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# Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment

Marcos Djun Barbosa Watanabe [*,1], Francesco Cherubini, Otavio Cavalett

*Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*

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## A B S T R A C T

The shipping sector is seeking options to reduce its emissions of greenhouse gases (GHGs) and achieve ambitious climate change mitigation goals. Unlike short-sea shipping that can rely on electrification of coastal vessels, drop-in biofuels are among the most promising options for deep-sea shipping decarbonization. However, environmental sustainability analyses of marine biofuels are limited, and usually do not include the influence of future changes in the background energy system nor the climatic effects of near-term climate forcers (NTCFs). In our study, we assess the climate change mitigation potential of various marine biofuels produced from forest residues in Norway (a country with ambitious plans for emission reduction from shipping) using a prospective life-cycle assessment (LCA) where the projected trends in the energy and transport sectors are integrated with improvements in the biofuel value chain for the next decades (2030–2050). Relative to fossil-based alternatives, climate mitigation potentials of biofuels range from 65% to 85% with short-term (GWP20) and to 78%–87% with long-term (GTP100) climate impacts. The inclusion of NTCFs reduces the mitigation benefits of biofuels in the short term, while it slightly increases them in the long term. The explicit modeling of technology and socio-economic changes under future policy scenarios indicates a reduction in the climate impacts of biofuels by up to 54% in 2050 when compared to the current situation. The amount of residues potentially available in Norway is sufficient to meet the present demand for liquid fuels in deep-sea shipping, thus providing yearly climate mitigation of 0.9–1.1 million tons of $CO_{2\text{-eq}}$ (equal to 6–7% of today's climate impacts from the entire transport sector in the country). Our analysis shows the large climate change mitigation potential of drop-in biofuels, and it provides new quantitative estimates that can help guiding a sustainability shift in the deep-sea shipping sector.

## 1. Introduction

Greenhouse gas emissions from the shipping sector were about one billion metric tons of $CO_2$ equivalents in 2018, approximately 3% of total global anthropogenic emissions. Without additional mitigation measures, marine fuel emissions projections indicate up to 130% increase by 2050 (IMO, 2020a). By contrast, the International Maritime Organization (IMO) has the ambition to decrease GHG emissions from the international shipping sector by at least 50% by 2050. Among the measures to be adopted – which include design-, technical- and operational-related measures – an important fraction of the planned reduction is expected to be achieved with the introduction of low-carbon fuel alternatives (Joung et al., 2020), including biofuels (IMO, 2020b). Differently from short-sea shipping whose operation on shorter distances can benefit from decarbonization via electrification of coastal vessels (Wu, 2020), biofuels are one of the most promising option for deep-sea shipping (EC, 2021) due to the possibility of being used as a drop-in (Kargbo et al., 2021) or in blends with no or minor modifications to existing engines and storage systems (Mukherjee et al., 2020). The FuelEU Maritime Initiative in Europe established a target of 75% reduction in the GHG intensity of energy used in ships by 2050 and estimates that biofuels should represent between 86% and 88% of the international maritime transport fuel mix in 2050 (EC, 2021). In general, biofuels are recognized as the option with the highest potential for climate change mitigation (Bouman et al., 2017). A variety of LCA studies find several environmental benefits for different types of biofuels, such as liquified bio-gas, methanol, bioethanol (Brynolf et al., 2014), biodiesel from soy and rapeseed oils (Gilbert et al., 2018), straight vegetable oils (Kesieme et al., 2019) and lignocellulosic fuels (Tanzer et al., 2019). These studies generally show that case-specific

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[*] Corresponding author.
*E-mail address:* marcos.d.b.watanabe@ntnu.no (M.D.B. Watanabe).

[1] Present address: Høgskoleringen 5, Postal Code 7034, Trondheim, Norway.

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aspects such as production location, type of biomass, logistics, industrial conversion pathway, and methodological assumptions can affect the range of emission savings.

In addition to GHGs, the shipping sector is characterized by emissions of near-term climate forcers (NTCFs) that can strongly affect the climate system, especially in the short-term and with spatial heterogeneities. However, there is a lack of studies covering the climate effects of marine biofuel deployment considering the contributions of NTCFs, the influence of different climate metrics, and the temporal dimension of the climate system response. NTCFs such as sulfates ($SO_x$), black carbon (BC), nitrogen oxides ($NO_x$), organic carbon (OC), carbon monoxide (CO), and other emissions, are excluded from most recent life-cycle assessments of marine fuel alternatives. This might be due to the complexity of these effects and their intrinsic uncertainties (IPCC, 2021). Some climate forcers (BC, CO) contribute to warming, while others ($SO_x$, OC) lead to cooling, making the net climate effects a balance of opposing contributions. There is a need to better understand the projected transition in the shipping sector towards low-carbon (IMO, 2020b), low-sulfur (IMO, 2019), and low-nitrogen oxides (IMO, 2016) emissions from alternative marine fuels under a perspective that includes an analysis of the effects of changes in emissions of NTCFs.

Many climate change assessments of developing technologies usually consider a constant background system, meaning that they assume today's energy and electricity mixes for technologies implemented in the future. How impacts are affected by projected technological changes (like improvements in efficiencies and progressive decarbonization trends) in energy, transport, material production, and other socio-economic factors are not captured. The concept of prospective Life-Cycle Assessment, which integrates future life cycle inventories with the outputs of Integrated Assessment Models (IAMs) according to different shared socio-economic pathways (SSPs) and temperature targets, is an emerging approach to explicitly include in LCA effects from future changes in the background system (Mendoza Beltran et al., 2020; Sacchi et al., 2022). This aspect is particularly important to be considered in the assessment of biofuels for the shipping sector, which are expected to be deployed at scale in the next decades.

Norway is a country with high interests in the maritime industry and with stated ambitions to favor a more climate-friendly shipping sector (NSA, 2021). The Norwegian's action plan for green shipping expects a reduction in emissions by introducing a quota of advanced biofuels produced from biomass residues (Regjeringen, 2019). However, comprehensive analyses of the climate change mitigation benefits of different marine biofuels produced in Norway are missing, thereby hindering a proper quantification of the mitigation potentials and an understanding of how much climate impacts are dependent on biofuel type, emissions considered (NTCFs and/or GHGs) or climate metric (based on either short or long-term perspective). In this study, we assess the climate impacts of four key marine biofuels for the deep-sea shipping: bio-synthetic natural gas (Bio-SNG), fast pyrolysis (FP), hydrothermal liquefaction (HTL), and gasification with Fischer-Tropsch synthesis (FT). The climate change mitigation benefits are estimated relative to specific fossil counterparts, i.e., heavy fuel oil (HFO), marine diesel oil (MDO), and liquified natural gas (LNG), which are currently 99.5% of the fuels used in deep-sea shipping (IMO, 2020a). The study is based on an LCA approach, and the climate impact analysis includes NTCFs and complementary climate metrics for assessing short-, medium-, and long-term perspectives. Biofuels are assumed to be produced from forest residues available in the country, so to minimize pressure on land resources and stimulate a circular economy perspective. Forest residues are mapped, and the potential biofuel capacity is estimated, so to quantify their potential climate change mitigation benefits in replacing current deep-sea shipping fuels used in Norway. Our study also quantifies the effects of technological changes in the background system according to selected SSPs and temperature targets, by integrating outputs from IAMs within a prospective LCA to investigate how climate change effects vary up to 2050. The robustness of the results is tested with a comprehensive uncertainty analysis (Monte-Carlo) that accounts for uncertainty and variability in key factors, such as biofuel conversion yields, transport distances of biomass and biofuels, emissions factors, fuel consumption, and emission metrics.

## 2. Materials and methods

### 2.1. Scope of the study

The scope of this study considered a "well-to-propeller" life cycle assessment that includes inventories for all inputs and emissions involved in raw material extraction, biomass production, transport of residues to the industrial plant, biomass conversion, biofuel distribution, and combustion – as depicted in Fig. 1. Emissions from storage and logistics operations located at seaport were not considered since they are expected to have negligible contributions to the results (Tanzer et al., 2019) and do not affect the results of this paper due to the similarity of operations between drop-in biofuels and their benchmarked fossil fuels.

Our climate analysis uses a multimetric approach (Cherubini et al., 2016) based on three complementary climate metrics to capture different dimensions of the climate system response (Levasseur et al., 2016). In the short-term with the 20-year global warming potential (GWP20), in the medium-term with the 100-year global warming potential (GWP100), and the long-term with the 100-year global temperature potential (GTP100). GWP is a normalized cumulative metric defined as the integrated radiative forcing of a gas between the time of emission and a chosen time horizon (20 years for GWP20 and 100 years for GWP100) relative to the integrated radiative forcing of $CO_2$ (Myhre et al., 2014). GTP, on the other hand, is an instantaneous normalized metric defined as the change in global mean surface temperature at a chosen point in time after a pulse emission, relative to the temperature change following a pulse emission of $CO_2$. In this sense, GTP100 is a better proxy for long-term impacts because it is an instantaneous indicator targeting the potential temperature change 100 years into the future (Shine et al., 2005). Because of the numerical similarity between metric values of GWP100 with GTP40, GWP100 can be interpreted as a metric informing about temperature change impacts about 40 years after an emission (Allen et al., 2016), here assumed to be representative of medium-term impacts.

### 2.2. Biomass resource availability and life-cycle inventory

This paper focuses on the use of forest residues, i.e., wood debris, branches, tops, and foliage from the most common commercial tree species in Norway, i.e., spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and deciduous species (mostly *Betula pubescens* and *Betula pendula*). In contrast with forestry practices in nearby Sweden and Finland, where a certain fraction of residues has been historically removed, forestry residues are usually left unused in Norway (Cavalett and Cherubini, 2018) and may represent an important feedstock for marine biofuel production. Additionally, biofuels produced from residues have the advantage to minimize pressure on natural resources, thus avoiding the direct and indirect effects from agricultural land expansion. In this context, we performed a spatially explicit analysis using statistics of species-specific average annual forest wood removals in the country based on national statistics for the period 2016–2020 (SSB, 2021b). A conservative rate of 34% extraction of forest residues (fraction of forest residues extracted to the total forest residues available at harvest) is considered according to previous studies on potentially sustainable removal rates of forest residues in Scandinavia de Jong et al. (2017) and Lundmark et al. (2014). This is applied to the weighted harvesting volumes of each tree species in each county, making a national annual residue potential of 1.25 $M_{tondb}\ yr^{-1}$. The description of forest residue potentials per county is available in Supplementary Table S1. Industrial wood residues available from the sawmill, pulp, and paper industry were estimated to be 0.60 $M_{tondb}\ yr^{-1}$(Cavalett and Cherubini, 2018).

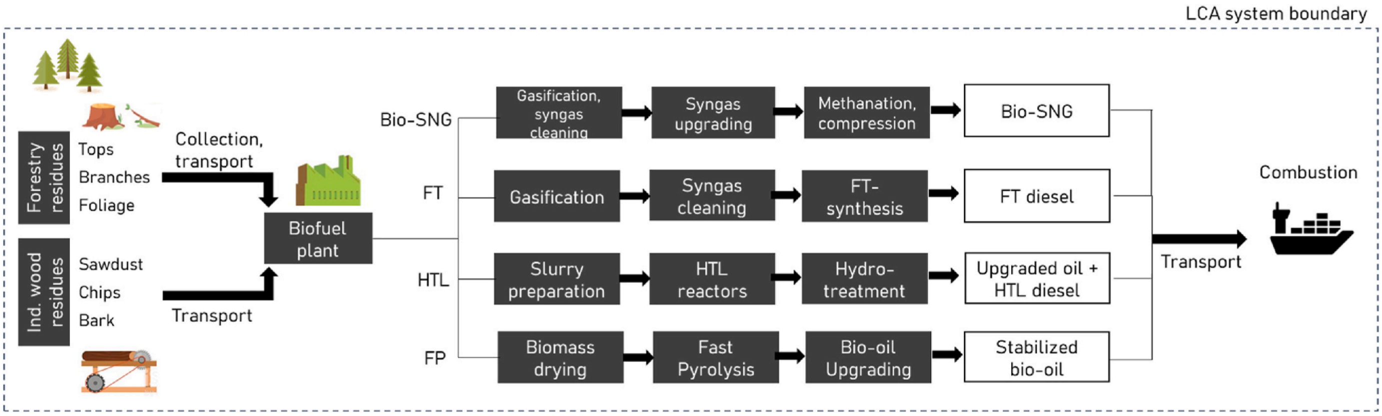

**Fig. 1.** Process-LCA system boundaries of marine biofuel production considered in this study.

Inputs and emissions related to the supply of forest residues and wood industry residues were modeled according to a previous study (Cavalett and Cherubini, 2018), whose data are updated with statistics for more recent years. Logistics considered transport of wood chips from the field to plants using trucks, with average country-specific travel distances to three idealized conversion plants located in the three main cities (Oslo, Stavanger, Trondheim) of 270 km. An average 20 km distance was assumed for delivery of the biofuels to the nearest port infrastructure, but a conservative range of up to 100 km truck transport was assumed in the uncertainty analysis. Inventories of material and energy requirements from biofuel supply chain processes and background economy database were obtained from ecoinvent 3.6 (Wernet et al., 2016), with the associated direct and indirect emissions to the environment.

### 2.3. *Norwegian demand for deep-sea shipping*

In Norway, the current demand for deep-sea marine fossil fuels is estimated according to the energy balance of production and consumption of maritime international bunkers (SSB, 2021a), i.e., those delivered to ships of all flags that are being used in international navigation. The average yearly energy consumption for the last five years (2016–2020) of MDO, HFO, and LNG were approximately 10.7, 1.2, and 2.1 PJ, respectively, totaling about 14 PJ per year (Table S3 of the Supplementary Material for details).

### 2.4. *Marine biofuel pathways and benchmarked fossil fuels*

In this paper, four drop-in marine biofuel pathways – bio-synthetic natural gas (Bio-SNG) production, fast pyrolysis (FP), hydrothermal liquefaction (HTL), and gasification with Fischer-Tropsch synthesis (FT) – were considered to substitute the three main fossil fuels currently used in deep-sea shipping: heavy fuel oil (HFO), marine diesel oil (MDO), and liquified natural gas (LNG)(IMO, 2020a). Being interchangeable with MGO, MDO and LNG is an advantage for the selected biofuels as nearly no adaptation in the existing ships engines technology (i.e., conventional diesel engines, modern gas engines, or dual-fuel engines) are needed and the already existing bunkering infrastructure can be used (Bach et al., 2021). For instance, liquid products from thermochemical processes can be fuels that are chemically different from conventional fuels but can be used directly or blended with fossil fuels in diesel engines, following specification requirements such as EN 16709 and EN15940 (DNV-GL, 2020a). Although biochemical conversion to ethanol is an alternative to produce biofuels from lignocellulosic feedstock, this biofuel is not compatible with most of the current marine diesel engines (Hsieh and Felby, 2017); therefore, this option is not considered in this study.

#### 2.4.1. *Gasification with Fischer-Tropsch synthesis (FT)*

Lignocellulosic biomass is dried, gasified, and then converted to fuels using an FT process. In gasification, there is high-temperature partial oxidation of solid material containing carbon with air, steam, or oxygen into a gas mixture called synthesis gas or syngas. Once the syngas is obtained, there is a cleaning step to remove contaminants such as sulfur, ammonia, chlorides, and other trace compounds. Fischer-Tropsch (FT) synthesis is carried out when cleaned syngas – mainly CO, $H_{2,}$ and other gases such as $CO_2$, $CH_{4,}$ and water vapor – reacts in the presence of metal catalysts to produce diesel, gasoline, and other compounds. The use of inputs, energy balance, process conditions, emissions, and fuel outputs was obtained from a previous study (Swanson et al., 2010) and is detailed in Tables S3 and S4 of the Supplementary Material. Considering that FT also generates gasoline and electricity in the high-temperature scenario, the allocation of impacts to co-products was made considering an energy allocation based on the lower heating value of products and co-products. In this study, emissions of FT diesel are compared with fossil marine diesel oil (MDO), whose upstream emissions were obtained from ecoinvent 3.6 assuming an average composition of 25% heavy oil and 75% marine gas oil based on their weighted average lower heating values (DNV-GL, 2018).

#### 2.4.2. *Bio-synthetic natural gas (Bio-SNG)*

Bio-SNG refers to the production of liquified bio-synthetic natural gas, where methane is produced from the gasification of forestry residues. After biomass drying and gasification, the obtained syngas is cleaned, upgraded (to decrease carbon dioxide concentration), and undergoes a methanation step. This consists of a reaction that transforms carbon monoxide and hydrogen present in the syngas into methane and water. After this process, Bio-SNG is dried, liquefied, and stored at the plant. Energy and material balances, inputs, and emissions are detailed in Tables S6 and S7 of the Supplementary Material based on data from the literature (Birgen and Garcia Jarque, 2013; Birgen and Jarque, 2015). Complimentary data are used for the estimation of chemical inputs consumed in the plant were taken from Larsson et al. (2018) and Thunman et al. (2019). Electricity is co-produced with Bio-SNG, and impacts are allocated on an energy basis. Methane losses in the gas upgrading step is an important parameter considered in the foreground life-cycle inventory, which was assumed to vary from 0.04% (Larsson et al., 2018) to 0.7% (Birgen and Garcia Jarque, 2013) in the uncertainty analysis.

The life-cycle emissions from Bio-SNG are compared against LNG. Despite being a fossil fuel, LNG is a fossil fuel that is gaining interest for the shipping sector as a measure to reduce sulfur pollution. It complies with the 0.50% sulfur limit on fuel used by ships stated from the MARPOL, and the 0.10% sulfur limit from Emission Control Areas (ECAs) (IMO, 2019). In this paper, life-cycle emissions of LNG are based on ecoinvent 3.6 data. Methane leakage rates up to 1% during natural gas extraction and distribution were considered (Rutherford et al., 2021).

#### 2.4.3. Hydrothermal liquefaction (HTL)

Life-cycle inventory data of the hydrothermal liquefaction (HTL) process are shown in Tables S8 and S9 of the Supplementary Material and are based on a previous study with material and energy balances (Jensen, 2018). In this biofuel pathway, a pumpable feed is prepared, which consists of size-reduced biomass from forestry residues, recycled oil, aqueous products, and homogeneous catalysts. The feed mixture is pressurized, heated, and sent to hydrothermal liquefaction reactors. Temperature and pressure conditions in the reactor reach supercritical conditions, thus decomposing and deoxygenating biomass feedstock into a high-energy-density biocrude oil. Biocrude is then upgraded through hydrotreatment, which applies pressurized hydrogen and catalysts to remove oxygen and aromatics. The outputs of HTL are drop-in renewable marine fuel (residue fraction) and diesel (distillate fraction) – which can be used to displace HFO and petroleum diesel, respectively. The environmental impacts between marine fuel oil and diesel were allocated based on the energy content of the two products. Fossil heavy fuel oil is the reference fuel for HTL, whose life-cycle emissions are based on ecoinvent 3.6 data.

#### 2.4.4. Fast pyrolysis (FP)

In the FP biofuel pathway, the industrial conversion processes are based on the literature (Tews and Elliott, 2014). Forestry residues are grounded, dried, and rapidly heated under atmospheric pressure in an oxygen-free environment. The products are pyrolysis vapors, char, ash, and non-condensable gases. Char is used in the plant to produce process heat and part of the non-condensable gases are recirculated to the reactor as a fluidizing medium. The unused part of non-condensable gases, as well as ash, are considered residues from the process. Pyrolysis vapors are cooled and condensed to produce fast pyrolysis bio-oil. Considering the high oxygen level content of FP bio-oil and its very low heating value, an additional stabilization step is considered, by assuming material flows (such as hydrogen) and energy consumption according to a previous study (Jones et al., 2009). The resulting output is a stabilized bio-oil with a lower heating value compatible to be used to displace fossil heavy fuel oil in deep-sea shipping. More data on material and energy balances are available in Tables S10 and S11 of the Supplementary Material.

### 2.5. Emissions from marine fuels combustion

Emission factors reported by the International Maritime Organization were considered for the combustion of HFO, MGO, and LNG (IMO, 2020a). These emission factors are available for ten species: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), carbon monoxide (CO), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), particulate material ($PM_{10}$ and $PM_{2.5}$), non-methane volatile compounds (NMVOCs), and black carbon (BC). For emissions of biofuels, data from IMO were adapted and complemented with studies detailing relative changes in emissions between fossil and renewable alternatives (Bengtsson et al., 2012) as well as combustion tests comparing emissions from fossil and biofuels use in diesel engines (Ogunkoya et al., 2015). Further assumptions regarding organic carbon (OC) emissions from particulate emissions were used according to data from literature (Bond et al., 2004). A detailed inventory of emission factors for each fuel alternative is included in Tables S12, S13, S14, and S15 of the Supplementary Material.

### 2.6. Prospective life-cycle assessment

A prospective LCA is performed to account for the influence of future technological changes in background systems. This is implemented by using the application *premise* (Sacchi et al., 2022) – version 0.4.2 –, which aligns life cycle inventories of key processes in ecoinvent 3.6 (Wernet et al., 2016) with the outputs of the REMIND Integrated Assessment Model, a global multi-regional model incorporating the economy, the climate system, and a detailed representation of the energy sector (Luderer et al., 2015). In this framework, new life cycle inventories are generated to represent technological systems according to future scenarios of evolutions in electricity production mixes, power plants efficiencies, average fleet, and energy mix used for transport, and improvements in efficiencies of advanced technologies to produce hydrogen, clinker, cement, metals, among others. New background inventories are built to represent the technological scenarios for 2030, 2040, and 2050 according to the 'SSP2 - Middle of the Road' under three climate policy scenarios (base, NDC, and PkBudg900). In SSP2, the world will follow intermediate challenges for climate change mitigation and adaptation, with moderate population growth, energy use declines, but slow progress in achieving sustainable development goals (Fricko et al., 2017). The climate policy scenarios are indicative of different international efforts in climate change mitigation. 'Base' represents a scenario without the implementation of any substantial climate policies, and the SSP2-Base scenario configuration is very likely to achieve by the end of the century a global average temperature rise of 2.1–3.5 °C (IPCC, 2021). 'NDC' represents the implementation of the emission reductions and other mitigation commitments stated by the different countries in the Nationally Determined Contributions under the Paris Agreement. 'PkBudg900' is a more stringent climate policy scenario that limits cumulative emissions to 900 $GtCO_2$ equivalents for the period 2011–2100, which is consistent with a global average temperature rise stabilization to 1.5 °C. Three new background databases are produced with the characteristics of these scenarios and applied to estimate how climate change effects of marine biofuels (foreground system) vary under different future socio-economic conditions. As the different SSP2 projections only include changes in the electricity production at an EU level, more specific predictions of changes in the future electricity mix in Norway are explicitly modeled and used in the prospective LCA instead of the EU-mix. The future changes in the electricity mix in Norway are shown in Supplementary Material, Table S2. In Norway, hydropower will remain the main generation source in the next three decades, but a gradual expansion of wind power – both onshore and offshore (DNV-GL, 2020b) – is expected. Overall, the climate impacts of the electricity mix in the country will decrease until 2050. Compared to the current situation, projected reductions of the climate impacts per kWh can reach up to 60% under the PkBudg900 scenario in 2050 (see Fig. S1 of the Supplementary Material).

### 2.7. Uncertainty analysis

A Monte-Carlo analysis is performed to test the robustness of our outcomes to a range of uncertainty factors. Uncertainty ranges are explicitly considered for biomass transport distances, biofuel conversion efficiencies, methane leakage rate (for both LNG and Bio-SNG), emission factors from fuel combustion, and emission metrics for NTCFs. Table S16 in the Supplementary material offers an overview of the different uncertainty factors and corresponding uncertainty ranges. For biomass transport distances, they are weighted by the size of each county and distances to conversion plants; for biofuel conversion efficiencies, they are from a literature review of Bio-SNG (Larsson et al., 2018; Birgen and Garcia Jarque, 2013), FT (Hannula and Kurkela, 2013), HTL (Jensen, 2018; Tews and Elliott, 2014), and FP (Jones et al., 2009; Tews and Elliott, 2014); for NTCFs, ranges are based on data from a previous study (Levasseur et al., 2016); for emission factors from combustion, they are a combination of uncertainties on engine fuel consumption and specific emissions of gases as reported by the IMO (IMO, 2020a). In the Monte-Carlo analysis, parameters were assumed to follow a triangular distribution, and results are produced for 10,000 individual simulations (then aggregated with statistical indicators).

## 3. Results and discussion

### 3.1. Climate impacts (GHG only)

Marine biofuels have a high climate change mitigation potential in comparison to fossil alternatives across complementary climate metrics representing short, medium, and long temporal perspectives (Fig. 2). Among the different alternatives, FT diesel has the lowest climate change impacts, followed by HTL, FP, and liquified Bio-SNG. For all biofuels except Bio-SNG, biomass production and transport and biofuel production are the main contributors for emissions, with more than 90% of impacts for all the metrics considered. FP and HTL have a higher share of emissions from biofuel production than FT diesel because they are more demanding on energy and chemical inputs for both thermochemical conversion and fuel upgrading. In the case of Bio-SNG, most of the climate impacts are associated with fuel use rather than biomass production and transport, mainly due to the possibility of methane leakages. This is the biofuel option with the largest uncertainty ranges, especially for GWP20 (Fig. 2b) where methane has a higher characterization factor. Bio-SNG impacts are smaller with GTP100 because methane is a short-lived gas, and its contribution to long-term climate change is reduced. Similarly, the same trend is found for LNG among the fossil fuel options.

In general, all drop-in liquid biofuels are associated with large potential mitigation of GHG emissions relative to fossil-based alternatives, especially in the long term. For FP, HTL, and FT, the median of climate impacts of marine biofuels varies between 13 and 18 $gCO_{2eq}$ $MJ^{-1}$ in the short-term (for FT and FP, respectively) and from 11 to 14 $gCO_{2eq}$ $MJ^{-1}$ in the long term. For the FT pathway, climate impacts of 11 $gCO_{2eq}$ $MJ^{-1}$ mean a decrease of up to 89% against HFO and MDO emissions (which are approximately 87 $gCO_{2eq}$ $MJ^{-1}$). For FP and HTL pathways, this reduction is 85% and 87% for long-term climate impacts, respectively. The median of Bio-SNG impacts for a long-term climate perspective is 16 $gCO_{2eq.}$ $MJ^{-1}$, approximately 78% less than LNG (73 $gCO_{2eq}$ $MJ^{-1}$). In the short- and medium-terms, the mitigation potential is somewhat smaller (74% and 72%, respectively).

### 3.2. Prospective life cycle assessment

Fig. 3 explores how results of the climate impacts of marine biofuels change with dynamic background inventories representative of future socio-economic transitions in line with SSP2 and three different climate change mitigation policies. Marine biofuels' life-cycle emissions largely benefit from the technological shifts projected for the upcoming decades. Relative to the current situation, the climate impacts from all marine biofuel pathways gradually decrease in the future, especially when moving towards more stringent climate policies (from the Base case to NDC and PkBudg900). This is due to the progressive decarbonization of electricity, energy, transport, and production systems, which is stronger in the scenario that aims to limit temperature rise to the lowest level (PkBudg900). The emission reduction increases when shifting from the present to the future (2030, 2040, and 2050), since the continuous technological improvements will contribute to declining background emissions of marine biofuels in time. The same results for other climate metrics are shown in Fig. S2 of the Supplementary Material. The highest relative decline in climate impacts is observed for GTP100. This occurs because the importance of short-lived gases like $CH_4$ is reduced with GTP100, whereas impacts from $CO_2$ emissions dominate, and are the latter that are mostly reduced by changes in the background activities of the future scenarios.

HTL is usually associated with the highest relative reduction in climate impacts, with a 51% decrease in GTP100 when the more stringent climate mitigation scenario (PkBudg900 - 2050) is compared with the current situation. HTL benefits from a combination of a future

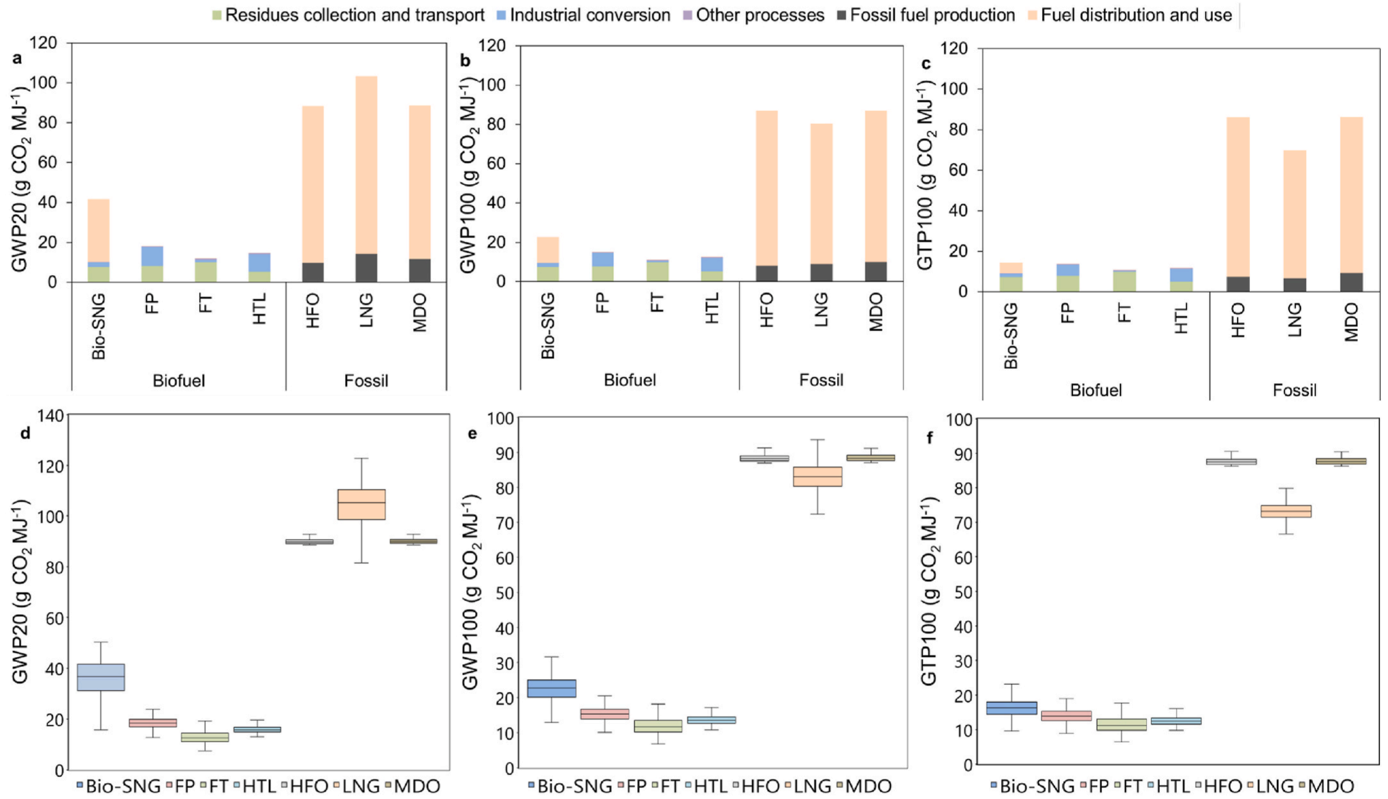

Fig. 2. Climate change impacts of marine biofuels and fossil fuels under multiple climate metrics considering life-cycle greenhouse gas emissions only. Results are for GWP20 (a, d), GWP100 (b, e), and GTP100 (c, f). Results with uncertainty ranges refer to the outputs of a Monte Carlo analysis, where the box, whiskers, and lines show the interquartile range (with the median), minimum and maximum values. Note variation in y-axis scales in the different panels.

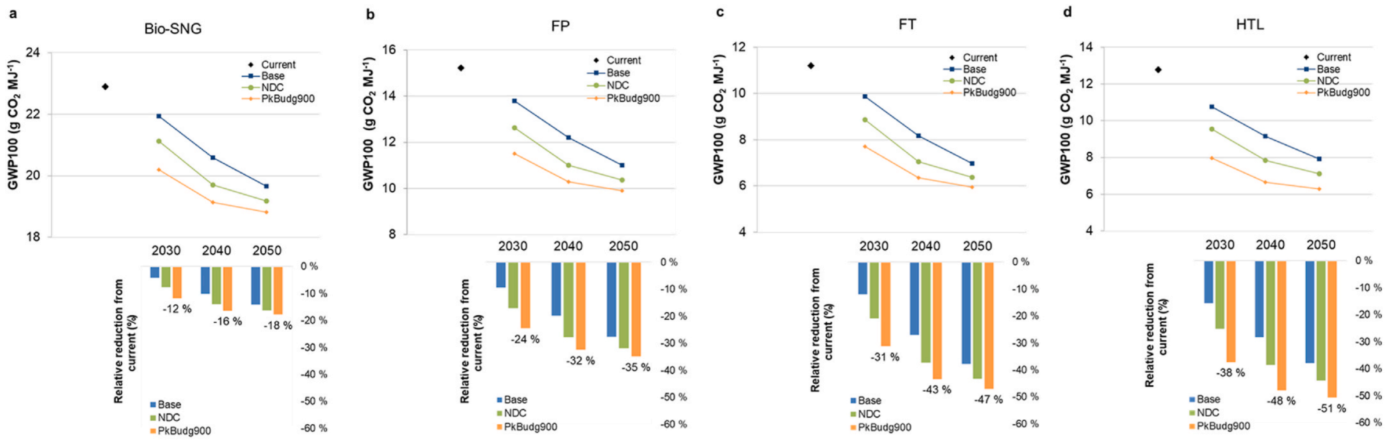

**Fig. 3.** Impact of projected background inventory databases on marine biofuel pathways for GWP 100. a) Liquified Bio-Synthetic Natural Gas (Bio-SNG), b) fast pyrolysis (FP), c) gasification and Fischer-Tropsch synthesis (FT), and d) hydrothermal liquefaction (HTL). Results consider the use of current background inventory and projections for 2030, 2040, and 2050 according to REMIND Integrated Assessment Model and SSP2 scenarios.

reduction in emissions during biomass logistics (e.g., lower shares of fossil fuels used to transport the feedstock) and biofuel conversion (e.g., chemicals used at feed preparation state). More details are found in the breakdown of impacts provided in Fig. 4d. On the other hand, Bio-SNG benefits the least from the evolution in future scenarios, especially in the short-term perspective (Fig. 4a). As most of the emissions are released during fuel combustion, relative reductions from background activities have limited influence on the results for the medium term (from 4% to 18%).

Looking at the results of the scenario connected to the implementation of the current NDC under the Paris Agreement, Bio-SNG, FP, FT, and HTL show an impact (GWP100) of approximately 19, 10, 6, and 8 $gCO_{2eq}$ $MJ^{-1}$, respectively, in 2050. For comparison, LNG and MDO climate impacts will be about 79 and 86 $gCO_{2eq}$ $MJ^{-1}$, considering a reduction in impacts from evolution in background activities of about 1 and 2% relative to their current values. This means that Bio-SNG can achieve a potential climate change mitigation of up to 76% relative to LNG, and the mitigation potentials from FP, FT, and HTL relative to MDO will be 88%, 92%, and 91%, respectively.

Among all marine biofuels, impacts related both to residues collection – such as forest residues chipping and forwarding operations – and transport to the biofuel plant gradually decrease in the future because they benefit from increases in fleet fuel efficiency and progressive declines in fossil fuel uses as they are replaced by other alternative transportation fuels like biodiesel, hydrogen, natural gas, and electricity. As a result, biomass production and transport emission can decrease from 10 g $CO_{2eq}$ $MJ^{-1}$ to 5 $gCO_{2eq}$ $MJ^{-1}$ (GTP100) in 2050 for the PkBudg900 scenario. Such 50% climate impact reduction in FT is an example of the potentially high influence that changes in background activities can have on LCA results.

For HTL and FP, there is a predominance of the industrial conversion on the overall well-to-propeller climate impacts (Fig. 4b and 4d). Most of the FP climate impacts are associated with hydrogen consumption during the hydrotreatment stage (ranging from nearly 40% to 60% of total emissions), a step that is necessary to upgrade and stabilize fast pyrolysis bio-oil for marine biofuel applications. The absolute contribution of the hydrotreatment stage for long-term climate impacts is reduced by 12%, from the current 5.5 to 4.3 $gCO_{2eq}$ $MJ^{-1}$ in the PkBudg900 2050 scenario. This is because of the increase in conversion yields from hydrocarbon cracking and the gradual expansion of electricity use from cleaner sources such as natural gas instead of hard coal for hydrogen production. Although HTL also benefits from such improvements on HTL biocrude hydrotreatment, reductions associated with improvements in the background activities related to the production of chemicals – mainly potassium carbonate and sodium hydroxide – used as inputs to the HTL feed preparation, significantly improve with the changes associated with cleaner sources of heat and electricity generation that are progressively used in the chemical industry. The long-term climate impacts of feed preparation are projected to drop from 4.1 to 1.1 $CO_{2eq}$ $MJ^{-1}$ in the PkBudg900 2050 scenario, corresponding to a relative reduction of 73%.

Although biofuel production also requires external energy input, mainly for HTL and FP pathways, the climate impacts from electricity use are relatively low since the current and future Norwegian electricity mixes are projected to remain largely based on hydropower, with a gradual increase of other renewable sources such as wind power in future inventories (DNV-GL, 2020b). Foreground inventories in this study rely on the Norwegian electricity mix which is projected to achieve 70% and 27% of hydro and wind power by 2050, respectively. As a result, medium-term climate impacts associated with the current Norwegian electricity mix decrease from approximately 21 $gCO_{2eq}$ $MJ^{-1}$ to 8 $gCO_{2eq}$ $MJ^{-1}$ according to assumptions made for the PkBudg900 2050 scenario (see complementary data in Fig. S1 of the Supplementary Material).

As indicated in Fig. 5a, Bio-SNG has the largest absolute climate impact differences among the selected metrics, with overall GTP100 climate impacts varying from 10.3 $gCO_{2eq}$ $MJ^{-1}$ for PkBudg900 2050 scenario to 41 $gCO_{2eq}$ $MJ^{-1}$ for GWP20 considering the current situation. This effect, however, is mostly attributed to the changes in the climate metrics and the temporal effects of methane slip (as previously discussed in section 3.1) instead of changes in background activities.

### 3.3. *Climate impacts of marine biofuels considering NTCFs*

Fig. 5 shows the contributions of NTCFs to the climate impacts of both marine biofuels and fossil fuels for the most ambitious climate mitigation scenario (PkBudg 2050). For the results obtained from using the current inventory, see Fig. S3 in the Supplementary Material. As the characterization of climate impacts from NTCFs is inherently more uncertain than that of GHGs, the uncertainty analysis shows larger uncertainty ranges, especially in the short-term (GWP20) where net climate impacts can be either positive or negative (Fig. 5b). Among fossil fuels, a net negative climate change impact is observed for HFO in the short term, in line with previous studies such as Eide et al. (2013) and IPCC (2021). This is largely due to the cooling effect from large sulfate emissions that scatter solar radiation leading to cooling contributions (intense but limited in time). The results for HFO are based on world-average emission factors of $SO_x$ relative to the period of 2012–2018 when most of the global fleet did not use scrubbers to abate emissions of pollutants and the sulfur content of the oil varied from 2.4%

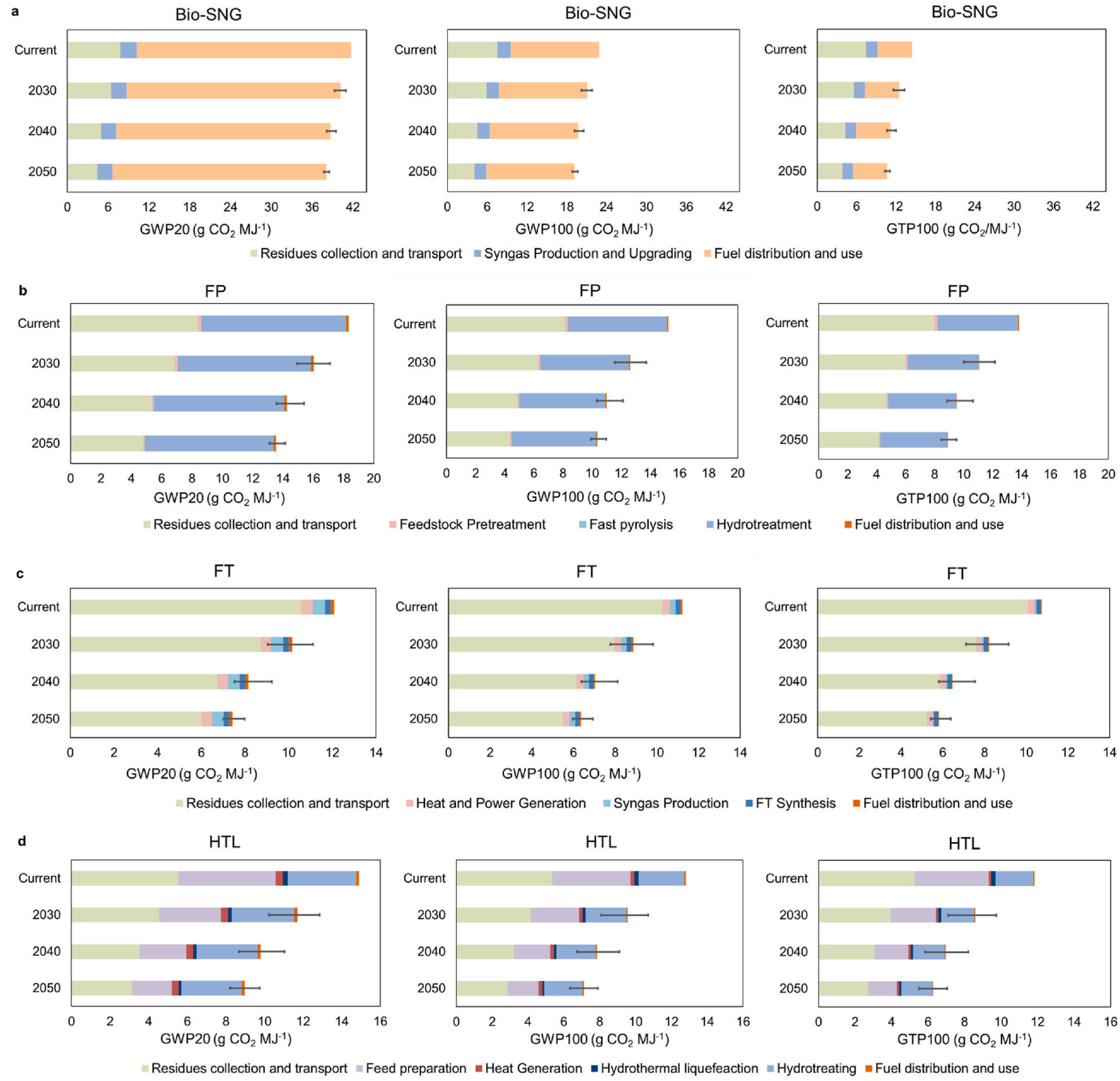

**Fig. 4.** Breakdown of climate impacts from marine biofuel pathways considering different climate metrics. a) liquified bio-synthetic natural gas (Bio-SNG), b) fast pyrolysis (FP), c) gasification and Fischer-Tropsch synthesis (FT) and d) hydrothermal liquefaction (HTL) marine biofuel pathways using current (3.6 ecoinvent) and future inventories from 2030 to 2050.

to 2.6% on a mass basis (IMO, 2020b). This is not consistent with recent IMO MARPOL regulations limiting sulfur content in fuel oil to 0.50% (IMO, 2019). Our results can thus significantly overestimate the cooling effects derived from HFO in future scenarios since sulfur emissions are very likely to decrease over the next years because of changes in legislation.

In general, climate change mitigation potential associated with marine biofuels can be larger in both the medium and long terms than in the shorter term, where the median of the climate impacts indicate net negative effects for all marine fuel options, except LNG. Biofuel emissions of $SO_x$ are very low, and most of them are associated with upstream fuel production activities instead of marine biofuel combustion. The major cooling contribution is from $NO_x$ emissions (mainly from biofuel combustion), which in the case of FP, FT and HTL can more than offset the warming associated with GHG emissions and other NTCFs for GWP20, resulting in net negative impacts. This does not occur for the Bio-SNG case, where the large impact from methane leakages results in net positive impacts. However, uncertainty ranges are quite large and for all the options the higher end of the impact interval approaches zero. When considering medium-term climate impacts, all biofuel pathways (except Bio-SNG) are projected to have their medians around climate-neutral values (see Fig. 5b), with the uncertainty ranges that go from cooling to warming contributions. This large uncertainty is mainly due to the influence of $NO_x$ emissions, whose emission factors are reported to be either comparable or slightly higher to those of fossil fuels (Ogunkoya et al., 2015). In all cases, biofuels perform better than fossil fuels. In the

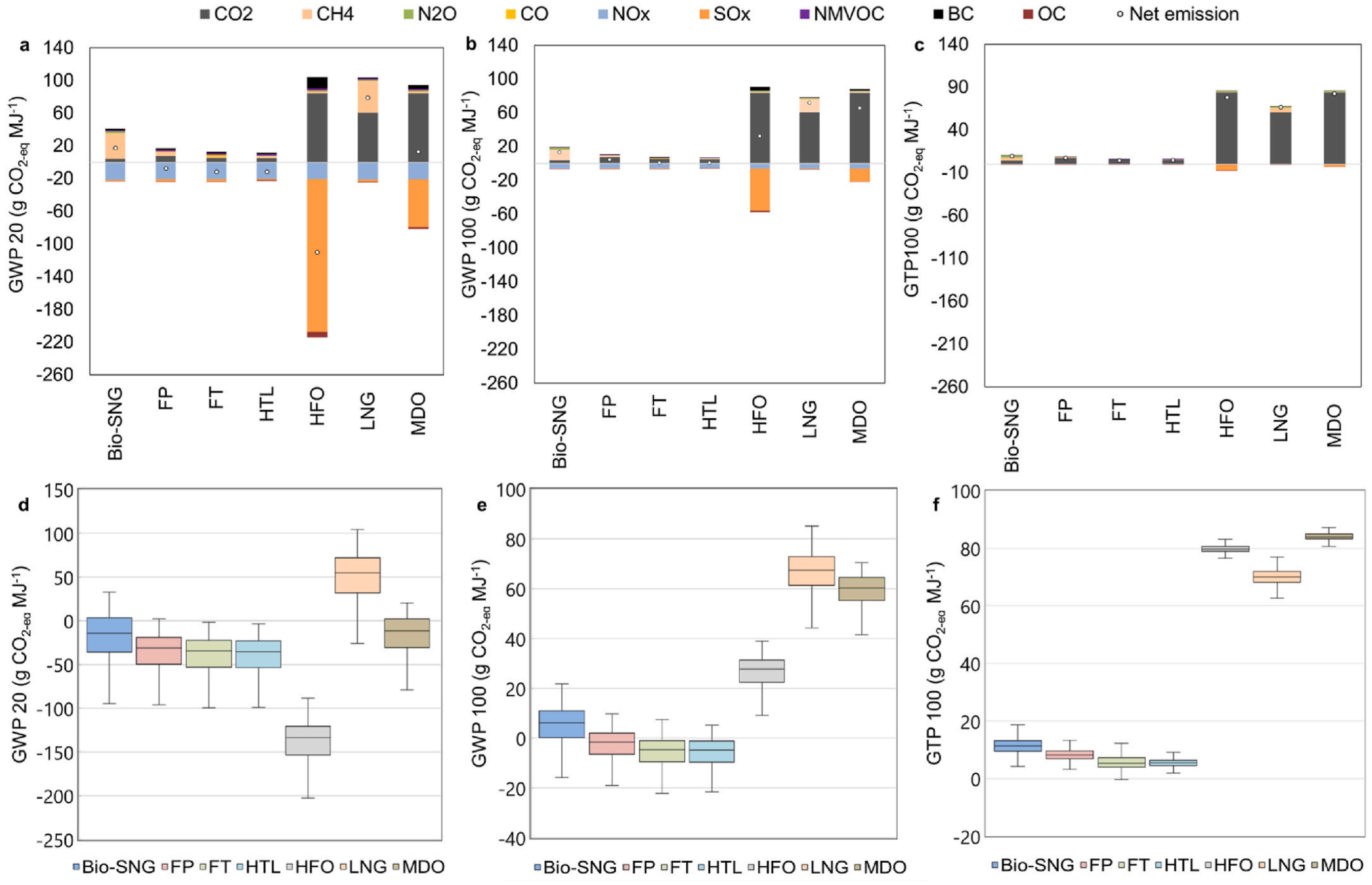

**Fig. 5.** Climate impacts of marine biofuels and fossil fuels under multiple global metrics considering near-term climate forcers in the PkBudg 2050 scenario. Bio-SNG is benchmarked against fossil LNG, FP against HFO, FT against MDO, and HTL against either HFO or MDO. a) Deterministic results for GWP20, GWP100 and GTP100 considering metrics for NTCFs. b) Uncertainty results from Monte Carlo analysis. The box, whiskers, and lines show the interquartile range, minimum and maximum, a median from all simulation data considering global metrics, with variation in y-axis scales in the different panels.

long term, the contribution from NTCFs is drastically reduced, and the climate impacts of the different fuel options are affected by GHG emissions only.

Despite the different sources of uncertainties and the possibility of including or not near-term climate forcers, the results from this paper converge in the medium- and long-term in indicating climate change benefits of biofuels relative to fossil fuels. Results in Figs. 2b and 5b, with and without NTCFs, respectively, are very similar: biofuels have the potential to provide at least 80% lower climate impacts than fossil alternatives regardless of the selected pathway or the methodological approach used. The lower climate change impacts for HFO achieved in the short-term when NTCFs are included in the analysis are to be interpreted with care. They are dependent on species for which the characterization of climate change effects is still affected by large uncertainties, and they are mostly connected to a short-term perspective. This means that the cooling contribution will last as long as emissions are sustained, but once they cease the cooling effect will vanish in a few years, and what will remain is the long-term climate change effect associated with $CO_2$ emissions from fossil fuel combustion. Moreover, the long-term perspective is key to achieving the temperature stabilization stated in the Paris Agreements. Although the choice of climate metrics should in principle align with their application purpose, GTP100 is the metric that is more consistent with the ambition of the Paris Agreement among those included in our analysis (Cowie et al., 2021; Tanaka et al., 2019). Applying a short-time perspective as a criterion for identifying suitable mitigation options is inconsistent with the long-term temperature goal of the Paris Agreement, which requires that a balance between emission and removals is reached in the second half of this century.

### 3.4. *Climate mitigation potential from marine biofuels in Norway*

Different mixes of biofuels can be considered to meet the demand for marine fuels in Norway, and we here consider two idealized strategies: Strategy #1 (Table 1), where FT diesel, FP-stabilized oil, and Bio-SNG are assumed to replace the current use of MDO, HFO, and LNG, respectively; strategy #2 (Table 2), where the fossil fuels are replaced by HTL diesel (distillate fraction),HTL marine fuel (residue fraction), and Bio-SNG. These strategies illustrate the different outcomes of biofuel pathway choice in since they differ in terms of energy conversion efficiency (from biomass to fuel) and specific mitigation potential (see main assumptions in Table S17(a) in the Supplementary Material). As Table 1

**Table 1**
Strategy #1 to supply marine biofuels considering the current energy demand from the Norwegian international marine fuels.

| Biofuel | Total energy (PJ) | Demanded forest residues ($Mt_{dry\ basis}$) | % Of total forest residues available in Norway |
|---|---|---|---|
| *Strategy 1* | | | |
| FT diesel | 10.7 | 1.9 | 101% |
| FP-stabilized oil | 1.2 | 0.1 | 6% |
| Bio-SNG | 2.1 | 0.2 | 10% |
| Total | 14 | 2.2 | 117% |

**Table 2**
Strategy #2 is to supply marine biofuels considering the current energy demand from the Norwegian international marine fuels.

| Biofuel | Total energy (PJ) | Demanded forest residues (Mtdry basis) | % Of total forest residues available in Norway |
|---|---|---|---|
| *Strategy 2* | | | |
| HTL diesel | 10.7 | 1.4 | 74% |
| HTL marine fuel (current demand) | 1.2 | – | – |
| HTL marine fuel (surplus) | 11.2[a] | – | – |
| Bio-SNG | 2.1 | 0.2 | 10% |
| Total | 14** | 1.6 | 84% |

[a] Surplus of marine fuel obtained in the HTL process when attending the diesel demand of 10.7 PJ. ** Without considering HTL marine fuel energy surplus.

shows, replacing marine diesel with FT would require more than the annual amount of forest residues estimated available in Norway. In this first strategy, the additional substitution of both heavy fuel oil and LNG by FP-stabilized oil and Bio-SNG, respectively, would require an additional 16% of the total available residues.

Considering that the HTL pathway is flexible to produce both heavier and lighter fuels, the available residues in Norway are enough to supply the demand for HFO and MDO. The production of 10.7 PJ of HTL diesel implies a co-production of 12.4 PJ of marine fuel (residual fraction). Considering that the HFO demand is approximately 1.2 PJ of marine fuel, then a surplus of 11.2 PJ is obtained. As shown in Table 2, approximately 74% of residues are used by HTL, and 10% by Bio-SNG to substitute LNG. This strategy leaves approximately 16% of residues left unused in the country.

Considering that HTL is associated with both the second-lowest climate impacts per unit of energy and the highest conversion yields for marine biofuels, the second strategy in Table 2 is selected to address climate mitigation when replacing fossil fuels in Norway. The climate mitigation potentials associated with fossil fuel substitution (Fig. 6a and b) are calculated based on the current situation. Fig. 6a presents the climate impacts without considering the influence of NTCFs and shows small variations in the mitigation potential across the different temporal perspectives. For GWP20, GWP100, and GTP100, the annual mitigation potential (green bars) is steady at approximately 1 million tons of $CO2_{eq}$, largely derived from the substitution of MDO by HTL-diesel (see the breakdown of contributions in Fig. S4 of the Supplementary Material).

The potential mitigation is different when including NTCFs. In Fig. 6b, there is a larger uncertainty associated with the mitigation effects from fossil fuel substitution by biofuels, which are dependent on the uncertainties on the characterization factors, especially for the short term, as previously discussed. In general, it is very likely that a mitigation effect would be obtained, with medians increasing from 0.2 to 0.8, and then to 1 million tons of $CO_{2\text{-eq}}$ for the short-, medium-, and long-term, respectively. The largest difference caused by NTCFs is observed in the short-term, when the net GWP20 climate impacts of fossil fuels can reach negative values because of SOx emissions; on the other hand, considering that climate impacts per unit of energy of HTL-diesel are much lower than those of MDO for GWP20, the biofuel introduction increases the mitigation effect in the short-term perspective as well (more details in Table S17 of the Supplementary Material).

Regardless of either the approach used to account for the climate impacts or the temporal perspective considered, marine biofuels mitigate the climate impacts of the Norwegian deep-sea shipping sector. Moreover, a wide group of solutions might contribute to achieve the climate mitigation goals established by the maritime sector in the country and internationally. Although BECCS (Bioenergy with carbon capture and energy storage) were not assessed in this study, they can be crucial over the next years since their negative emissions can contribute to reverting the current pattern of carbon dioxide accumulation in the atmosphere, especially when considering climate change mitigation pathways that limit global warming to 1.5 to 2 °C (Hanssen et al., 2020).

### 3.5. Techno-economic aspects

Although this study focused on the climate change mitigation potential of biofuels, the economic feasibility is an important aspect to be considered when discussing alternatives to substitute fossil fuels in the shipping sector. Considering that fuel costs play a major role in the operating costs for deep-sea shipping, variations in marine fuel prices may impact significantly the economic performance of ship operators (EC, 2021). A recent techno-economic analysis of biofuel options for marine applications (Tan et al., 2021) showed that different biofuel options are currently associated with minimum fuel selling prices (MFSPs) between US$ 2.36 to 4.58 per heavy fuel oil gallon equivalent (HFOGE), whereas the fossil fuel price may range between 1.50 and 2.50 US$ per HFOGE. The economic feasibility of biofuels, such as biomass-to-liquid alternatives – with an average MFSP of 3.62 US$ per HFOGE – will largely depend on the price of low-sulfur HFO and other

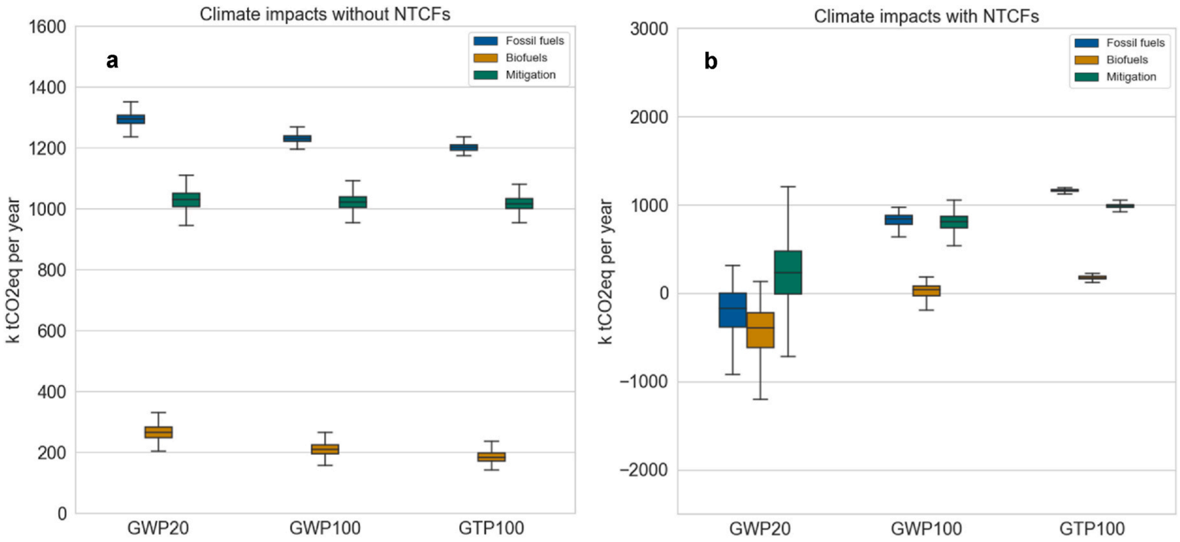

**Fig. 6.** Uncertainty analysis of climate impacts from fossil-based fuels, marine biofuels, and annual mitigation associated with biofuels in Norway across different temporal perspectives. Results are without (a) and with (b) the influence of near-term climate forcers (NTCFs) are based on the current inventory database.

compliance costs with emission regulations from the International Maritime Organization, such as the reductions in sulfur oxides. A current review on the perspective of biofuel use for mitigation in the marine sector (Mukherjee et al., 2020) also highlighted that fossil fuel prices are in a lower price range – from 4.5 to 17 €/GJ – when compared to biofuels' minimum fuel selling prices: 20–30 €/GJ for Bio-SNG, 20–35 €/GJ for upgraded pyrolysis bio-oils, 6–23 €/GJ for raw pyrolysis bio-oil. Another techno-economic assessment performed by Kargbo et al. (2021) highlighted that MFSPs of FT, HTL, and FP drop-in biofuels are in the range of 5–6 US$ per gallon, which is approximately 2 times higher than the average fossil fuel price (ca. 3 US$ per gallon).

Although there is still a gap in competitiveness between fossil and alternative fuels for marine applications, the existing literature highlights that a large part of the emission savings need to be achieved by the use of renewable and low-carbon fuels since the improvements in the energy efficiency of operations in vessels is limited (Bouman et al., 2017). In the European context, the FuelEU Maritime initiative suggests the need for policy intervention to scale up the production of sustainable alternative fuels and reduce the price gap between current fuels and biofuels. With the necessary technology development and increase in demand for renewable and low-carbon fuels in the European Union, the shares of biofuels and bio-SNG would reach up to 53% share in the fuel mix by 2050 (EC, 2021).

## 4. Conclusions

The projected climate mitigation effects of producing marine biofuels with forestry residues available in Norway highlight the opportunity for large-scale fossil fuel substitution by drop-in biofuels. Marine biofuels produced from forest and wood industry residues have lower climate impacts than the fossil alternatives. FT is related to the lowest climate impacts per unit of energy of biofuel output, but higher marine biofuel production volumes are achieved with HTL and FP pathways considering their higher conversion yields in the biofuel plant. When considering the effects of future background inventories and the possibility of benefiting from technology improvements in upstream activities, the climate mitigation effects become larger. The application of prospective life cycle assessment in the context of marine fuels brings a new perspective in quantifying the potential of climate change mitigation for the upcoming decades in the shipping sector. Moreover, the results from this study indicate that biofuel conversion pathways are expected to be impacted in different ways by future technology improvements. Although some biofuel alternatives are projected to derive higher benefits than others in terms of relative climate impacts from background activities for the upcoming decades, all pathways evaluated in this study are expected to achieve emission reductions in the future. In this context, the selection of REMIND scenarios can highly influence the results of climate change mitigation from marine biofuels and, for this reason, further studies using either different IAMs 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.

## CRediT authorship contribution statement

**Marcos Djun Barbosa Watanabe:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft. **Francesco Cherubini:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **Otavio Cavalett:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision.

## 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.jclepro.2022.132662.

## Abbreviations

| | |
|---|---|
| BC | Black carbon |
| BECCS | Bioenergy with carbon capture and storage |
| Bio-SNG | Bio-synthetic natural gas |
| ECAs | Emission-controlled areas |
| EU | European Union |
| FP | Fast Pyrolysis |
| FT | Fischer-Tropsch |
| GHG | Greenhouse gases |
| GJ | Giga joule |
| GTP | Global temperature change potential |
| GWP | Global warming potential |
| HFO | Heavy fuel oil |
| HFOGE | heavy fuel oil gallon equivalent |
| HTL | Hydrothermal Liquefaction |
| IAM | Integrated Assessment Model |
| IMO | International Maritime Organization |
| LCA | Life cycle assessment |
| LNG | Liquified natural gas |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MDO | Marine diesel oil |
| MFSP | Minimum fuel selling price |
| MGO | Marine gasoil |
| Mt | million metric tons |
| NDCs | National Determined Contributions |
| NMVOCs | Non-methane volatile organic compounds |
| NTCFs | Near-term climate forcers |
| OC | Organic carbon |
| PJ | petajoules |
| REMIND | Regional Model of Investment and Development |
| SSPs | Shared Socioeconomic Pathways |

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