to the electrolyzer efficiency, hydrogen GWP factor and wind/PV ratio for electricity since these three parameters have high δ values across all transport routes in the optimistic case (see Fig. 9). The hydrogen GWP factor remains a sensitive parameter, despite assuming reduced hydrogen emissions in the optimistic case. Furthermore, the GWI is sensitive to the wind/PV ratio for the electricity supply even though we assume a conservative deviation of ±5% for the triangular distribution of the wind/PV ratio. Broadening the ranges of the wind/PV ratio would lead to higher sensitivity. In accordance to Section 3.1.2, this result highlights that the overall GWI of all transport routes is most sensitive to the GWI of the electricity used in the supply chain operations.

For hydrogen transport routes, the overall GWI is also sensitive to hydrogen emissions during production, compression, and liquefaction (see Fig. 9). Furthermore, the GWI of all hydrogen transport routes is sensitive to the water production, which is a background uncertainty, i.e., the uncertainty is taken from ecoinvent [60]. The energy demand for hydrogen liquefaction in shipping routes is another sensitive parameter. Furthermore, the overall GWI of the ammonia transport routes is sensitive to the uncertainty in wind full-load hours and the construction of the Haber-Bosch process, which is also a background uncertainty from ecoinvent [60]. As shown in Fig. 7, the import routes with ammonia as hydrogen carrier have the highest uncertainty range in the optimistic case. The GSA reveals that the higher uncertainty range is caused by uncertain parameters of the ammonia splitting process, particularly hydrogen emissions during splitting, the hydrogen recovery rate and the total heating demand (see Fig. 9). For increasing transport distances in ship-based transport routes, the overall GWI becomes increasingly sensitive to shipping parameters, particularly speed (see Fig. 9). Similarly, for pipeline import routes, pipeline construction and leakage are more sensitive with increasing transport distances.

The results of the GSA for the impact category Ecotoxicity of freshwater (ET_{FW}) are given in Fig. 45 in Section 3.5.4 of the SI. The GSA reveals that uncertainties are dominated by ecoinvent processes since water production and pipeline, storage and plant construction achieve the highest δ values across all transport routes. Consistent with Section 3.3, direct ammonia emissions across the supply chain are among the most sensitive parameters in the ammonia transport routes due to ammonia's characterization factor.

We remark that the choice of uncertainty distributions for the uncertain input parameters have an influence on the results of the UA and GSA. We assume that all foreground parameters follow a triangular distribution (see Section 2.1 of the SI). However, if we would chose a less informative distribution (e.g. uniform), the overall uncertainty range of the GWI and the sensitivity of the parameter would also increase.

3.6. Overview of GWI results from all countries

In Fig. 10, we provide an overview of the Global Warming Impact (GWI) for all considered countries and transport routes in the base case with a renewable supply chain and the optimistic case. The GWI of all transport routes is obtained by calculating the mean and standard deviation using the Uncertainty Analysis (UA) conducted in Section 3.4.

The results for the base case show that hydrogen imports via pipeline from short distance countries (500–5,000 km) are in the range of 38–90 $kg_{CO2\text{-}eq}/MWh_{H2}$ (74–91 % reduction compared to the fossil hydrogen production), while ammonia imports from short distance countries are in the range of 51–95 $kg_{CO2\text{-}eq}/MWh_{NH3}$ (75–87 % reduction compared to fossil ammonia production). For hydrogen imports via ships in the base case, the GWI ranges between 136–328 $kg_{CO2\text{-}eq}/MWh_{H2}$ (5–60 % reduction) for middle (5,000–10,000 km) and long distance countries (10,000–20,000 km). For middle and long distance countries, import via ammonia as hydrogen carrier has a lower GWI than hydrogen imports via ships. For ammonia imports via ships from middle and long distance countries, the GWI ranges between 89–188 $kg_{CO2\text{-}eq}/MWh_{H2}$ (51–77 % reduction). Consequently, in the base case, hydrogen imports via pipeline and ammonia imports via ships from short distance countries have a similar GWI. However, for hydrogen imports via ships, rising transport distances have a strong influence on the GWI. Thus, for middle and long distance countries, importing ammonia or hydrogen via ammonia are better options from an environmental perspective.

In the base case, only ammonia imports within short distance have a lower GWI than the local production in Germany because of the high percentage of wind electricity for fuel production (compare Fig. 10). Compared to PV-based fuel production in Germany, hydrogen imports via pipeline within short distance have a lower GWI, while for ammonia even middle and long distance imports have a lower GWI in most cases.

In the optimistic case, however, using hydrogen and ammonia as shipping fuel leads to a GWI below 87 $kg_{CO2\text{-}eq}/MWh$ (>75 % reduction) for all import options. Contrary to the base case, hydrogen imports via ships have the lowest GWI compared to the other transport options (see Fig. 10). However, the overlap of the GWI of ammonia and hydrogen imports via ships for some countries (e.g. Brazil or Australia) highlight the competitiveness between both import options. In the optimistic case, using ammonia as hydrogen carrier has a higher GWI than hydrogen imports via ships for all import countries, even the ones within long distance. Furthermore, hydrogen imports from various countries have a comparable GWI to the local hydrogen production. For ammonia imports, most import options have a lower GWI than the local ammonia production. Additionally, if we consider PV-based fuel production in Germany as reference, all hydrogen (even via ammonia as hydrogen carrier) and ammonia imports result in a lower GWI, as Fig. 10 shows. Thus, in the optimistic case, the GWI of imports is not only substantially lower than the fossil production but also lower than renewable fuel production within Germany.

Using Eq. (1) of the SI, we can calculate the emission reductions of the considered import routes compared to the respective fossil references (see Fig. 33 of the SI). The emission reductions of ammonia imports are higher than those of hydrogen imports, even in the optimistic case where the overall GWI of hydrogen imports is lower than the GWI of ammonia imports. The higher emission reductions for ammonia routes in the optimistic case is explained by the different fossil benchmarks: Fossil ammonia has a higher GWI than fossil hydrogen. The GWI differences between hydrogen and ammonia imports are smaller than the differences between their respective fossil references, leading to higher emission reductions for ammonia.

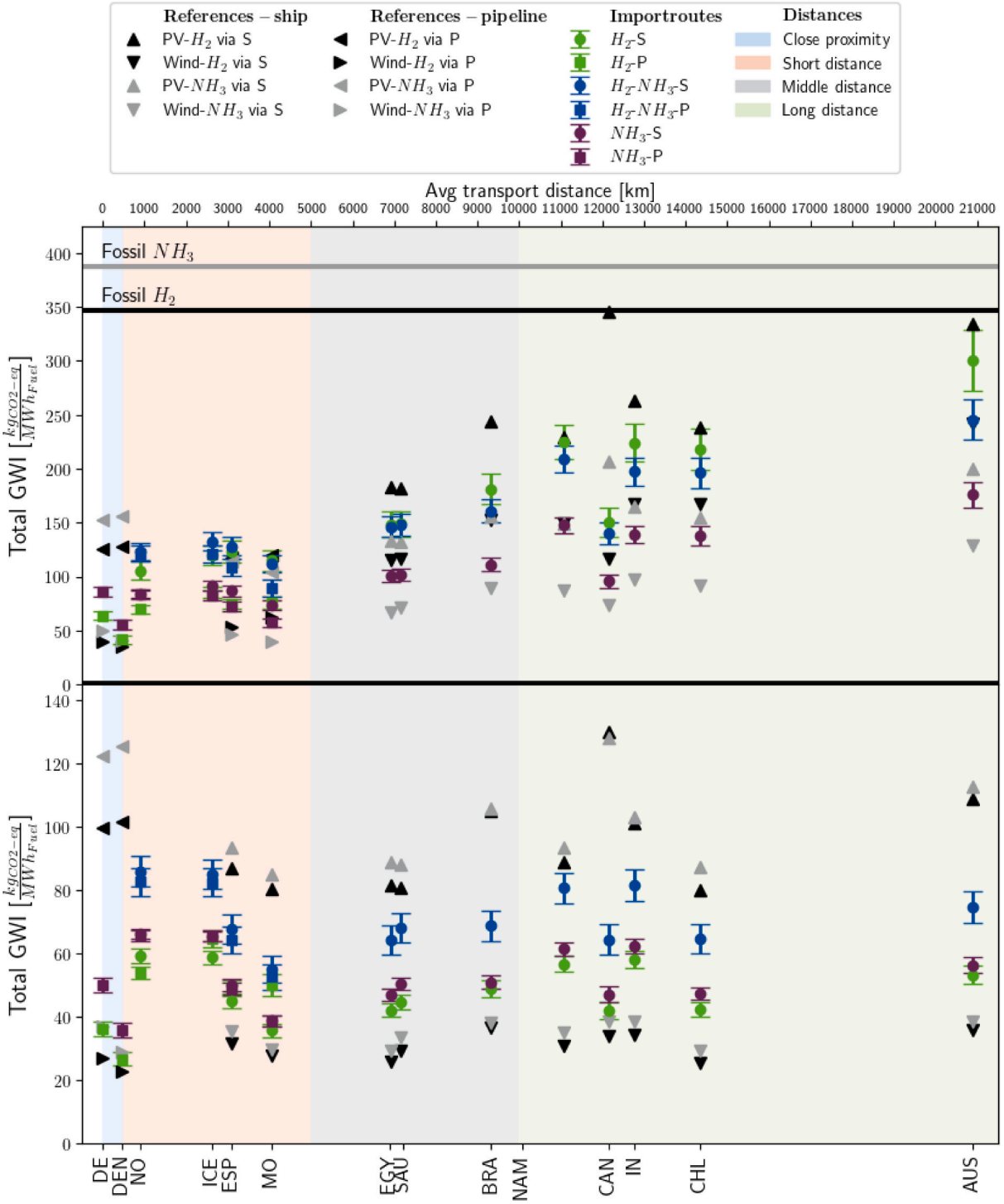


Fig. 10. Overview of the Global Warming Impact (GWI) per MWh_{Fuel} for all considered import routes. In the top subplot, the base case with a fully renewable supply chain and in the bottom subplot, the optimistic case is depicted. For each import route, the marker represents the mean with standard deviation. The mean and standard deviation are calculated using the GWI distribution from the results of the Uncertainty Analysis (see Section 3.4). The different black and silver triangles mark references for the fuel production using either PV- or Wind-electricity in the entire supply chain. H_2-S: Liquid hydrogen transport via ships, H_2-P: Compressed hydrogen transport via pipelines, H_2-NH_3-S: Ship transport of ammonia as hydrogen carrier, H_2-NH_3-P: Pipeline transport of ammonia as hydrogen carrier, NH_3-S: Ship transport of ammonia, NH_3-P: Pipeline transport of ammonia. PV-H_2: Hydrogen produced using PV electricity. Wind-H_2: Hydrogen produced using wind electricity. PV-NH_3: Ammonia produced using PV electricity. Wind-NH_3: Ammonia produced using wind electricity, P: pipeline, S: ships. Close proximity: Countries within close proximity (<500 km), Short distance: Countries within short distance (500–5,000 km), Middle distance: Countries within middle distance (5,000–10,000 km), Long distance: Countries within long distance (>10,000 km). GWI: Global warming impact. DE: Germany, DEN: Denmark, NO: Norway, ESP: Spain, ICE: Iceland, MO: Morocco, EGY: Egypt, SAU: Saudi-Arabia, BRA: Brazil, NAM: Namibia, CAN: Canada, IN: India, CHL: Chile, AUS: Australia.

In Table 1, we provide emission reductions for a 2030 and 2045 import scenario for Germany. For the 2030 scenario, the emission reductions are 19,880 $Mt_{CO2\text{-}eq,red}$ (74 %), while for the 2045 scenario the emission reductions reach 139,190 $Mt_{CO2\text{-}eq,red}$ (85 %). The emission reductions for a 2030 and 2045 scenario show that the measures within the German import strategy are in accordance with emission reduction targets to reach net zero.

Our findings are comparable to previous studies. De Kleijne et al. find that the median GWI of hydrogen production without transport across over 1,000 planned hydrogen projects is 2.9 $kg_{CO2\text{-}eq}/kg_{H2}$ or 87 $kg_{CO2\text{-}eq}/MWh_{H2}$ [36], which is higher than in our study, because we assume lower GWI for the electricity used in the production phase. Furthermore, De Kleijne et al. emphasize that imports are only favorable for short transport distances, because they assume heavy fuel oil (HFO) as shipping fuel. Our results in the base case in Fig. 10 show similar results as transport emissions increase steeply with the transport distance if HFO is used as shipping fuel. However, contrary to our results, De Kleijne et al. find that using ammonia as hydrogen carrier results in a higher GWI than liquid hydrogen imports, even when using HFO as shipping fuel. The main reason for this is that ammonia production requires additional electricity and is therefore more sensitive to changes in the GWI of the electricity used in the production phase. Since we assume electricity with a lower GWI, the GWI for ammonia production is lower in our study than in [36]. In alignment to our study, De Kleijne et al. also find that the transport impacts of shipping liquid hydrogen are higher than shipping ammonia because of ammonia's higher volumetric density.

Kolb et al. emphasize that the environmental impacts of liquid hydrogen supply chains are sensitive to changes and assumptions in each process step [42]. In alignment to our results in Section 3.1.1, Kolb et al. find that using grid electricity for the supply chain, especially during liquefaction and compression, can lead to a higher GWI than fossil hydrogen production for some import routes. Furthermore, as we emphasize in Section 3.1.2, Kolb et al. also state that using HFO as shipping fuel for liquid hydrogen imports results in a higher GWI than the local hydrogen production. Kolb et al. emphasize that while wind-based hydrogen production in Germany can be competitive to imports, PV-based imports always outperform the local PV-based hydrogen production, as shown in our work as well.

Furthermore, Scheffler et al. recommend hydrogen imports via pipelines and ammonia imports via ships in the short to medium term, while ship-based liquid hydrogen imports are attractive in the long term [44]. This aligns well with our findings as hydrogen imports via pipelines and ammonia imports via ships have a comparable or lower GWI than the local production even in the base case with renewable supply chain, while liquid hydrogen imports via ships only outperform local production in the optimistic case where hydrogen is used as shipping fuel.

Table 1
Emission reductions for a 2030 and 2045 import scenario for Germany. The import quantities and emission reductions from each country can be found in the Supporting Information in Section 3.8.

2030 scenario		
Import route	**Import quantity [TWh]**	**Emission reductions [$Mt_{CO2\text{-}eq,red}$] (reduction in %)**
Hydrogen via pipelines	50	13,860 (80)
Ammonia via ships	15	4,160 (72)
Hydrogen from ammonia as energy carrier via ships	10	1,860 (54)
Total	**75**	**19,880 (74)**
2045 scenario		
Hydrogen via pipelines	150	44,700 (86)
Ammonia via ships	206	69,190 (86)
Hydrogen from ammonia as energy carrier via ships	50	13,890 (80)
Liquid hydrogen via ships	38	11,410 (86)
Total	**444**	**139,190 (85)**

4. Recommendations and conclusions

We conduct a comprehensive Life Cycle Assessment to assess the impacts of hydrogen and ammonia imports to Germany from 13 countries in 16 environmental impact categories considering various scenarios. We quantify uncertainties via Monte Carlo Analysis and determine the most sensitive input parameters in the supply chain using Global Sensitivity Analysis.

In the following, we highlight some of our key findings and evaluate measures within the German import strategy from an environmental perspective [19]. Firstly, we emphasize that hydrogen emissions increase the Global Warming Impact (GWI) of hydrogen supply chains. We therefore urge technology developers to minimize hydrogen emissions throughout the supply chain. Furthermore, hydrogen supply chains have a higher energy demand during liquefaction and transport compared to ammonia. Thus, powering the entire hydrogen supply chain with renewable energy is essential to achieve a low GWI. Using grid electricity for hydrogen liquefaction and transport can even result in a higher GWI than fossil hydrogen production.

While the employment of green hydrogen and ammonia can reduce climate change compared to the fossil production, environmental burdens are shifted to at least 6 other categories even under optimistic assumptions. The main reason for environmental burden-shift are increased electricity, material and water demands. Future studies should investigate the severity of environmental burden-shift through performing an absolute environmental sustainability assessment. Additionally, future studies should perform a prospective LCA to account for future changes in material production as well as improve material efficiency of components through higher recycling rates.

Ammonia imports consistently demonstrate a low GWI throughout all cases. Ammonia imports, even long distance imports from Chile or Australia, have a lower GWI than both fossil and green ammonia production in Germany. While the shipping industry is not decarbonized, the import of hydrogen via ammonia results in a lower GWI than importing liquid hydrogen for long transport distances. Consequently, while direct ammonia imports have a lower GWI than using ammonia as hydrogen carrier, the import of hydrogen via ammonia is a viable option from an environmental perspective. Technology developers should work on improving the efficiency of ammonia splitting to maximize the benefits of using ammonia as a hydrogen carrier.

In the short to medium term, the German import strategy envisages a *trans*-European hydrogen pipeline network [19]. This network also includes Denmark, Norway, Iceland, Spain and Morocco. Our analysis shows that importing from these countries via pipeline is a promising option, especially in the near future, as the GWI is between 38–90 $kg_{CO2\text{-}eq}/MWh_{H2}$ and thus leads to a GWI reduction of $>$ 74 % compared to the local fossil production. The German government also plans to import ammonia by ship in the short to medium term, but initially no liquid hydrogen is to be imported [19]. We support this plan since the import of liquid hydrogen with fossil fueled ships leads to a high GWI and is therefore not recommended from an environmental point of view. For ammonia imports, even with fossil fueled ships, the GWI is between 70–155 $kg_{CO2\text{-}eq}/MWh_{NH3}$ and thus $>$ 60 % lower compared to the local fossil ammonia production. The import of ammonia in the short to medium term is therefore recommended from an environmental perspective. The import strategy also states that ammonia should be used directly wherever possible, e.g., in fertilizer production. As the GWI for the direct ammonia routes is always lower than for those where ammonia is considered as hydrogen carrier, we also recommend to prioritize ammonia imports to meet the current ammonia demand in Germany. However, as long as ships are fueled with fossil fuels, ammonia as hydrogen carrier is a better alternative than importing liquid hydrogen from an environmental perspective. Therefore, ammonia imports should also be used to cover additional hydrogen

demands.

The establishment of so-called green corridors make imports even more attractive, as ships can be fueled with hydrogen or ammonia [19]. In this case, the plan is to expand ammonia imports by including additional countries and higher import volumes in the import portfolio. Our work supports the plan to increase ammonia imports if the ships are fueled with ammonia since the emission reductions are ~ 85 % compared to the fossil ammonia production. Furthermore, the import of liquid hydrogen also leads to emission reductions ~ 85 % compared to fossil hydrogen production. Therefore, from an environmental point of view, the import of liquid hydrogen might be an attractive option in the medium to long term. This case is also discussed in the import strategy, but the economic competitiveness of liquid hydrogen is still questionable [19].

With the *trans*-European hydrogen pipeline network and various shipping routes, the German import strategy aims to import hydrogen and ammonia from as many countries as possible to create a diversified import portfolio that avoids dependence on individual countries. For a 2030 and 2045 scenario with a diversified import portfolio, the emission reductions compared to the fossil production are 19,880 $Mt_{CO2\text{-}eq,red}$ (74 %) and 139,190 $Mt_{CO2\text{-}eq,red}$ (85 %), respectively. Therefore, our results show that the measures within the German import strategy can lead to high greenhouse gas emission reductions.

CRediT authorship contribution statement

Karan Anand: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Fabian Welker:** Writing – review & editing, Visualization, Software, Data curation. **Hagen Seele:** Writing – review & editing, Visualization, Methodology. **Hendrik Pötting:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Niklas von der Assen:** Conceptualization, Funding acquisition, Methodology, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2025.120923.

Data availability

All data generated or analyzed during this study are available in the supplementary material files.

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