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Climate change mitigation potentials of on grid-connected Power-to-X fuels and advanced biofuels for the European maritime transport

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ABSTRACT

This study proposes a country-based life-cycle assessment (LCA) of several conversion pathways related to both on grid-connected Power-to-X (PtX) fuels and advanced biofuel production for maritime transport in Europe. We estimate the biomass resource availability (both agricultural and forest residues and second-generation energy crops from abandoned cropland), electricity mix, and a future-oriented prospective LCA to assess how future climate change mitigation policies influence the results. Our results indicate that the potential of PtX fuels to achieve well-to-wake greenhouse gas intensities lower than those of fossil fuels is limited to countries with a carbon intensity of the electricity mix below 100 gCO_{2eq} kWh^{-1}. The more ambitious FuelEU Maritime goal could be achieved with PtX only if connected to electricity sources below ca. 17 gCO_{2eq} kWh^{-1} which can become possible for most of the national electricity mixes in Europe by 2050 if renewable energy sources will become deployed at large scales. For drop-in and hydrogen-based biofuels, biomass residues have a higher potential to reduce emissions than dedicated energy crops. In Europe, the potentials of energy supply from all renewable and low-carbon fuels (RLFs) range from 32 to 149% of the current annual fuel consumption in European maritime transport. The full deployment of RLFs with carbon capture and storage technologies could mitigate up to 184% of the current well-to-wake shipping emissions in Europe. Overall, our study highlights how the strategic use of both hydrogen-based biofuels and PtX fuels can contribute to the climate mitigation targets for present and future scenarios of European maritime transport.

1. Introduction

Accelerating the large-scale production and use of renewable and low-carbon fuels (RLFs) is recognized as a key factor in achieving the climate mitigation targets set for the international maritime sector throughout the next years [1–3]. In Europe, a climate neutrality goal by 2050 was recently proposed within the context of the FuelEU Maritime initiative. This is based on the ambition to increase the GHG intensity reduction target of fuels used onboard from 75% to 80% by 2050 when compared to the fossil fuel mix benchmark [4]. The expected transition towards RLFs requires a gradual introduction of alternative fuels such as biofuels, bio-LNG, e-fuels, e-gas, hydrogen, ammonia, and methanol [5].

The extent of GHG emission reduction brought by RLFs, however, will be shaped by region-specific factors and the fuel value chains that are structured according to geographical feedstock availability, dynamic market interactions, and other opportunities related to new storage, distribution, and use of novel RLFs technologies [6]. In Europe, for instance, the possibility of large-scale deployment of renewable and low-carbon fuels in a heterogeneous landscape of fuel value chains can lead to different well-to-tank GHG intensities, thus requiring an integrated assessment with a common life-cycle framework to both assess their environmental impacts and to identify more adequate technological pathways to be used in specific regions of Europe.

The large-scale deployment of RLFs in Europe can rely on the use of

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Abbreviations: ASU, Air Separation Unit; BH2, Bio-hydrogen; Bio-LNG, Bio Liquefied Natural Gas; Bio-SNG, Bio Synthetic Natural Gas; BMeOH, Bio-methanol; BNH3, Bio-ammonia; CCS, Carbon Capture and Storage; CCU, Carbon Capture and Utilization; $CO_{2\text{-}eq}$, carbon dioxide equivalents; ESA-CCI, European Space Agency Climate Change Initiative; EU, European Union; FP, Fast Pyrolysis; FT, Fischer-Tropsch; g, grams; GAEZ, Global Agro-Ecological Zones; HTL, Hydrothermal Liquefaction; IAM, Integrated Assessment Model; IPCC, International Panel on Climate Change; kWh, kilowatt-hour; LCA, Life Cycle Assessment; MJ, Megajoule; Mt, million metric tonnes; NECPs, National Energy Climate Plans; PtG, Power-to-Gas; PtL, Power-to-Liquid; PtX, Power-to-X; RLF, Renewable and Low-carbon Fuel; SMR, Steam Methane Reforming; tondb, metric tonnes, dry basis; TWh, Terawatt-hour; yr, year.

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multiple feedstock sources and technological conversion pathways aiming to diversify and expand the supply of alternative fuels for the maritime sector. The options are essentially constrained to the production of advanced biofuels and Power-to-X (PtX) technologies, where the last will depend on the conversion of electricity into hydrogen, ammonia, methanol, and synthetic fuels – such as e-diesel and e-gas. PtX technologies, and particularly large-scale e-fuel deployment, are understood as a possible solution in the medium and long run to so-called 'no-regret' sectors such as long-haul transport where direct electrification is not possible [7]. At European level, the National Energy and Climate Plans (NECPs) as well as national strategies and roadmaps include opportunitie for PtX technologies that contribute to achieving the climate and energy targets of the European Union for the upcoming decades [8]. In the context of large-scale PtX fuels deployment, the electricity required to produce the projected consumption of e-fuels in EU maritime transport is projected to reach 246 TWh in 2050, which would correspond to c.a. 2% of the gross electricity generation in the EU by 2050 [5].

Advanced drop-in biofuels – such as upgraded bio-oils, biodiesel, biogas, and bio-SNG – can coexist with the implementation of PtX technologies and are an attractive solution for the energy transition in the maritime sector because the existing fleet is still heavily dependent on internal combustion engines using heavy fuel oil, marine diesel, marine gasoil, and liquefied natural gas [1,3]. As some advanced biofuel conversion technologies might depend on hydrogen for biofuel upgrading, there are potential symbiotic relationships between PtX and advanced biofuel value chains [9] that may offer a possibility of better integration among different RLFs options. Moreover, some pathways such as biomass gasification can provide both drop-in and hydrogen-based biofuel options [6], thus offering flexibility to adjust the type of output if, in a longer time perspective, non-drop-in fuels such as hydrogen and ammonia prevail as the main options of deep-sea maritime fuels. Therefore, a novel study comparing PtX fuels and advanced biofuel production strategies is important to understand the potential climate mitigation impacts on European maritime transport under current and future scenarios.

Although advanced biofuels from agricultural and forestry residues have a great potential to contribute to climate neutrality in maritime transport, substantial growth of dedicated bioenergy crops is expected in most IPCC future scenarios consistent with a global temperature rise stabilization at relatively low levels (e.g., below 2 °C) [10]. Some projections for 2050 estimate that about 36 million tons of biomass will be needed only for biofuel production for European maritime transport [5]. Given that land availability is a vital constraint for the large-scale deployment of biofuels from dedicated bioenergy crops, achieving the maximum biophysical mitigation potential would require, for instance, efficiency improvements in the agri-food sector to release large areas of grazing lands and croplands from food and feed production and dedicate them to the implementation of carbon dioxide removal strategies [11]. In this sense, the utilization of abandoned cropland areas can be understood as key for sustainable mitigation in future scenarios of bioenergy production and phasing out of fossil fuel utilization [12,13]. The possibility of coupling bioenergy production with carbon capture and storage (CCS) systems also offers a great opportunity of delivering negative emissions for the international maritime sector with both drop-in and hydrogen-based biofuel production [6,15,15].

Several life-cycle assessments of PtX technologies have been published over the past few years, covering the potential greenhouse gas emissions from both Power-to-Liquid (PtL) and Power-to-gas (PtG) technologies. Hydrogen production from both proton exchange membrane (PEM) and alkaline electrolysis (AE) has been studied with a focus on different applications and geographical locations, such as road transport in Germany, [16] Switzerland [17,18], and Europe [19], as well for maritime applications in the United States [20]. The production of methane in the general European context has been studied aiming at the road transport sector [19], multiple applications [21], or no specific application [22]. Some studies, however, indicate Power-to-Methane in specific countries such as Spain – with methane produced by integration with biogenic CO_2 [23] and for maritime applications in the United States [20]. Other Power-to-Gas technologies include the production of syngas in Germany using PEM technology applied to the chemical industry [24] or without specific application when produced from high-temperature co-electrolysis [25]. Ammonia production from electrolysis has also been studied as an energy carrier for road transport in Germany and Switzerland [16,20], as well as an alternative feedstock for the chemical industry at a global scale [26]; studies of ammonia without specific application have explored the impacts in the European context [21] and in the United States [27]. Other studies focused on the climate change impacts of Power-to Liquid (PtL) fuels such as green diesel production from electrolysis for the European transport sector [28,29]; for methanol, studies cover its use as a transport fuel in Germany [30] and the United States [31]. These LCA studies, however, have performed an analysis of individual (or a limited number of) PtX fuels and do not provide any comparison against other RLFs, such as biofuels. Moreover, each publication differs in terms of methodological approach, and system boundaries, thus indicating the need for a broader comparison of RLFs for the maritime transport sector at the European scale.

The novelty of this study is a country-based comparison of climate impacts among grid-connected Power-to-X fuels and advanced biofuel production technologies in Europe to identify possible strategies to maximize GHG mitigation potentials from the different RLFs and countries. In terms of feedstock sourcing, we assess the impacts of advanced biofuel production from both dedicated bioenergy crops from recently abandoned cropland and today's available biomass residues from agriculture and forestry in Europe. To consider the possible synergetic interactions between PtX fuels and advanced biofuels, we include scenarios where biofuel upgrading occurs with H_2 from electrolysis and scenarios where PtX (e-diesel) fuel production uses biogenic CO2 captured from biofuel plants. The integration of the advanced biofuel upgrading stage with fossil-sourced hydrogen from steam methane reforming (SMR) is also analyzed to identify the pros and cons relative to the use of green H_2. To assess how cleaner electricity sources can benefit the on grid-connected PtX fuel production, this paper embeds a prospective-LCA perspective [32] that projects technological improvements in background activities up to 2050, such as power generation systems, whose carbon intensity might decrease over the next decades according to environmental policy implementation scenarios adopted by European countries.

2. Methodology

2.1. Scope of the study

The climate impacts of different Renewable and Low-Carbon Fuels (RLFs) are based on a well-to-wake life cycle perspective which includes all the inputs and emissions from raw material extraction, electricity production, feedstock cultivation, and transport to the industrial plant, conversion into fuel, distribution, and combustion in internal combustion engines. The climate metrics consider the updated 100-year global warming potential (GWP100) [33] and the RLFs in Europe consider variations in biomass feedstock sourcing, conversion pathways, biofuel upgrading strategies, implementation of carbon capture and storage (CCS), different electrolyzer technologies, hydrogen storage alternatives, and CO_2 sourcing for Power-to-X fuels. To facilitate the comparison among the multiple RLF pathways (11 options for PtX and 44 for biofuels), we grouped all RLFs into 3 main categories: Hydrogen-based biofuels, Drop-in biofuels, and Power-to-X fuels, as depicted in Fig. 1.

2.2. Biomass resource availability: Residues and dedicated bioenergy crops

This study is based on the spatial distribution of biomass potentials in

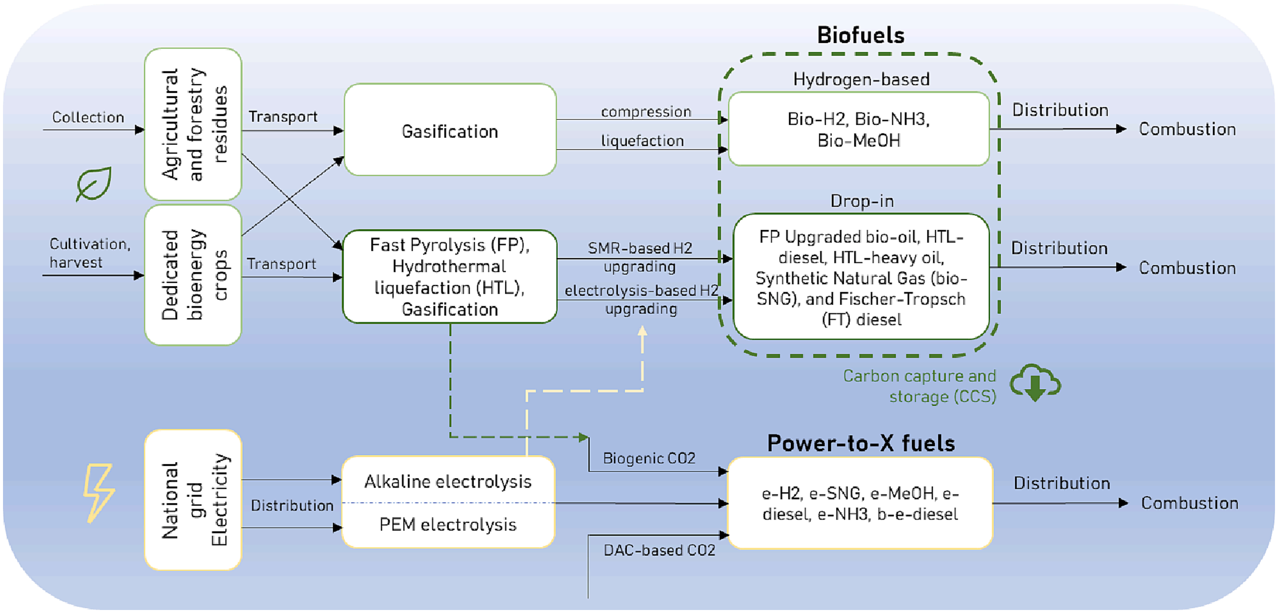

Fig. 1. Simplified scheme and system boundaries of Biofuels and PtX conversion routes for deep-sea maritime applications considered in this study.

28 European countries, namely Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. Based on data from previous studies [34,35], we mapped the yearly availability of agricultural and forestry residues in Europe as estimated in 159.5 M ton/yr (dry basis). Only the burdens associated with the collection and transport of residues to the biofuel plant are accounted as emissions since those from forest and crop cultivation have already been allocated into their main products (seeds, grains, and wood). The average residue transport distances per country, the residue availability per area in different European countries, and the optimal distances from the fields to biofuel plants of a capacity of 560 thousand tons yr^{-1} (dry basis) follow the assumptions made in a previous study [6]. Even though part of agroforestry residues is currently in use by other industries and sectors, this paper has a conservative assumption regarding the removal rates, around 30%. For agricultural residues, we assume a ‘sustainable’ potential [35], which represents a sustainable residue removal rate that avoids the depletion of soil organic carbon stocks in the cultivated areas. For forestry residues, we consider the ‘base’ potential [34] that refers to forest residue availability in line with current guidelines of sustainable forest management and covers legal restrictions from management plans in protected areas. The estimates of biomass residue potentials used in our study are thus conservative.

We use the land cover data from European Space Agency Climate Change Initiative (ESA-CCI) to identify the abandoned cropland. These data are available as annual time series, and we considered the period from 1992 to 2018. The land cover product has a 300 m (or 10 arc seconds) horizontal resolution at the equator and is obtained by combining several earth observation products and by using the GlobCover unsupervised classification chain. Recent studies used these data to identify abandoned croplands from 1992 to 2015 [13,36]. Here, by integrating the ESA-CCI and the Copernicus Climate Change Service (C3S-CDS) [37,38] datasets, we further extend the identification of cropland abandonment to 2018. Originally, there are 37 land cover classes in the ESACCI land cover dataset, and we aggregate them into more generic IPCC land cover classes with a walking table. Abandoned cropland is identified by selecting the grid cells classified as cropland classes in 1992 but not in 2018. Cropland translated to urban settlements is excluded since it is reasonable to assume that they are not suitable for bioenergy crops [39].

The total biomass production from the selected bioenergy crops in abandoned cropland areas is based on the yields of perennial grasses under rainfed water supply according to the model Global Agro-Ecological Zones (GAEZ) [40]. Agroclimatic yields for miscanthus, reed canary grass, and switchgrass are collected at 5 arc minutes spatial resolution and consider several constraints such as local temperature, moisture, and leaf area index, as well as risks of pests and diseases. A detailed analysis of the energy potentials and LCA of farming perennial grasses as energy crops on European abandoned cropland is available elsewhere [41]. Based on the total bioenergy production per country, we estimate the current potential of dry biomass production in the selected 28 European countries as approximately 98.4 M ton_{db} yr^{-1}. The environmental burdens considered in this study for miscanthus, reed canary grass, and switchgrass are based on the life cycle inventories from [11], which include cultivation of perennial grasses, including the major farming activities (soil preparation, fertilization, harvesting) specific to each type of perennial grass. The emissions from biomass transport to the biofuel plant follow the same approach of a previous study for advanced biofuel production pathways [6], which estimates country-specific average transport distances for residual biomass sources (see Table S1, Supplementary Material).

2.3. Policy context of European maritime transport emissions

In this study, we refer to the European Parliament’s Regulation proposal EU 2017/352 which establishes a gradual decrease in the GHG intensity – measured as g CO_{2eq} MJ^{-1} – of the energy used on-board by a ship for the next decades when considering well-to-wake life cycle emissions. The percentage reductions achieved by RLFs relative to the current fossil fuel GHG intensity should be at least 75 % by 2050, which encourages the development of more advanced, zero-emission technologies [5].

2.4. Drop-in biofuels

This category refers to RLFs that can directly replace fossil fuels using the current infrastructure of deep-sea maritime transport. In this paper, the description of foreground inventories follows our previous study [6] which provides the life cycle inventories and data collection regarding Fast Pyrolysis (FP), Hydrothermal Liquefaction (HTL), gasification with

Fischer-Tropsch (FT) synthesis, and gasification to bio-synthetic natural gas (BNGS). Besides, technologies with carbon capture and storage (CCS) are considered as an alternative to achieve negative emissions in the case of HTL, FT, and BSNG. This paper expands the scope of our previous study by implementing variations in the biomass sourcing – agriculture and forestry residues and dedicated bioenergy crops –, including two options for the biofuel upgrading stage of both HTL biocrude and FP bio-oil – gray hydrogen sourced from steam methane reforming (SMR) and hydrogen from electrolysis.

The Fast Pyrolysis (FP) of biomass to FP bio-oil is according to mass and energy balances as described in[42], followed by an additional stabilization step [43]. The resulting output is a stabilized bio-oil with a higher LHV that is compatible to displace heavy fuel oil (HFO) in deep-sea shipping. For hydrothermal liquefaction (HTL), we base our foreground inventory on data from [44], whose outputs are drop-in renewable marine fuel (residue fraction) and diesel (distillate fraction) – which can displace HFO and petroleum diesel, respectively. The integration of HTL with carbon capture and storage systems is based on mass and energy balances from [45]. FP and HTL pathways with CCS in this study assume the additional infrastructure and energy used to transport the CO_2 over a 200 km pipeline and store it in a saline aquifer based on inventories from [46].

Data for the compilation of foreground inventories for Gasification with Fischer-Tropsch (FT) synthesis is based on [47], which describes the gasification plant that converts dried lignocellulosic biomass into syngas which, in turn, undergoes a catalytic reaction that produces diesel. Considering the co-production of gasoline and surplus electricity, the distribution of environmental impacts is based on energy allocation. For the integration with CCS, additional materials and energy used in the absorptive unit based on monoethanolamine (MEA) and in the CO_2 drying and compression sections were included according to [48].

2.5. *Hydrogen-based biofuels*

Hydrogen-based biofuels are associated with deeper changes in the current maritime infrastructure, thus representing a transition to new value chains based on the production and distribution of gaseous and liquid fuels such as hydrogen, ammonia, and methanol deployed at a global scale. Similarly, the inputs and environmental burdens associated with the production, transport, and use of internal combustion engines, whose foreground inventories are based on [49], which describes a compilation of mass and energy balances biomass gasification into bio-hydrogen (BH_2), bio-ammonia (BNH_3), and bio-methanol (BMEOH), according to [50,50,52], and [53], respectively. As for drop-in biofuels, we also include different combinations of biomass sourcing – agricultural and forestry residues and dedicated bioenergy crops – and CCS technologies associated with BH_2, BNH_3, and BMEOH are based on [54,52], and [53], respectively.

2.6. *Power-to-X fuels*

This paper expands the scope of RLF production pathways by including on grid-connected Power-to-X fuels (PtX), i.e., those fuels primarily based on the production of hydrogen from electrolysis which can be further used as an energy carrier or combined with a carbon source to produce methane, methanol, and other synthetic fuels. Although many upcoming projects of PtX fuels consider off-grid production of hydrogen, the GHG intensities from such would be more dependent on the technology – i.e., solar, wind, etc. – rather than the region that is produced. For this reason, we focused on the on grid-connected PtX fuel production to identify the current potential of countries to deliver the lowest GHG intensities with the current carbon intensity of national electricity grids. Moreover, this paper considers the effects of the increased use of renewable energy sources on the GHG intensity of PtX fuels when running future electricity mix in European countries from the prospective LCA for 2050, as discussed in section 2.7.

Considering that maritime transport is the targeted sector, we also consider the production of e-ammonia by combining e-hydrogen with nitrogen sourced from the atmosphere. The data sources to compile mass and energy balances for Power-to-X fuels are further described in this section. The emissions associated with the current electricity mix at the country level are based on the ecoinvent 3.8 database [55].

2.6.1. *E-hydrogen (e-H_2)*

The production of e-hydrogen (e-H_2) is based on water electrolysis according to the current state-of-the-art [16] which includes data on system parameters, energy, and materials consumed in polymer electrolyte membrane (PEM) electrolyzer, stack, and balance of plant. To check possible variations in terms of process efficiencies, we included e-hydrogen production utilizing current Alkaline electrolysis (AE) technology, whose life cycle inventories, as well as mass and energy balances from another study [26]. To minimize electricity consumption in the hydrogen production value chain, we assumed that e-H_2 will be compressed (to 350 bar) instead of liquefied (see foreground inventories in Tables S2 and S3, Supplementary material).

2.6.2. *E-synthetic natural gas (e-SNG)*

In e-synthetic natural gas (e-SNG) production, hydrogen is sourced from electrolysis and carbon dioxide from Direct Air Capture (DAC). The process design, mass, and energy balances are based on [18]. It includes all the inputs, outputs, and emissions related to water electrolysis, DAC system, CO_2 compression, thermochemical methanation, methane dehydration, conditioning, and compression to 200 bar. Inventories for PEM and AE electrolysis technologies follow the same assumptions made for e-H_2 production in this study [16,26]. See the complete inventory in Tables S4 and S5, supplementary material.

2.6.3. *E-methanol (e-MeOH)*

The synthesis of e-methanol (e-MeOH) is based on data from [31], whose process design for a standalone scenario describes the consumption of hydrogen, carbon dioxide, electricity, and the resulting outputs from the methanol synthesis. In this two-step process, hydrogen reacts with CO_2 producing CO through a reverse water-gas shift reaction; the resulting carbon monoxide then reacts with hydrogen to generate methanol. We assume that carbon dioxide is sourced from direct air capture (DAC), whose inventory is based on [18]; for hydrogen sourcing, PEM and AE electrolysis technologies follow the same assumptions made for e-H_2 production [16,26]. See the complete inventories in Tables S6 and S7 in the supplementary material.

2.6.4. *E-diesel*

In this study, we assumed e-diesel production inventories according to mass and energy balances from [28] whose foreground inventories are based on two specific scenarios for carbon dioxide sourcing: atmospheric carbonic dioxide (DAC) and biogenic carbon dioxide. In this study, we exclude fossil CO_2 sources – e.g., flue gases from natural gas-based power plants – since they have a negligible contribution to climate impact mitigation when compared to DAC and biogenic sources [28]. The last scenario (b-e-diesel) represents an integrated biofuel and e-fuel plant co-producing both e-diesel and FT-diesel from biomass gasification. In the case of the integrated scenario, the environmental burdens from the co-production of both e-diesel and FT-diesel are distributed according to the energy allocation criteria.

2.6.5. *E-ammonia*

The production of ammonia is based on the foreground inventories from [26] which describes the NH_3 synthesis based on the Haber-Bosch process. In this study, nitrogen is sourced from an Air Separation Unit and cryogenic distillation provides high-purity N_2 from the air. Foreground inventories for hydrogen based on both alkaline electrolysis and proton exchange membranes are also based on [26], as described in Table S8 in the supplementary material.

2.7. Prospective life cycle assessment

We perform a prospective LCA that considers the influence of future technological evolution on background systems – i.e., the suppliers of goods and services for fuel production plants – over the next three decades. Using premise version 1.3.2 [31], we align life cycle inventories of key processes in ecoinvent 3.8 with the outputs of the REMIND Integrated Assessment Model [56]. The output databases embed technological improvements in electricity production mix, power plant efficiencies, average fleet, and energy mix used for transport, and advanced technologies to produce fuels and materials. New background inventories are built to represent the technological scenarios for 2050 according to the 'SSP2 – Middle of the Road' where the world faces intermediate challenges for climate change mitigation and adaptation, with reasonable population growth, lower energy use, but slow progress in achieving sustainable development goals. In terms of the environmental policy scenario, we consider the National Determined Contributions (NDC) which represent the implementation of the emission reductions and other mitigation commitments stated by the different countries in the Paris Agreement. As REMIND projects improvements in European electricity production as an aggregated region of the world, we assume that a similar pace of decarbonization – in terms of percentage reductions – will be achieved at the country level over the next decades, with electricity carbon emissions disaggregated at country level following the assumptions in our previous study [6].

3. Results

3.1. GHG intensities and mitigation potential of RLFs in European countries

Fig. 2 shows the country-based GHG intensities of RLF pathways grouped into three main categories: drop-in biofuels, hydrogen-based biofuels, and on grid-connected Power-to-X fuels. Results are shown as statistical scores across all production pathways in these three fuel categories and biomass feedstock per country. Hydrogen-based biofuels appear to be the most promising options to decrease climate impacts. Although the emissions from pathways such as liquid bio-hydrogen can lead to higher climate impacts on average, the overall performance of other RLFs such as compressed hydrogen, ammonia, and methanol – especially if obtained from the gasification of biomass residues – lead to lower GHG intensities than some drop-in fuel categorie. Although the lowest bound of drop-in biofuels GHG emissions (roughly 2 g $CO_{2eq}MJ^{-1}$ for Fischer-Tropsch diesel based on biomass residues) are very close to those from hydrogen-based biofuels (ca. 3 g $CO_{2eq}MJ^{-1}$ for bio-methanol based on biomass residues) in most of the European countries, the need for fuel upgrading in pathways such as Hydrothermal Liquefaction and Fast Pyrolysis contributes to increasing the upper bounds of life-cycle emissions, particularly when hydrogen is produced in countries with carbon-intensive electricity mix. In the most extreme cases, such as Fast Pyrolysis with bio-oil upgrading from hydrogen obtained from electrolysis using the average Polish electricity mix, the GHG intensity could exceed 158 g $CO_{2eq}MJ^{-1}$. In the case of on grid-connected Power-to-X fuels, FuelEU Maritime reduction targets for 2050 are achieved in Norway, Sweden, and Switzerland, especially if producing from compressed e-hydrogen, when GHG intensities are all below 22 g $CO_{2eq}MJ^{-1}$. In this case, targets would be essentially reached due to the lower carbon intensity of their national electricity grids, which is the case of compressed hydrogen production from alkaline electrolysis in Norway. For drop-in biofuels, almost all countries can achieve the 2050 GHG intensity target when considering their lowest bounds (which is associated with RLF conversion pathways based on gasification of biomass residues, such as BSNG and FT); in the case of hydrogen-based biofuels, a similar situation is observed, when compressed bio-hydrogen and bio-methanol produced from biomass residues achieve values as low as 3 g $CO_{2eq}MJ^{-1}$.

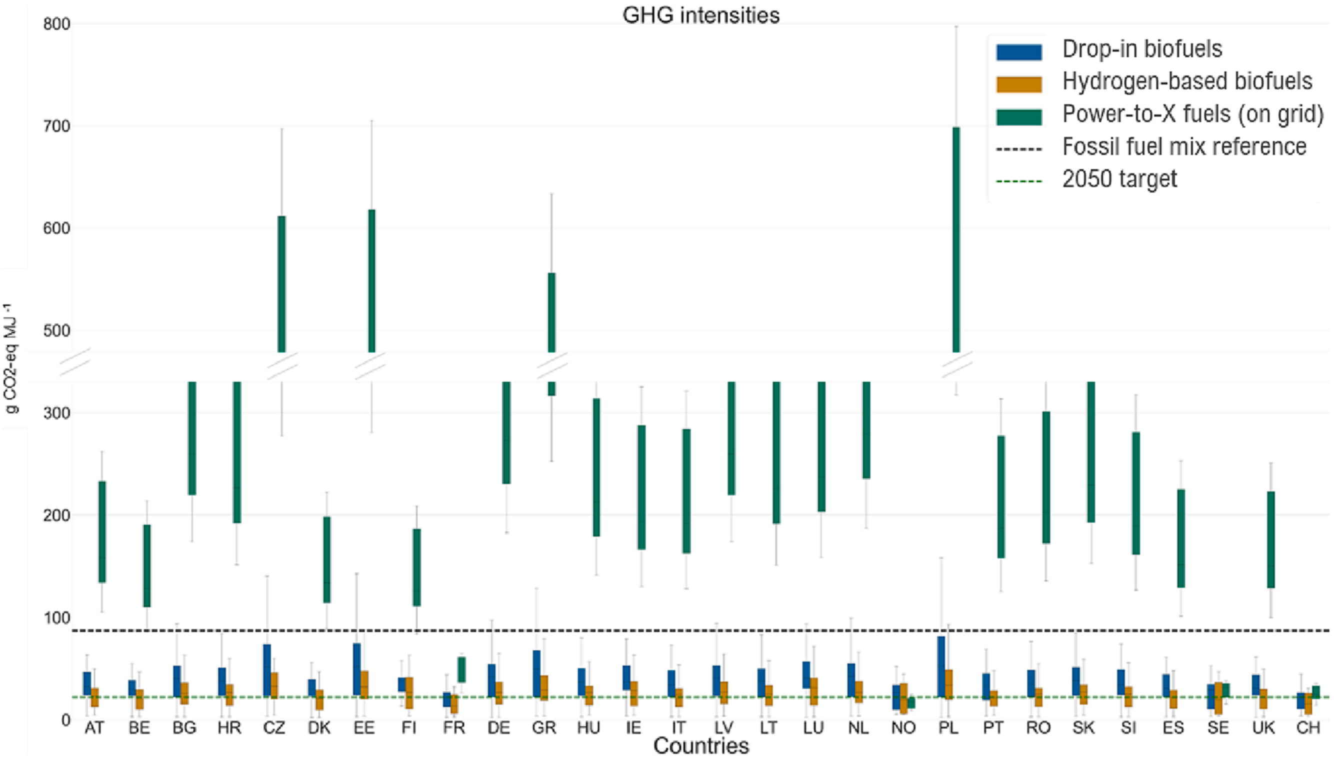

Fig. 2. GHG intensities of renewable and low-carbon fuels (RLFs) in European countries. Boxplots are grouped into drop-in biofuels, hydrogen-based biofuels, and Power-to-X fuels. Y-axis is broken to fit the highest GHG intensities. The horizontal black dashed line shows the average intensity of today's fossil fuel mix, while the green dashed line shows the 2050 reduction target according to the FuelEU Maritime proposal [4]. Box limits indicate the range of the central 50% of the data, with a central line marking the median value. Whiskers extend from each box to capture the range of the remaining data.

Considering the variability associated with the current carbon intensity of the national electricity grids and the RLF conversion pathways, the on grid-connected Power-to-X fuels can be perceived as a more limited solution to European maritime transport, since GHG intensities range from 8 to 797 g $CO_{2eq}MJ^{-1}$ depending on the pathway and country. However, such an RLF would contribute to mitigating fossil fuel emissions only if integrated into very low carbon-intense electricity grids such as Norway, Switzerland Sweden, and France (with GHG intensities in Finland and Belgium below but very close to the fossil reference), whose values are all below 87 g $CO_{2eq}MJ^{-1}$. As Fig. 3 shows, e-H_2 can be produced with the lowest GHG intensities in Norway (8 g $CO_{2eq}MJ^{-1}$), although the integrated production of b-e-diesel (i.e., those plants producing both biofuels and e-fuels) is associated with the lowest GHG intensities for all the other countries when based on biomass residues when a minimum value of 9 g $CO_{2eq}MJ^{-1}$ is observed. The non-linear patterns from b-e-diesel GHG intensities are noticed especially when integrated with dedicated crops (dark green line). Such an effect comes from the different biomass transport distances in countries with lower emissions in the national electricity grid. As the carbon intensity of the national electricity mix increases above 100 gCO_{2eq} kWh^{-1}, these non-linear effects become negligible; above this threshold, biofuels would be preferable to increase the mitigation potentials instead of PtX under the current technology scenario. Among the PtX fuel alternatives, e-diesel from direct air capture leads to the highest GHG intensities in almost all countries (up to 797 g $CO_{2eq}MJ^{-1}$). In Norway, however, the highest value (24 g $CO_{2eq}MJ^{-1}$) is associated with b-e-diesel production from dedicated crops. This effect is related to the low availability of abandoned croplands and higher biomass transport distances in the country. In the case of Switzerland and Sweden, the highest GHG intensities among PtX fuels are associated with the e-SNG route, when values reach 38 and 36 g $CO_{2eq}MJ^{-1}$, respectively.

Although Figs. 2 and 3 provide an overview of GHG intensities associated with the different RLF categories – i.e., indicating their performance in g $CO_{2\text{-}eq}$ MJ^{-1}–, the maximum yearly mitigation potentials per country measured in tons of $CO_{2\text{-}eq}$ depend on the combination of the lowest GHG intensities with the maximum potential in terms of yearly energy outputs (which depend on the national resource availability). Such results are plotted in Fig. 4, which highlights the top-ten potential mitigation values with their respective European countries and associated conversion pathways. It represents yearly mitigation values and their correlation both with the country's biomass average density and average carbon intensity from the national electricity mix. The maximum yearly mitigation values (up to 35.7 M tCO_{2eq} yr^{-1} in France) originate from the production of drop-in biofuels, given both their relatively lower GHG intensities and higher biomass-to-fuel energy conversion yields when compared to either Power-to-X or hydrogen-based biofuels. France, Germany, Spain, Italy, Poland, and Romania are among the top-ten countries regardless of the biomass sourcing strategy since both options would lead to relatively high biomass availabilities. In the case of dedicated bioenergy crops (Fig. 4a), high mitigation potentials (up to 15 M tCO_{2eq} yr^{-1} in France) can be also observed in Bulgaria, Greece, Portugal, and Lithuania due to the relatively larger availability of biomass in abandoned cropland so that yearly mitigation can exceed that from biofuel production based on biomass residues. The UK, Sweden, Hungary, and Denmark are among the top ten if only agricultural and forestry residues are considered as an option (whose highest yearly mitigation potential would achieve 11.8, 7.6, 6.1, and 4.8 M tCO_{2eq} yr^{-1}, respectively). As Fig. 4a shows, HTL coupled to electrolysis-based hydrogen for upgrading (HTL, ELEC H_2) is preferable in countries situated on the left-hand side of the chart, whose national electricity mix GHG intensities are much lower. The transition amongst colors representing changes in the technologies providing maximum mitigation potentials can be observed from the left to the right bubbles, demonstrating their higher sensitivity to electricity sourcing rather than to the average biomass density per area. In countries with the electricity mix GHG intensity ranging from 200 to 600 g

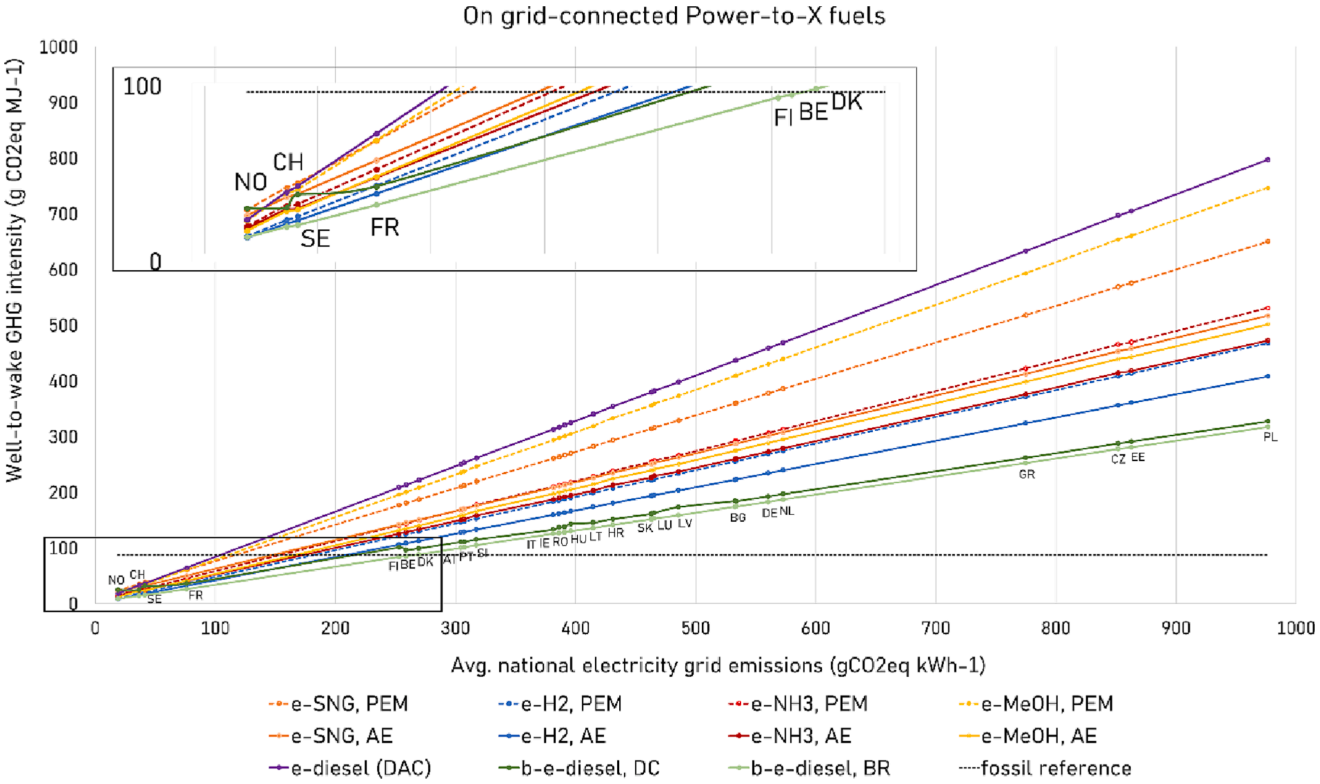

Fig. 3. On grid-connected Power-to-X fuels GHG intensities in the current European electricity grid: compressed synthetic natural gas (e-SNG), hydrogen (e-H_2), ammonia (e-NH_3), and synthetic diesel (e-diesel). Integrated Power-to-X and biomass gasification to FT-diesel (b-e-diesel). AE: alkaline electrolysis, PEM: proton exchange membrane electrolysis, BR: biomass residues from agricultural and forestry activities, DC: dedicated crops.

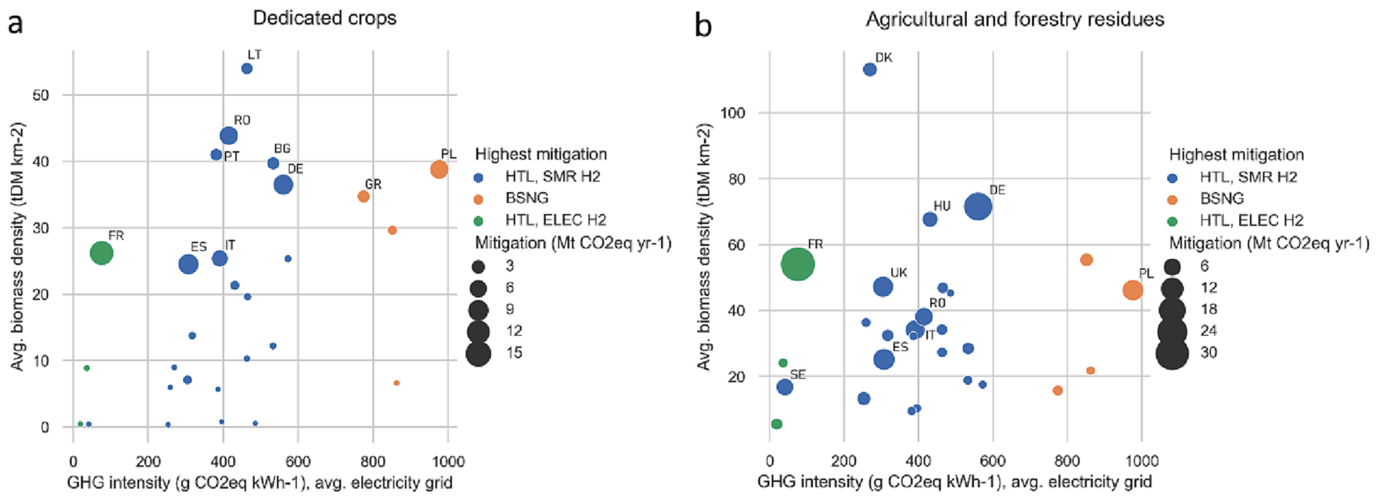

Fig. 4. Yearly mitigation potentials (million metric tons CO_{2eq} yr^{-1}) of RLF technology options. The bubbles refer only to the technological option leading to the highest potentials in each European country. We consider two different biomass sources for biofuel production: dedicated bioenergy crops (a) and agricultural and forestry residues (b). The top-ten countries with higher mitigation potentials are highlighted with labels. The country's biomass average density is given in tons of dry biomass per square kilometer; the country's average GHG intensity in g CO_{2eq} kWh^{-1} for the electricity mix.

CO_{2eq} kWh^{-1}, HTL with SMR-based hydrogen would be preferable to the electrolysis-based for the upgrading. Gasification of biomass to BSNG would be the pathway leading to the highest mitigation in countries with electricity mix above 700 gCO_{2eq} kWh^{-1} since provides the best combination of GHG intensity and biomass-to-fuel energy conversion yields.

Fig. 4b depicts larger yearly potential up to ca. 35 $MtCO_{2\text{-}eq}$ in France, whereas this potential decreases to about 26 $MtCO_{2\text{-}eq}$ when dedicated crops are considered as the biomass source (Fig. 4a). This effect is induced by the larger biomass availability of agricultural and forestry residues when compared to dedicated crops (which, in turn, depends on the availability of abandoned cropland areas). Furthermore, the emissions associated with the cultivation of dedicated bioenergy

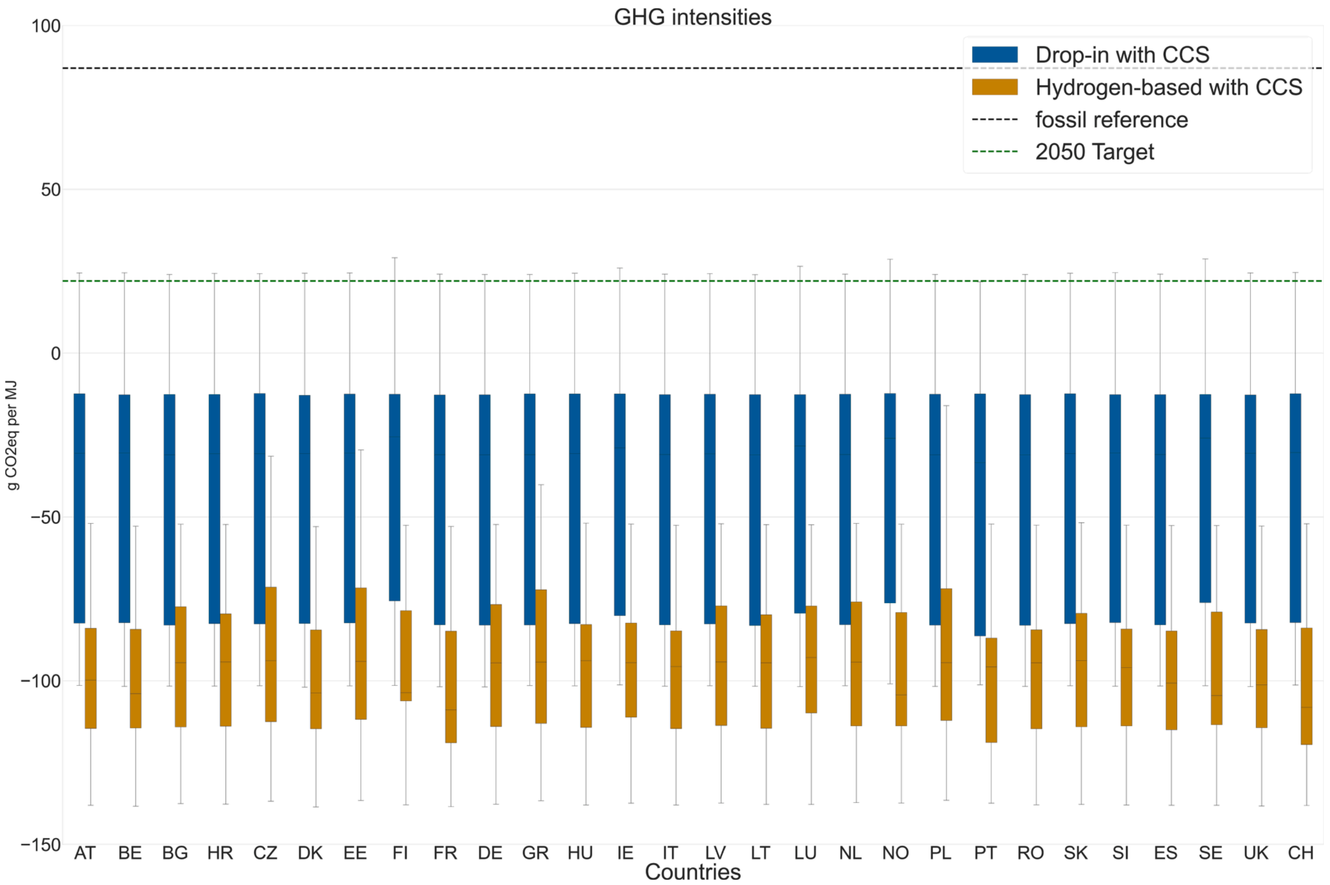

Fig. 5. GHG intensities of renewable and low-carbon fuels (RLFs) integrated into CCS technologies for maritime transport in Europe are grouped as drop-in biofuels and hydrogen-based biofuels. The green dashed line shows the 2050 reduction target according to the FuelEU Maritime proposal [4]. Box limits indicate the range of the central 50% of the data, with a central line marking the median value. Whiskers extend from each box to capture the range of the remaining data.

crops are higher (per kg of dry matter) than biomass residues whose environmental burdens, in turn, are essentially associated with its collection and transport operations [6]. On the other hand, countries such as Bulgaria, Portugal, Greece, Lithuania, and Netherlands would induce higher yearly mitigation if biofuels are produced from dedicated bioenergy crops (3.5, 3.2, 3.3, 2.9, and 0.7 $MtCO_{2\text{-eq}}$, respectively). This occurs because their biomass production potentials in abandoned cropland areas would be much higher than the current availability of agricultural and forestry residues. In these cases, mitigation induced by higher biomass availability compensates for the slightly higher GHG intensities associated with crop cultivation when compared to biomass residues.

As Fig. 5 depicts, GHG intensities are enormously reduced when CCS technologies are considered. In most European countries, when industrial CO_2 emissions from hydrogen-based biofuel production are captured and stored, negative emissions ranging from −50 and −100 gCO_{2eq} MJ^{-1} are observed. The lowest values (below −100 gCO_{2eq} MJ^{-1}), are associated with the production of bio-methanol and compressed bio-hydrogen from biomass residues. In the case of bio-methanol, up to 52% of carbon dioxide is captured after syngas gas cleaning (acid gas removal); for compressed bio-hydrogen, CO_2-rich streams are separated after the PSA (pressure swing adsorption) unit are combusted in a boiler to produce the steam and electricity required in the plant. Thereafter, the exhaust gas undergoes a gas separation polymeric membrane process for CO_2 capture, which can take up to 51 % of carbon input in the biomass. On the other hand, the highest GHG intensities are related to the production of liquid bio-hydrogen, due to the additional emissions associated with the increased electricity demand to achieve the cryogenic state for storage and transport. Drop-in biofuels have negative emissions ranging from 0 to −50 gCO_{2eq} MJ^{-1}, on average, but can reach GHG intensities as low as hydrogen-based biofuels' lowest bounds, especially when producing Fischer-Tropsch drop-in fuels from biomass residues. We can notice that most of the RLF options are very likely to reach the 2050 GHG intensity reduction target established by the FuelEU Maritime initiative. Power-to-X fuels are not included in this comparison since they refer to a Carbon Capture and Use (CCU) strategy (in the case of e-methane, e-methanol, and e-diesel) whose GHG intensities were previously presented in Figs. 3 and 4.

Fig. 6 depicts the climate mitigation potentials when carbon capture and storage are considered. Hydrogen-based biofuels with CCS lead to individual mitigation potentials higher than 50 $MtCO_{2eq}$ yr^{-1}, achieved with bio-methanol from biomass residues in France (Fig. 6b). Germany, Poland, and Spain have the potential to achieve approximately 43, 24, and 22 M tCO_{2eq} yr^{-1} with the same conversion pathway, due to the higher availability of biomass residues in those countries. When dedicated crops are considered (Fig. 6a), bio-ammonia is a pathway leading to the highest potential in countries such as France, Denmark, Sweden, Belgium, Norway, and Finland. Although bio-ammonia provides a lower biomass-to-fuel output than bio-methanol, overall GHG intensity can be reduced in countries with electricity mix below 300 g CO_{2eq} kWh^{-1}. Above this value, bio-methanol is preferable since it requires less electricity in the biofuel plant, thus maximizing climate mitigation. In Fig. 6b, bio-methanol production from gasification is the predominant pathway for biomass residues and is not sensitive to electricity GHG intensities since the biofuel plant does not require external electricity input [53].

Table 1 summarizes the energy supply and mitigation potentials achieved in European countries considering the diverse RLF pathways assessed in this study. The minimum energy supply potentials from each country are related to bio-hydrogen production due to its lower biomass-to-biofuel conversion energy efficiency among the assessed RLF pathways whereas the maximums are associated with HTL due to the coproduction of both diesel and heavy oil. The maximum yearly GHG mitigation potentials come from bio-methanol CCS based on the gasification of biomass residues, as previously detailed in Fig. 6b. Such technologies can enhance the capacity of achieving negative emissions in both drop-in and hydrogen-based biofuels. A minimum of zero yearly GHG mitigation potentials in most countries represent situations by which one or multiple RLF pathways lead to higher GHG intensities in comparison to the current fossil fuels; for example, when e-diesel is considered, no mitigation would be achieved in most countries since their GHG intensities would be much higher than fossil's (87 gCO_{2eq} MJ^{-1}). Exceptions are Norway, Sweden, and Switzerland whose minimum potentials are associated with liquid bio-hydrogen, instead of Power-to-X fuels. The last row in Table 1 shows the range of effects from a total fossil fuel substitution by RLFs. If its full potential is deployed in Europe, the overall energy supply would range from 32 to 149% of the current yearly fuel consumption in the European maritime transport – approximately 1826 PJ (EC, 2020). In the case of yearly mitigation, the choice of pathways with the highest GHG intensities in all countries would provide a reduction of only 2% of current emissions in maritime transport; the full deployment of RLFs with CCS technologies, on the other hand, would mitigate 184%.

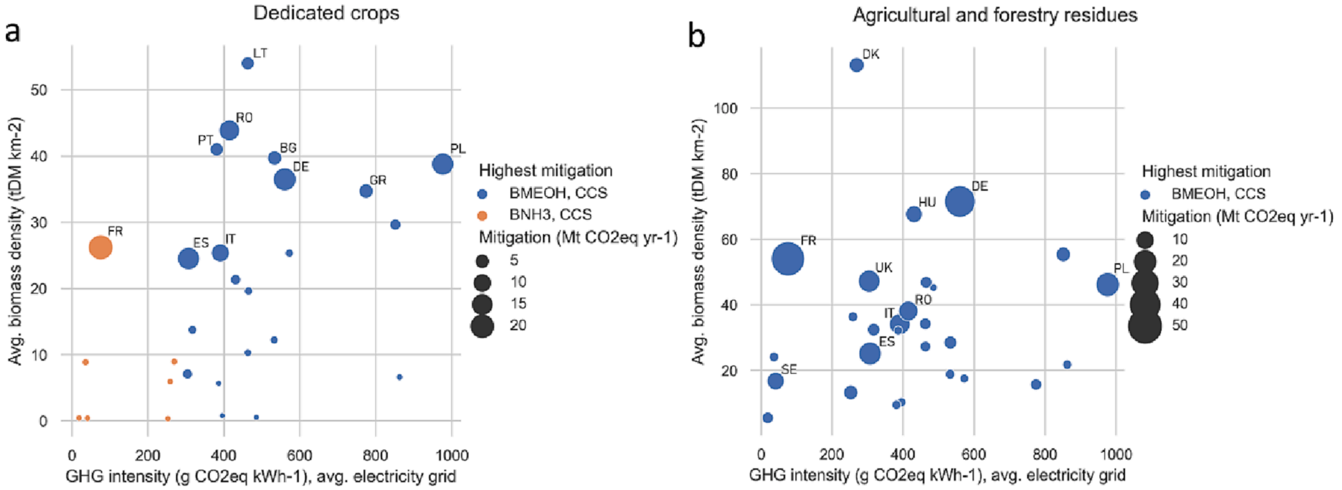

Fig. 6. Yearly mitigation potentials (million metric tons CO_{2eq} yr^{-1}) of RLF technology options with CCS. The bubbles refer only to the technological option leading to the highest potential in each European country. We consider two different biomass sources for biofuel production: dedicated bioenergy crops (a) and agricultural and forestry residues (b). The top-ten countries with higher mitigation potentials are highlighted with labels. The country's biomass average density is given in tons of dry biomass per square kilometer; the country's average GHG intensity in g CO_{2eq} kWh^{-1} for the electricity mix.

Table 1

Breakdown of the maximum and minimum values for the annual potentials of energy supply and GHG mitigation in Europe. Results relative to the annual energy demand of fuels and GHG emissions from the EU maritime transport sector are also shown.

	Yearly potential of energy supply (PJ yr^{-1})[a]		% of current energy demand in the European maritime transport[b]		Yearly mitigation potential ($MtCO_{2\text{-eq}}$)[c]		% GHG emissions in the European maritime transport[d]	
	min	max	min	max	min	max	min	max
AT	7.7	42.7	0.4%	2.3%	0.29	4.6	0.2%	2.9%
BE	1.2	17.6	0.1%	1.0%	0.05	1.9	0.0%	1.2%
BG	20.6	70.4	1.1%	3.9%	0.71	7.0	0.4%	4.4%
HR	3.9	24.7	0.2%	1.4%	0.02	2.7	0.0%	1.7%
CZ	15.5	68.3	0.9%	3.7%	0.03	7.4	0.0%	4.6%
DK	2.6	72.3	0.1%	4.0%	0.10	7.9	0.1%	5.0%
EE	2.0	15.1	0.1%	0.8%	0.05	1.6	0.0%	1.0%
FI	0.8	64.3	0.0%	3.5%	0.02	7.0	0.0%	4.4%
FR	95.6	472.7	5.2%	25.9%	3.42	52.0	2.2%	32.7%
DE	86.7	399.3	4.7%	21.9%	1.93	43.6	1.2%	27.5%
GR	13.5	73.0	0.7%	4.0%	0.23	7.2	0.1%	4.5%
HU	13.2	98.6	0.7%	5.4%	0.17	10.7	0.1%	6.7%
IE	0.4	11.3	0.0%	0.6%	0.01	1.2	0.0%	0.8%
IT	50.9	162.2	2.8%	8.9%	1.26	17.7	0.8%	11.2%
LV	5.2	18.7	0.3%	1.0%	1.26	2.0	0.8%	1.3%
LT	14.3	56.3	0.8%	3.1%	0.16	5.6	0.1%	3.5%
LU	0.0	1.8	0.0%	0.1%	0.00	0.2	0.0%	0.1%
NL	3.9	15.1	0.2%	0.8%	0.13	1.5	0.1%	0.9%
NO	1.1	32.0	0.1%	1.8%	0.04	3.5	0.0%	2.2%
PL	80.4	225.8	4.4%	12.4%	0.70	24.5	0.4%	15.4%
PT	5.8	58.3	0.3%	3.2%	0.78	5.9	0.5%	3.7%
RO	58.3	167.0	3.2%	9.1%	1.33	16.6	0.8%	10.4%
SK	6.4	36.0	0.4%	2.0%	0.03	3.9	0.0%	2.5%
SI	0.8	10.4	0.0%	0.6%	0.02	1.1	0.0%	0.7%
ES	81.2	200.7	4.4%	11.0%	3.18	22.0	2.0%	13.8%
SE	1.2	109.1	0.1%	6.0%	0.05	12.0	0.0%	7.5%
UK	11.5	182.4	0.6%	10.0%	0.43	20.0	0.3%	12.6%
CH	2.3	15.2	0.1%	0.8%	0.13	1.7	0.1%	1.0%
Total	586.9	2721.2	32.1%	149.0%	16.52	293.10	10.4%	184.5%

[a] Based on the current potential of biomass production and biomass-to-fuel conversion.

[b] Based on the overall energy demand for maritime transport in the European Economic Area (EEA) in 2019[57].

[c] Minimum values refer to the RLFs with the highest GHG intensities below the fossil fuel GHG intensity.

[d] Estimated WtW GHG emissions from fossil fuels in the European Economic Area[6,57].

3.2. *Prospective LCA and impacts in 2050*

When considering the implementation of the prospective REMIND SSP2-NDC 2050 scenario (Fig. 7), we notice a significant decrease in GHG intensities (especially for technologies without CCS) from mitigation commitments stated by the different countries until 2050. The progressive decarbonization of electricity, energy, transport, and other production systems has a higher impact on Power-to-X fuels when comparing results from Fig. 7 to Fig. 2. We observe narrower ranges for drop-in biofuels, hydrogen-based biofuels, and Power-to-X fuels, whose values vary from 1 to 29, 1–68, and 4–37 $gCO_{2eq}\ MJ^{-1}$, respectively. GHG intensities can achieve the FuelEU 2050 targets in most European countries. Although some PtX fuels exceed the limit in countries like Czechia, Estonia, Greece, and Poland, the selection of pathways such as e-H2 and integrated BtL-e-diesel production can lead to GHG intensities reaching the target set for 2050. Although values for hydrogen-based biofuels have a wider variability when compared to drop-in biofuels, we notice that both categories are very likely to stay below the 2050 GHG intensity target in most of the cases, having a more homogenous range of values regardless of the selected country.

REMIND SSP2-NDC 2050 scenario has a significant impact on the yearly mitigation potentials of European countries, mainly on the technologies without CCS. Compared to the results without prospective analysis, the maximum yearly GHG mitigation potentials increase by 42–43% if HTL based on forestry residues and electrolysis-based hydrogen is considered, especially in countries with more carbonized electricity grids like Czechia, Estonia, Greece, and Poland. On the other hand, countries with less carbonized grids like Norway, France, and Switzerland, have their mitigation potentials increased by only 3–4%. If dedicated bioenergy crops are considered as biomass feedstock, then the relative improvements associated with the prospective analysis are higher: HTL technologies have yearly mitigations increased by up to 55% in 2050 in Estonia, whose GHG emissions associated with biomass cultivation, transport, and electricity consumption in the HTL plant are significantly reduced.

PtX fuels become a viable option for achieving GHG intensity reduction targets in 2050 if the relative reduction trend in Europe is observed in all countries as forecasted for the REMIND-SSP2-NDC 2050 scenario. As Fig. 8 shows, all PtX fuels would achieve the 75% GHG intensity reduction target if national electricity grid emissions stay below ca. 17 $gCO_{2eq}\ MJ^{-1}$. Although e-SNG and e-diesel are associated with well-to-wake GHG intensities which do not reach the target for 2050 in some cases, most European countries could achieve the targets under these pathways. In all countries, e-H_2 and integrated b-e-diesel production (from biomass residues) provide the largest reductions, thus reaching the FuelEU targets set for 2050. As previously discussed, b-e-diesel production (based on biomass residues) is associated with the lowest emissions among pathways because the background emissions from electricity used in the electrolysis process are decreased when integrated into a gasification plant whose cradle-to-gate emissions are substantially lower than any PtX option. For compressed e-H_2 production, a high climate mitigation potential is observed because of the relatively lower electricity consumption when compared to other PtX fuels which, in turn, require additional industrial conversion steps to incorporate carbon and nitrogen into the fuel composition (which is the case of methanol, diesel, and ammonia). E-NH_3, e-MeOH, and integrated b-e-diesel production (with dedicated crops) are also options whose GHG intensities are below the maximum value in most countries. Although the well-to-wake climate impacts of e-SNG pathways decrease due to technological improvements in the background system, emission

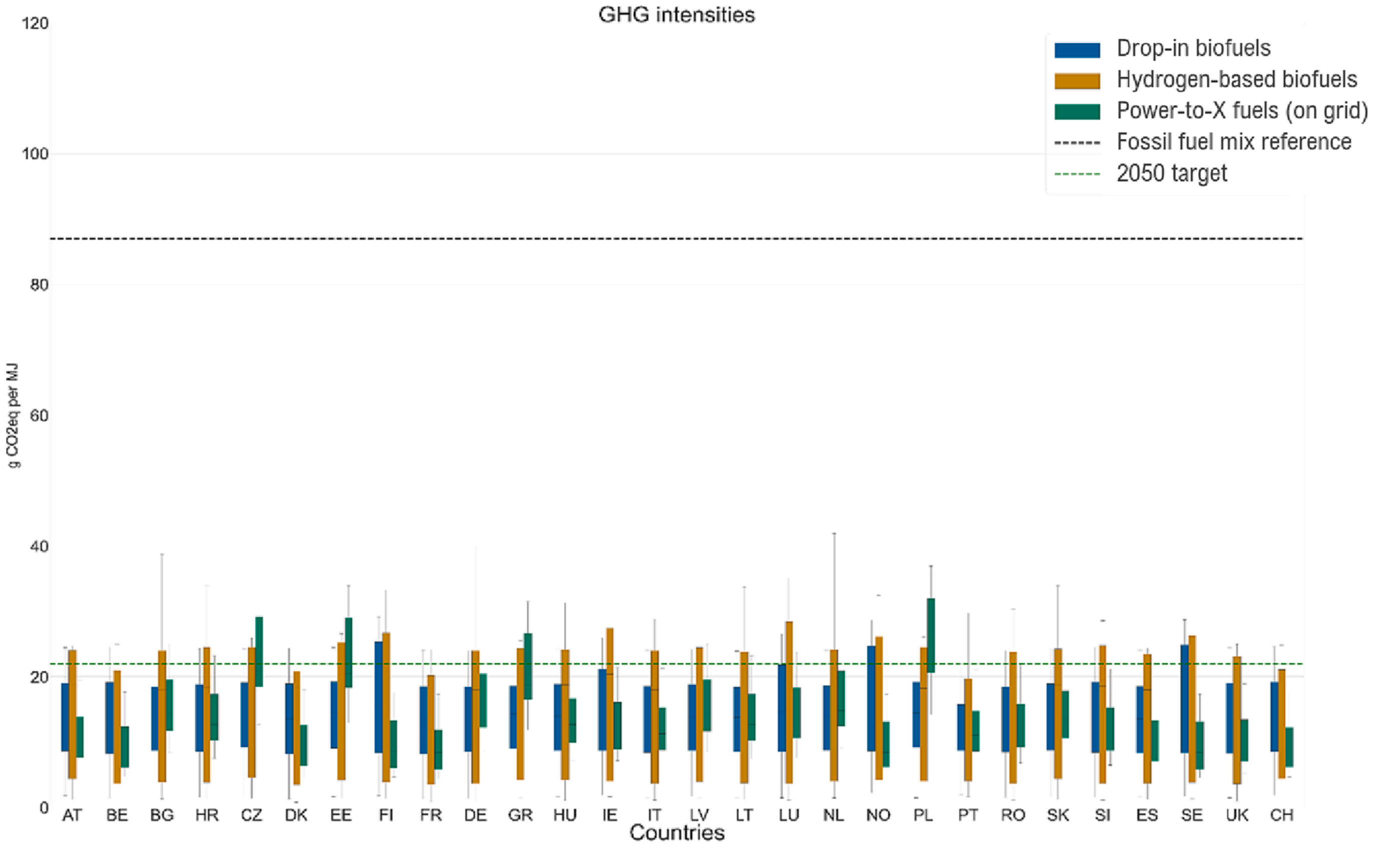

Fig. 7. Projected GHG intensities of renewable and low-carbon fuels (RLFs) in European countries in 2050 considering REMIND SSP2-NDC scenario. Results are grouped into drop-in biofuels, hydrogen-based biofuels, and on grid-connected Power-to-X fuels. The green dashed line shows the 2050 reduction target according to the FuelEU Maritime proposal [4]. Box limits indicate the range of the central 50% of the data, with a central line marking the median value. Whiskers extend from each box to capture the range of the remaining data.

reductions are limited by methane slips during combustion which is assumed to remain unchanged in the future [6].

In Fig. 8, the main non-linear pattern is associated with the integrated b-e-diesel production based on dedicated crops as biomass sources, whose main fluctuations are related to the variations in biomass transport distances in the different European countries. In the case of other PtX fuels not integrated into biofuel production, minor fluctuations refer to the different transport distances associated with fuel distribution.

The GHG intensities of RLFs coupled with CCS have different sensitivities to improvements led by the prospective inventory databases. For drop-in biofuels, gasification-based pathways have a net decrease in GHG intensities ranging from 2 to 10 g $CO_{2\ eq}$ MJ^{-1} with dedicated crops and from 1 to 3 g $CO_{2\ eq}$ MJ^{-1} with biomass residues; for HTL from biomass residues with CCS, then the net decrease in GHG intensity goes up to 82 g $CO_{2\text{-eq}}$ MJ^{-1} when electrolysis-based hydrogen is used in the upgrading (see the variability of GHG intensities in Fig. S1 of the supplementary material).

In terms of decreasing the yearly GHG mitigation potential for the best-performing technologies, the relative improvements for CCS technologies are relatively low by 2050 when compared to current scenarios. When considering the results for the best-performing pathways based on biomass residues – bio-methanol with CCS, in this case -, then the overall increase in yearly mitigation does not exceed 1–2% in all European countries. For dedicated bioenergy crops, relative improvements range from 4 to 15% although yearly mitigations are lower when considering bio-ammonia and CCS (see the best-performing pathways for the prospective analysis in Figs. S2 and S3 of the Supplementary Material).

4. Limitations of the study

Although a portion of the crop and forest residues are currently in use by other industries [58,59] and other sectors (e.g., aviation) may exacerbate competition for biomass, this paper considers that all available residues are converted into biofuels to estimate the overall potential at European scale. This assumption was also made for dedicated crops in abandoned cropland areas; therefore, the maximum mitigation potentials would be reduced in case competition for biomass with other industries increase throughout the forthcoming years. On the other hand, this study did not consider the effects of changes in soil organic carbon after the establishment of perennial grasses in abandoned cropland areas. If soil organic carbon changes are included, the net climate effects turn negative for all perennial grasses under rainfed conditions, showing potential for increasing the climate mitigation effects by storing carbon in soils while delivering renewable energy [41].

The approach used in this study considers that both biofuel and Power-to-X fuel plants are connected to the average national electricity mix. One of the limitations of such an assumption is related to the competition for electricity use with other industries and the need for further expansion of power generation in the different European countries. Although ongoing and future projects might consider off-grid PtX fuel production from specific renewable sources such as wind, solar, and others, there are still many challenges related to the intermittency of renewable power. In this sense, using grid electricity can be important as a backup power source when renewable energy is not sufficient. Furthermore, on grid-connected PtX can be more economically competitive by maintaining productivity and decreasing the need for large intermediate storage systems [60]. In this sense, the GHG intensities calculated in this study can be somehow related to off-grid PtX

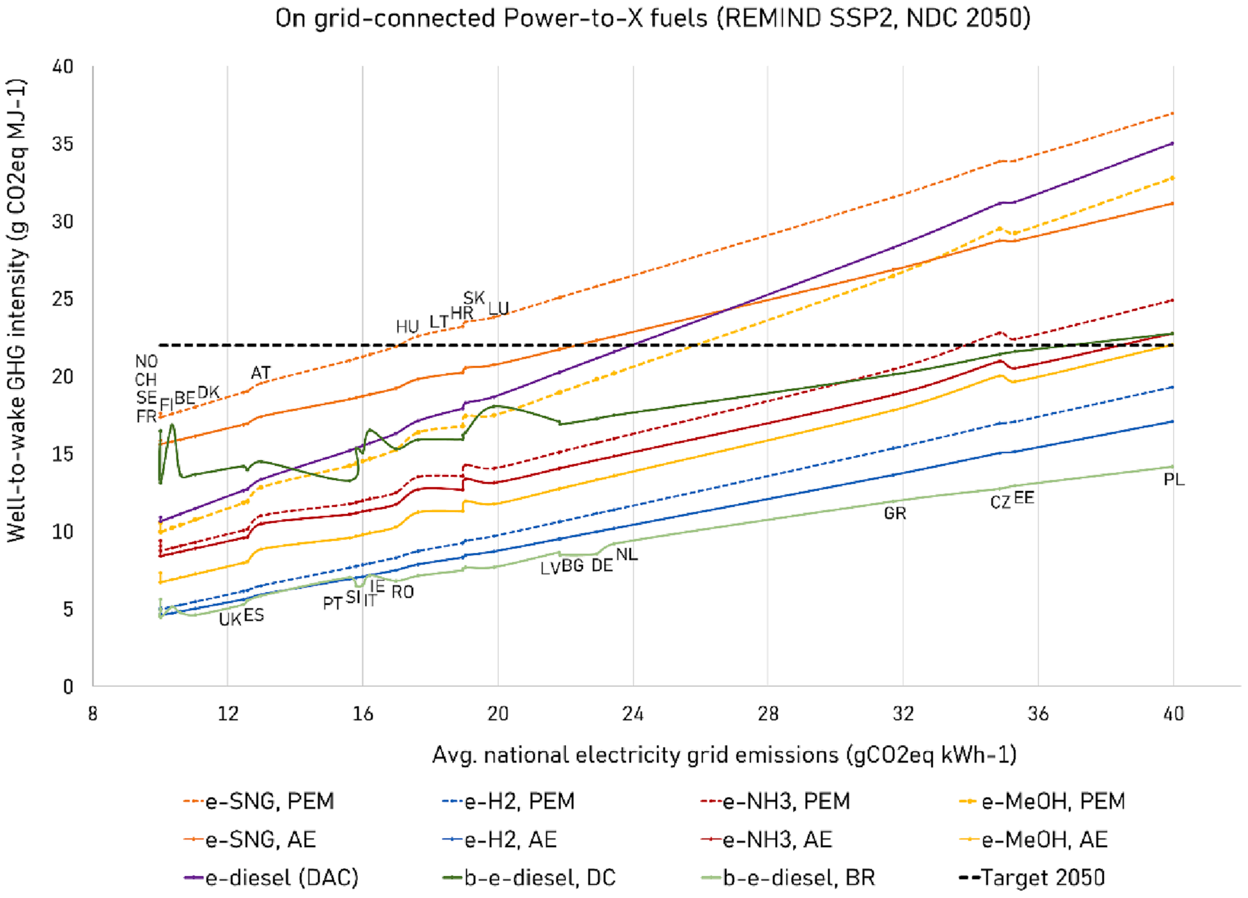

Fig. 8. On grid-connected Power-to-X fuels GHG intensities in the projected REMIND SSP2 NDC 2050: compressed synthetic natural gas (e-SNG), hydrogen (e-H2), ammonia (e-NH3), and synthetic diesel (e-diesel). Integrated Power-to-X and biomass gasification to FT-diesel (b- e-diesel). AE: alkaline electrolysis, PEM: proton exchange membrane electrolysis, BR: biomass residues from agricultural and forestry activities, DC: dedicated crops.

fuel production when backup electricity comes from the national grid.

5. Conclusion

The potentials of Power-to-X fuels to provide mitigation potentials – i.e., obtaining well-to-wake GHG intensities below fossil fuels – are limited to national grids with carbon intensities below 100 g CO_{2eq} kWh^{-1}. Although there are variations in the impacts from the different PtX conversion pathways, the technological improvements from the prospective analysis project a much larger potential of PtX to contribute to mitigation in the maritime sector by 2050. The results from our analysis show that the range of GHG intensities from the current scenario at the European level (8–797 g $CO_{2eq}MJ^{-1}$) can be enormously reduced to a range of 4–37 g $CO_{2eq}MJ^{-1}$ depending on the selected PtX fuel and country. To achieve FuelEU Maritime's goal of a 75% reduction in GHG intensities, PtX fuels should be connected to electricity sources below ca. 17 g CO_{2eq} kWh^{-1}, which would be possible due to the predominance of renewable electricity production in most of the European national grids.

At the European level, the ranges of GHG intensities of drop-in and hydrogen-based biofuels in the current scenario are 2–158 and 3–93 g $CO_{2eq}MJ^{-1}$, respectively, thus indicating climate mitigation will depend a lot on the right RLF pathway for each European country. For biofuels, our analysis shows that current mitigation potentials could be higher with the full deployment of biofuel production from agricultural and forestry residues, especially in France and Germany, which together could provide more than 50% mitigation of the current European maritime transport emissions if CCS technology was considered)At the European scale, both types of biomasses – residues and dedicated crops – could be sourced together and achieve high yearly mitigation potentials if the proper conversion pathways are selected in each region. To produce biofuels substituting diesel, electrolysis-based hydrogen for upgrading HTL fuel is preferable in countries whose national electricity mix GHG intensities below 200 g CO_{2eq} kWh^{-1}, whereas SMR-based hydrogen would be preferable in countries with carbon intensities between 200 and 600 gCO_{2eq} kWh^{-1}. For countries with electricity carbon emissions higher than 600 g CO_{2eq} kWh^{-1}, then gasification pathways such as BSNG would provide the highest yearly mitigation values. REMIND SSP2-NDC 2050 prospective scenario has a relatively higher impact on GHG intensities of biofuel production technologies without CCS. However, the employment of biofuels with CCS has the highest mitigation potentials, enough to neutralize and achieve negative yearly carbon emissions for the current European maritime transport. The choice of REMIND scenarios can highly affect the results of climate change mitigation from RLFs and, for this reason, further studies using either different IAMs (Integrated Assessment Models) or SSPs would be of interest to fully cover the implications of technology evolution forecast on the climate impacts of the biofuels used for deep-sea shipping in Europe.

This study identified possible strategies to achieve higher GHG mitigation among grid-connected Power-to-X fuels and advanced biofuel production technologies in European countries. However, the selection of the most appropriate RLFs will depend also on other factors related to technology readiness levels, techno-economics, safety, standards, and other important aspects associated with the implementation of such alternative fuel options for maritime transport.

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.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2023.100418.

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