



## Life cycle greenhouse gas emissions and cost of marine transport with conventional fuels and methanol

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### ARTICLE INFO

#### Keywords:

Methanol  
Life cycle emissions  
Life cycle cost  
Renewable electricity  
Embodied emissions

### ABSTRACT

In this study, the production and use of renewable-based methanol as a low carbon intensity fuel for a SUEZMAX tanker is evaluated for energy transport from Saudi Arabia to Asia (Japan) and Europe (the Netherlands), in comparison to the conventional fossil-based fuels. Renewable-based methanol production has been modeled in all three regions from hydrogen, produced with solar or wind energy, and carbon dioxide (CO<sub>2</sub>) captured from sources relevant to each region. The Well-to-Wake life cycle GHG emissions analysis and life cycle cost analysis was performed for the two types of trips of the SUEZMAX tanker operating on renewable-based methanol, natural gas-based methanol, liquefied natural gas (LNG), very low sulfur fuel oil and high sulfur fuel oil. A sensitivity analysis was performed by varying the cost and carbon intensity of hydrogen production based on annual variation in renewable energy in the three regions, as well as changing the source for CO<sub>2</sub> captured to produce renewable-based methanol in each region. Sensitivity analysis results for life cycle cost (399 to 921 million US dollars) and life cycle emissions (0.5 to 2.1 million metric tonnes) were used to evaluate the cost of carbon abatement, which was observed to be the lowest (3 to 12 US dollar per metric tonne of CO<sub>2</sub>) when the hydrogen cost was assumed to be \$1/kg. Of the three regions examined, Saudi Arabia was the location for renewable-based methanol production with lowest life cycle emissions (0.5 to 0.8 million metric tonnes) and cost (588 to 597 million US dollars), while Europe was shown to be the next most cost-effective region for renewable-based methanol production.

### Introduction

Global energy demand has long been dependent on fossil fuels, including the energy demand for the transportation sector [1]. According to the Intergovernmental Panel on Climate Change (IPCC), in 2022, the transportation sector alone contributed 15 % of the total Greenhouse Gas (GHG) emissions worldwide [2]. Almost 95 % of those

emissions (primarily carbon dioxide) came from combustion of fossil fuels, mainly gasoline and diesel, in internal combustion engines to provide motive power [3]. There are desires that fuels have low GHG emissions on a life cycle basis yet are economically sustainable as well [4]. The International Maritime Organization (IMO) of the United Nations (UN) has set ambitious targets to reduce GHG emissions by 2050, with indicative checkpoints of 20 % reduction (striving for 30 %) in GHG

**Abbreviations:** AIS, Automatic Identification System; CAPEX, Capital Expenditure; CCA, Cost of Carbon Abatement; CI, Carbon Intensity; DAC, Direct Air Capture; ECA, Emission Controlled Areas; EU, European Union; GHG, Greenhouse Gases; GREET, Greenhouse gases, Regulated Emissions, and Energy use in Technologies; HFO, High Sulfur Fuel Oil; IEA, International Energy Agency; IMO, International Maritime Organization; IPCC, Intergovernmental Panel on Climate Change; JP, Japan; KSA, Kingdom of Saudi Arabia; LCA, Life Cycle Analysis; LCC, Life Cycle Cost; LHV, Lower Heating Value; LNG, Liquefied Natural Gas; LSMGO, Low Sulfur Marine Gas Oil; MeOH, Methanol; MMT, Million Metric Tons; MW, Mega Watt; NL, Netherlands; OPEX, Operational expenses; PEM, Proton Exchange Membrane; PV, Photo Voltaic; SB, Solar Based; SFC, Specific Fuel Consumption; TJ, Terajoules; TMY, Typical Metrological year; UN, United Nations; USD, United States Dollar; VLSFO, Very Low Sulfur Fuel Oil; WB, Wind based; WTT, Well to Tank; WTW, Well to Wake.

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<https://doi.org/10.1016/j.ecmx.2025.101116>

Received 10 March 2025; Received in revised form 19 June 2025; Accepted 20 June 2025

Available online 21 June 2025

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emissions from international shipping by 2030, and 70 % by 2040 (striving for 80 %) [5,6]. To comply with these legislations, a transition from conventional fuel oils to low-GHG fuels may be needed [7].

Since international shipping vessels have very high energy demand (around hundreds of MWh) per trip, battery electrification is a big challenge across the sector [8]. Thus, renewable low-GHG fuels, such as methanol and other alternatives are being considered to replace the conventional fuel oils for international bunkering [9]. When produced from renewable sources, methanol combustion can have GHG emissions significantly lower than conventional fuel oil, although methanol has almost half the lower heating value (LHV) of conventional fuels [10]. The low lifecycle GHG emissions of renewable-based methanol is due to the lower carbon intensity of its key ingredients: hydrogen and captured CO<sub>2</sub> [11]. Thus, the emissions from the combustion are offset by the carbon capture involved in the fuel production process and even further when the hydrogen is produced via water electrolysis using renewable energy [12].

This study evaluates the lifecycle GHG emissions and cost associated with a SUEZMAX tanker for two different trips: Kingdom of Saudi Arabia (KSA) to Asia, specifically to Japan (JP), and to Europe (EU), specifically the Netherlands (NL). This builds off of previous work performed by the research group for conventional fuel oils and liquified natural gas (LNG) [13]. The intent of the current research was to compare the use of renewable-based methanol and natural gas based (gray) methanol as alternatives to conventional fuels, such as High Sulfur Fuel Oil (HFO) with use of a scrubber, Very Low Sulfur Fuel Oil (VLSFO), and LNG. The carbon intensity (CI) and cost of methanol production in KSA, JP, and Europe were evaluated. The Well-to-Wake (WTW) lifecycle GHG emissions and life cycle cost (LCC) was calculated for each trip, and for methanol production and bunkering at the port on either end of the journey, which varied from 0.5 to 2.1 million metric tonnes (MMT) and 399 to 921 million US dollars (MUSD), respectively. The fuel demand is assessed for the main engine, auxiliary engines, and boilers based on their power output, specific fuel consumption (SFC), and the operating profile of the trips, as obtained from Automatic Identification System (AIS) [14].

The CI and cost of renewable-based methanol were evaluated for each region based on the local CI and cost of hydrogen, and the captured CO<sub>2</sub> in each region. Solar-based (SB) and wind-based (WB) hydrogen was considered in all three regions, while the captured CO<sub>2</sub> source was considered based on the major sources of CO<sub>2</sub> emissions in each region [15,16]. Therefore, this study provides a comparison of GHG emissions and costs on a life cycle basis of SUEZMAX tanker for energy transport powered by conventional fuels and renewable-based methanol, by

considering the methanol production at three different global regions. This makes the study unique to investigate the production of methanol at different locations and then also evaluate GHG and cost for different trips of a marine vessel, operating on the produced methanol. Moreover, a sensitivity analysis was also performed for methanol production by varying: the plant size, the captured CO<sub>2</sub> sources and the variation in the hydrogen cost, and CI due to annual weather fluctuations and plant capacity factor.

## Methodology

This study was performed in the following steps: (1) Fuel consumption, (2) Hydrogen source, (3) CO<sub>2</sub> source, (4) Renewable-based methanol production, (5) Life cycle GHG analysis, (6) Life cycle cost analysis, (7) Sensitivity analysis and (8) Cost of Carbon Abatement. Each of these steps are explained separately within this section, highlighting the main assumptions and framework considered for this analysis. Further, an outline of the main research framework followed for this analysis is shown in Fig. 1.

### Fuel consumption

The fuel consumption calculation approach for the two trips from KSA to JP and NL was considered like the one followed previously for the LNG comparison with HFO and VLSFO as fuels for a SUEZMAX tanker from KSA [13]. The HFO (2.7 % sulfur) involved added use of scrubbers to meet international regulations for SO<sub>x</sub> emissions [17]. While for the VLSFO vessel, a 100 % switching to low sulfur marine gas oil (LSMGO) with a 0.1 % sulfur limit was considered while operating in emissions-controlled areas (ECA) [18]. Further, in the case of LNG, LSMGO was used for as a pilot fuel at higher loads but operates 100 % on LSMGO during maneuvering to avoid methane slip at low engine loads [19,20]. For methanol operation, no fuel switching or additional equipment was considered. Although methanol has a LHV almost half that of conventional fuels, this study did not consider a cargo penalty for methanol ship operation. In the previous study, additional fuel storage capacity for LNG was assumed to be on the ship deck, not affecting the ship's cargo capacity. For consistency in this work, it was assumed that the size of the fuel tanks for methanol had a negligible effect on the cargo capacity. To note, for a typical SUEZMAX tanker with a 4,000 m<sup>3</sup> fuel tank and 185,000 m<sup>3</sup> of cargo tanks, even doubling the fuel tank would only affect the cargo capacity by 2 % [21,22]. Furthermore, for the trips assessed in this work (KSA to Europe and KSA to Japan), the methanol consumption would be less than the fuel capacity of a SUEZMAX tanker. Therefore, to

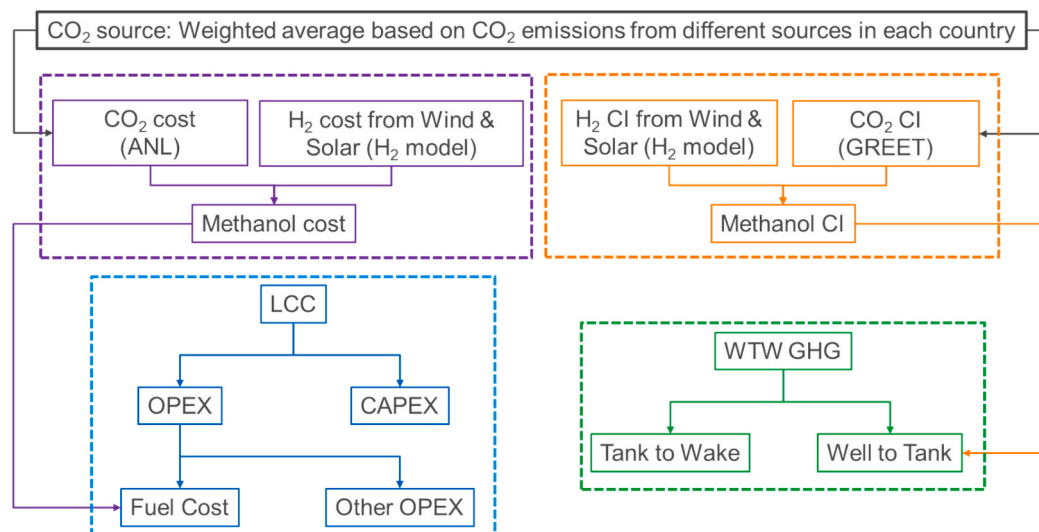


Fig. 1. Outline of the research methodology followed for the analysis.

be consistent with the LNG comparison, no change to the cargo capacity was considered.

The fuel consumption was calculated assuming these fuel changes only for the main engines, as LSMGO was always used for auxiliary engines and boilers [23]. The IMO 4th GHG study was used as the source for the installed power and SFC values for each energy convertor type [14]. While the AIS data was used to obtain the average speed and time spent in each operating mode (i.e. cruise, maneuvering, anchoring, etc.). Using this AIS information the load factor was estimated by the Admiralty formula, mentioned in the 4th IMO GHG study, and expressed as equations (1) and (2). Where  $P_{p,i}$  (in kW) represents the propulsion engine operating power for a given operating mode  $i$ ,  $P_{ref}$  represents the vessel's installed main engine maximum power rating (in kW),  $V_i$  represents the average speed (in knots) in the operating mode  $i$  and  $V_{ref}$  represent the vessel's maximum design speed (15.1 knots). While constants  $\eta_w$  and  $\eta_f$  represents the weather and hull fouling correction factors which are 0.867 and 0.917 for SUEZMAX tankers, respectively. Further, the draft of the vessel is assumed to be equal to the maximum draft thus the equation (2) doesn't consider that into account.

$$LoadFactor = \frac{P_{p,i}}{P_{ref}} \quad (1)$$

$$P_{p,i} = (P_{ref}) \left( \frac{V_i}{V_{ref}} \right)^3 / (\eta_w * \eta_f) \quad (2)$$

Based on the load factor obtained for each operating mode from equation (1) and (2), the SFCs are obtained using the load adjustment factor as mentioned in the 4th IMO GHG study, which is expressed in the equation (3).

$$SFC_{ME} = SFC_{base} * (0.455 * Loadfactor^2 - 0.710 * Loadfactor + 1.280) \quad (3)$$

Where the SFC base is also taken from the 4th IMO GHG study for each of the fuels (HFO, VLSFO, LNG, LSMGO as well as Methanol) and to be consistent in the approach. Although there is no data for methanol dual fuel operation, there is information for LNG dual fuel operation with pilot fuel consumption, in the 4th IMO GHG study. Thus, the fuel consumption of the LNG is converted into the corresponding methanol consumption using the ratio of their LHVs, while the same pilot fuel consumption is assumed.

### Renewable based hydrogen

The sources of renewable based hydrogen production considered in this study are from electricity generated from solar photo-voltaic (PV) systems and wind turbines, separately, involving detailed modeling of renewable energy sources, hydrogen production systems, and system sizing using multi-objective optimization. The modelling of the renewable energy systems as well as the techno-economic and environmental evaluations are explained in detail within this sub-section.

### Modelling renewable energy systems

**PV system model.** The hourly energy production from PV systems is estimated using Typical Metrological Year (TMY) data from PVGIS software including ambient temperature, wind speed, and solar radiation components [24]. The technical specification of PV modules from Canadian Solar were used in the model [25]. Solar radiation incident on PV modules is calculated using diffuse horizontal and direct normal irradiance, corrected for energy losses using a factor ( $L_s$ ) of 0.85 due to shading, wiring, and inverters, like the methodology presented by Al-Ghussain et al as well as accounting for annual degradation (0.7 % per year) [16,26,27]. The hourly energy production from the PV system ( $E_{PV}$ ) is estimated by equation (3).

$$E_{PV} = \eta_{PV} \times I_T \times A_m \times N_m \times L_s \times f_{d,PV} \quad (3)$$

Where  $\eta_{PV}$  is the efficiency of the PV module (accounts for the ambient temperature effect, see Al-Ghussain et al for more details) [16],  $I_T$  is the total irradiance incident on the PV module,  $A_m$  is the module area (see HiKu5 Mono PERC for more details) [25],  $N_m$  is the number of PV modules, and  $f_{d,PV}$  is the annual lifetime average degradation factor.

**Wind turbine system.** The hourly energy production from the wind turbines ( $E_{WT}$ ) is estimated using wind speed data extracted from PVGIS software and using the specifications of a Gamesa G114-2.0 wind turbine, represented by equation (4) [24,28]

$$E_{WT} = N_{WT} \times f_{d,WT} \times \begin{cases} 0 & : u_h < u_C \text{ or } u_h > u_F \\ a + b(u_h)^\omega & : u_C \leq u_h \leq u_R \\ P_{e,R} & : u_R < u_h \leq u_F \end{cases} \quad (4)$$

Where  $N_{WT}$  is the number of wind turbines,  $f_{d,WT}$  is the annual lifetime average degradation factor assuming annual degradation of 1.19 % [29],  $u_h$  is the wind speed at hub height estimated using the methodology in Al-Ghussain et al [16] assuming shear coefficient of 1/3 [30],  $u_C$  is the cut in speed of the wind turbine,  $u_R$  rated speed,  $u_F$  cut off speed,  $P_{e,R}$  rated capacity (for wind turbine specifications see [28]),  $\omega$  is the Weibull distribution coefficient estimated using the methodology by Kumar et al [31], and the constants  $a$  and  $b$  are estimated using the methodology by Al-Ghussain et al. [16].

**Hydrogen production system.** Hydrogen is produced using a Proton Exchange Membrane (PEM) electrolyzer, powered by standalone PV or wind systems. The electrolyzer operates within a defined load range (0–100 % of capacity) and adjusts to fluctuating electricity supply from PV and wind systems. The efficiency of the electrolyzer ( $\eta_{PEM}$ ) is modeled through electrical circuit-based equations that account for reversible voltage and resistance changes under varying temperatures and pressures based on the methodology reported by Atlam et al. [32]. The efficiency is then used to estimate the specific electricity consumption of the PEM electrolyzer ( $SE_{PEM} = \frac{LHV_{H_2}}{\eta_{PEM}}$ ) using lower heating value of the hydrogen ( $LHV_{H_2}$ ) which is assumed to be 33.3 kWh/kg $_{H_2}$ . It is assumed that the PEM electrolyzer operates at a temperature of 80 °C and a pressure of 30 bar, consistent with literature [33]. PEM system operation includes adjustments for degradation (5.03 % annually) and calculates hourly hydrogen production using parameters like input energy, specific electricity consumption, and the electrolyzer's optimal capacity ( $PEM_{CAP}$ ) [34]. The system excludes startup/shutdown phases for conservatism, focusing on steady-state operations for hydrogen output estimation. The amount of hydrogen produced at each hour ( $AM_{H_2}^t$ ) is estimated by equation (5) with  $E_{RES}^t$  being either  $E_{PV}^t$  or  $E_{WT}^t$ .

$$M_{H_2}^t = \begin{cases} \frac{E_{RES}^t}{SE_{PEM}}; & \text{if } E_{RES}^t < PEM_{CAP} \\ \frac{PEM_{CAP}}{SE_{PEM}}; & \text{else} \end{cases} \quad (5)$$

### Techno-economic and environmental evaluations

**Economic evaluation.** The levelized cost of hydrogen (LCOH) is used to assess the economic feasibility economic of the PV and wind-based hydrogen systems [35–37] as follows;

$$LCOH = \frac{C_{PEM} + C_{RES} + (O\&M_{PEM} + O\&M_{RES}) \times LT}{H_{2,PEM} \times LT}$$

with  $C_{PEM}$  and  $C_{RES}$  being the capital cost of the PEM electrolyzer and renewable energy system (with PV or wind), respectively.  $O\&M_{PEM}$  and  $O\&M_{RES}$  are the annual maintenance and operation costs of PEM and RES, respectively.  $H_{2,PEM}$  is the annual amount of hydrogen and  $LT$  is the lifespan of the hydrogen system which is assumed to be 30

years.  $C_{PEM}$  includes the balance of plant cost which is around 55 % of  $C_{PEM}$  and stack capital cost. It should be noted that the stack lifespan is assumed to be 10 years [38]. It should be noted that the hydrogen compression, storage, and transportation costs are not included in this work. Table 1 summarizes the economic parameters used in this work.

**Environmental impact assessment.** The carbon intensity (CI) renewable hydrogen is estimated using the embodied emissions of PV, wind and PEM electrolyzer extracted from Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (R&D GREET) model [29]. These embodied emissions include lifecycle emissions from material extraction, manufacturing, and transportation. The embodied emissions of PV and wind systems depend on the supply chain of these systems [27,29], Table 2 shows the supply chain of PV and wind systems used in this study. The embodied emissions of PV and wind systems transportation are estimated assuming shipping CI of 0.0113  $g_{CO_2,eq}$  per mile per kg of shipment [29] with the average shipping distances summarized in Table 3. Moreover, the mass of the shipment is estimated according to R&D GREET 2023 [29], where a single PV module is assumed to weigh 12.8  $kg/m^2$  whereas the 2 MW wind turbine weighs 1630 ton. On the other hand, it is assumed that the embodied emissions of the electrolyzer is the same for all the countries (14.55  $kg_{CO_2,eq}/kW$  associated with balance of plant ( $EE_{BoP}$ ) and 71.73  $kg_{CO_2,eq}/kW$  associated with stack manufacturing ( $EE_{stack}$ ) [29,46]. Finally, the CI of renewable hydrogen ( $CI_{H_2}$ ) is estimated using the embodied emissions presented in Table 3 as follows,

$$CI_{H_2} = \frac{EE_{RES} \times CAP_{RES} + (EE_{BoP} + EE_{stack} \times RP_{stack}) \times PEM_{CAP}}{H_{2,PEM} \times LT}$$

with  $EE_{RES}$  is the embodied emissions in the RES technology,  $CAP_{RES}$  is the capacity of the RES,  $RP_{stack}$  number of replacements of the PEM stacks during the lifespan of the system ( $LT$ ),  $PEM_{CAP}$  is the PEM electrolyzer capacity. The optimal capacity of the electrolyzer is determined using multi-objective optimization aiming to reduce both the cost and the CI of renewable hydrogen, for more details see [16]. This optimization explicitly accounts for the variation in electrolyzer efficiency due to cyclic and partial loading, which are inherent to the intermittent nature of RES.

The resulting values for CI and cost for SB and WB hydrogen as used in this study are shown in Table 4. Where the values in parenthesis represent the maximum and minimum values across the entire region/country. Geographic variation in solar and wind resources significantly influences the annual energy yields of these systems, directly impacting the CI and cost of hydrogen. Notably, wind resources typically exhibit greater variability than solar resources within a country or region, leading to more profound variations in hydrogen production metrics.

#### CO<sub>2</sub> source

The CO<sub>2</sub> source for carbon capture was calculated based on the share of emissions from the top contributing sources in each region. This was done using the 2023 data for GHG emissions from Climate Trace, in

**Table 1**  
Economic parameters used in modeling the LCOH.

Parameter	System	EU	KSA	Japan	USA
Capital Cost (USD/kW)	PV [39]	1039	653	1905	1119
	Wind [39]	1626	1418	1715	1285
	PEM Unit	583 [40,41]			
O&M Cost (USD/kW)	PV	13 [39]			
	Wind	28 [39]			
	PEM Unit	4 % of $C_{PEM}$ [42]			
Lifespan (years)	PV	30 [43]			
	Wind	30 [44]			
	PEM Unit	30 [42,45]			

**Table 2**

PV and wind systems supply chain [29]. APAC stands for Asia-Pacific countries.

PV System in	USA	China	APAC	EU
USA	30 %	5 %	65 %	0 %
EU	0 %	72 %	0 %	28 %
Other Countries	4 %	70 %	25 %	1 %
Wind System in	US	China	EU	Others
All Countries	17 %	53 %	25 %	5 %

**Table 3**

Embodied emissions of PV and wind as well as the average ocean shipping distance.

Country/Region	Embodied Emissions [29] ( $kg_{CO_2,eq}/kW$ )		Average Ocean Shipping Distance (miles) [47]			
	PV	Wind	China	USA	APAC	EU
USA	1324.9	834.0	11,197	0	11,906	5391
EU	1375.5	829.6	11,345	5391	9427	0
Japan	1375.6	810	1149	9350	2209	11,562
KSA	1379.3	831.6	7289	10,349	4725	6882

**Table 4**

CI and cost of hydrogen used in this study.

Regions	SB		WB	
	CI ( $kg_{CO_2,eq}/kg_{H_2}$ )	Cost (USD/ $kg_{H_2}$ )	CI ( $kg_{CO_2,eq}/kg_{H_2}$ )	Cost (USD/ $kg_{H_2}$ )
EU	3.0 (2.7–3.8)	5.8 (5.3–7.0)	2.4 (0.8–7.8)	8.0 (3.4–20.4)
Saudi Arabia	2.3 (2.1–3.7)	3.9 (3.7–5.5)	1.0 (0.5–6.1)	4.1 (2.2–19.9)
Japan	3.3 (2.9–4.7)	7.9 (7.9–10.8)	3.6 (0.4–37.8)	11.8 (2.0–49.4)

MMT, for the three regions as shown in Table 5 [15]. Where the share (in %) from the power, manufacturing and fossil fuel operations sectors were used to calculate the weighted average of the cost and CI associated with the captured CO<sub>2</sub> as the share varies in each region.

Further, within the power sector, there are different shares of emissions based on the type of fuel used. Therefore, to estimate the split within the power sector, the country specific data from the international energy agency (IEA) was taken for the year 2023 and the share of the emissions from coal and natural gas are shown in Table 6 [48]. Moreover, for the Manufacturing sector the most common industry that has the highest emission share in all the three regions are Cement or Steel and was considered for the analysis [15]. While natural gas processing was considered to represent the fossil fuel operations sector [49].

Based on the share, weighted average cost of captured CO<sub>2</sub> was calculated using the cost of CO<sub>2</sub> from different sources based on a past study published by the research group [50]. Similarly, the weighted average CI of methanol production was calculated by using the CI of the CO<sub>2</sub> captured from different sources considered in this study.

**Table 5**

GHG emissions and share (in %) from the different sectors in each region [15].

	EU		JP		KSA	
	GHG (MMT)	Share (%)	GHG (MMT)	Share (%)	GHG (MMT)	Share (%)
Power	1821	37 %	459	58 %	310	38 %
Manufacturing	1261	26 %	288	36 %	212	26 %
Fossil fuel operations	1817	37 %	48	6 %	290	36 %

**Table 6**  
GHG share (in %) within the power sector by fuel type in 2023 [48].

Fuel type	EU	JP	KSA
Natural Gas	63 %	32 %	100 %
Coal	37 %	68 %	0 %

#### Renewable based methanol production

The production of renewable based methanol in this study was considered by chemically combining renewable hydrogen, produced from solar or wind, with captured CO<sub>2</sub> from different emission sources in each region [10]. For the carbon intensity of renewable-based methanol production, the e-methanol pathway was used from the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model [50]. Where e-methanol pathway refers to production of methanol from hydrogen (produced from electrolysis) and captured carbon dioxide. The changes were made to the CI of hydrogen for SB and WB, and CO<sub>2</sub> capture pathways based on the share of GHG emissions contribution for each region, as considered in this study. Accordingly, the CI of SB and WB methanol was calculated and then used to evaluate the WTW life cycle GHG emissions for the methanol consumed by the tanker during the two trips.

For the cost of renewable-based methanol, different published literature was used to calculate the cost according to the hydrogen and CO<sub>2</sub> cost in each region [51,52]. This was done using the reported dependance by Schorn et al., where a table was shown for methanol production cost from a 300 megawatt (MW) plant, for varying hydrogen and CO<sub>2</sub> costs [53]. The renewable-based methanol cost was interpolated for each region in this study. However, it was observed that in the case of a plant size of 2300 MW, the cost of methanol can be much lower, as reported by Arnaiz del Pozo et al. [54]. This was directly compared for the results in Germany as it was a common country evaluated by both research groups in their research. Thus, the ratio between methanol production cost from a 2300 MW and a 300 MW plant was obtained for Germany and used across the other three regions for plant technology scale up. The cost of methanol production was calculated for a 300 MW plant by varying the cost of hydrogen and captured carbon corresponding to each region. Then by maintaining the same plant technology scale-up as obtained for the studies in Germany, the fuel cost was scaled up for a 2300 MW plant in each of the three regions. The comparison between the cost of renewable-based methanol in different regions from wind (WB) or solar (SB) energy is shown in Fig. 2.

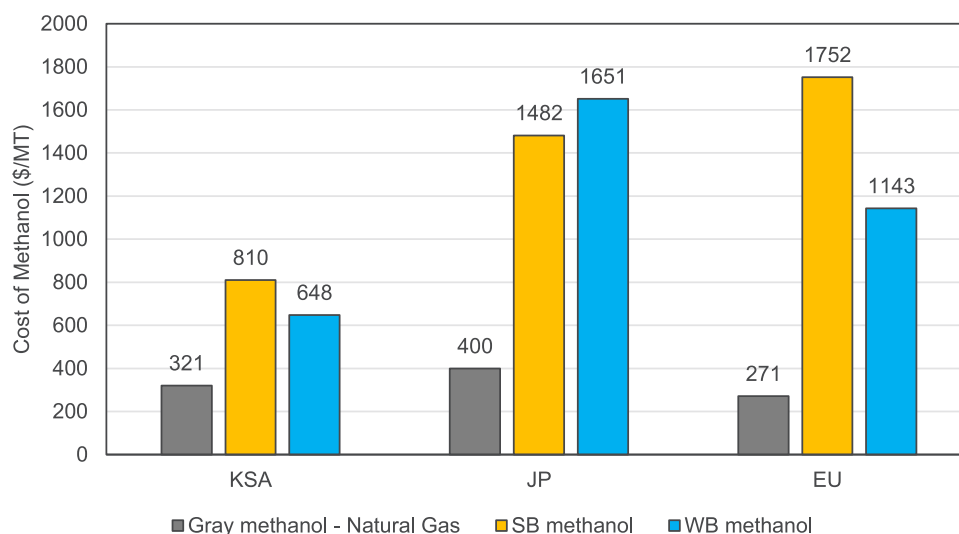
#### Life cycle GHG analysis

As in the case of fuel consumption, the methodology used for the life cycle GHG analysis is consistent with the previous work published by the research group [13]. Thus, all the assumptions in terms of vessel activity/utilization, were similar in this analysis for all the vessels. Only methanol as an alternative fuel was added into the scope, with a GHG assessment done for gray methanol, produced from natural gas, in each region, to estimate the current market scenario. And further expanded and compared with renewable-based methanol produced from different hydrogen and CO<sub>2</sub> sources. The WTW life cycle analysis includes feedstock, conversion and combustion related emissions associated with the fuel consumed during the lifetime of the vessel. Thus, in the case of methanol, only the feedstock and conversion related emissions varied based on the production pathway, while the combustion emissions remained the same in each case. Further, the results were evaluated in GHGs, i.e., by accounting for the combined CO<sub>2</sub> equivalent contribution of CO<sub>2</sub>, methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) using 100-year emission factors as per IPCC AR5 [14]. The results are presented later for the vessel operation during the two trips with methanol produced at the origin and the destination. And compared later with HFO, VLSFO and LNG vessels.

#### Life cycle cost analysis

The life cycle cost analysis too was based on the same framework and assumptions as in previous works by the research group, considering the capital expenditures (CAPEX) and operating expenses (OPEX) [13]. The majority of the cost component values were taken from the NavigaTE model developed by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [55]. The vessel cost was adjusted based on a COVID correction factor which was observed when comparing with current shipbuilding prices for SUEZMAX tankers, consistent with previous research [13]. However, for the fuel, the Ship & Bunker platform was used to obtain the fuel prices as an annual average for the year 2023 in KSA for all conventional fuels [56]. For renewable based methanol, it was calculated based on the assumptions from the literature and by varying the cost of hydrogen and captured carbon dioxide in each region, as explained in the sub-section “Renewable based methanol production”.

It is to be noted that in previous research for LNG, the vessel was bunkered only at KSA. However, in this study bunkering cost was calculated for both the origin and destination as in case of the CI calculation for fuel production. It is also important to highlight that port



**Fig. 2.** Cost of methanol considered in the different regions.

side infrastructure was not accounted in the scope of this analysis. Thus, what is accounted for is the fuel cost only, which is taken from the real cost of bunkering at the port in each region from the website: Ship & Bunker. However, the levelized cost of methanol is calculated in each region by also considering the CAPEX and OPEX associated with the methanol and hydrogen production plant. For the final LCC results, the interest to the CAPEX was calculated using a 10 % interest rate and was then added to the sum of CAPEX and OPEX of the different vessels [55]. The results are shown later for the different methanol bunkering locations and compared with the LCC results of the HFO, VLSFO and LNG vessels.

### Sensitivity analysis

Based on the different parameters involved in this study it was important to perform a sensitivity analysis to see the effect on the results due to change in one of the input parameters. Since this study is focused on renewable-based methanol, the main parameters that affect the cost and the emissions are sources of hydrogen and CO<sub>2</sub>. Therefore, the sensitivity analysis was performed by considering three cases: base, best and worst, with variations in the CO<sub>2</sub> and hydrogen sources. In the best case, the manufacturing sector emissions were assumed to all come from the Ammonia plant instead of Cement/Steel, due to it having the lowest cost of captured CO<sub>2</sub> [50]. While for hydrogen a cost of \$1/kg is considered for both the cases of solar and wind as it is the future projected target to make hydrogen cost competitive [12].

However, in the worst case, the CO<sub>2</sub> source was assumed to be Direct Air Capture (DAC) that has high cost as well as CI due to the added energy requirement for the low concentration CO<sub>2</sub> source. For hydrogen, the maximum value for cost and CI were used from the hydrogen model discussed earlier. Further, as the hydrogen plant size was also observed to be a critical parameter for cost, the best and the base case considered a plant size of 2300 MW, and the worst case considered a size of 300 MW. Based on these parameter variations, the resulting Well-to-Tank (WTT) emissions factors are presented in Table 7 and the cost numbers considered are shown in Table 8, for this study. It is also to be noted that the scope of this study is to evaluate the lifecycle GHG emissions and cost for methanol vessels, where methanol is produced from different technologies in three regions. The supply and demand of the methanol fuel application is not studied, as it was out of scope for this analysis.

### Cost of carbon abatement

As considered in the previous study on LNG by the research group, the cost of carbon abatement was calculated for methanol to estimate its GHG reduction potential, which was done by dividing the increase in the

**Table 7**

Well to Tank CI (in gCO<sub>2</sub>e/MJ) of methanol produced from different carbon capture sources by life cycle stage in the three regions for the base, best and worst scenario.

Source	Case	Feedstock			Conversion		
		KSA	Japan	EU	KSA	Japan	EU
Solar	Base (Manufacturing: Cement/Steel)	-52	-39	-45	16	16	16
	Best (Manufacturing: Ammonia)	-58	-48	-51	16	16	16
	Worst (DAC only)	-19	-9	-12	16	16	16
	Base	-66	-36	-56	15	16	16
Wind	Base (Manufacturing: Cement/Steel)	-66	-36	-56	15	16	16
	Best (Manufacturing: Ammonia)	-72	-45	-57	15	16	16
	Worst (DAC only)	-19	-9	-12	16	16	16
	Base	-66	-36	-56	15	16	16

**Table 8**

Cost numbers and methanol plant size considered for the sensitivity analysis of LCC.

Source	Parameter	Region	Best case	Base case	Worst case	
Solar	CO <sub>2</sub> price (USD/MT)	Europe	46	68	200	
		Japan	59	90	200	
		Saudi Arabia	45	68	200	
	Hydrogen price (USD/kg)	Europe	1	6	7	
		Japan	1	8	11	
		Saudi Arabia	1	4	6	
		All	2300	2300	300	
	Wind	CO <sub>2</sub> price (USD/MT)	Europe	46	68	200
			Japan	59	90	200
			Saudi Arabia	45	68	200
Hydrogen price (USD/kg)		Europe	1	8	20	
		Japan	1	12	49	
		Saudi Arabia	1	4	20	
		All	2300	2300	300	

LCC results by the reduction in GHG emissions. This was considered for only the fuels that provide some carbon abatement or reduction on a WTW basis, compared to the reference HFO vessel. Thus, the cost of carbon abatement can be defined as the additional cost needed to reduce one metric ton of GHG emission. The variation in cost and CI of methanol in each region makes it interesting to estimate the effect on the final cost of carbon abatement. This metric is also very important to understand the applicability of methanol for marine applications compared with HFO vessels in terms of CI and cost together. The results are shown later based on the sensitivity analysis results for LNG, VLSFO and renewable-based methanol for different cases of the sensitivity analysis as well. The comparison is made for both SB and WB methanol.

## Results and discussion

### Direct fuel consumption in trips

The fuel consumption results are shown in Fig. 3(a) for the trips to Japan and the Netherlands from Saudi Arabia. Where the consumption of both primary and secondary fuels is shown, i.e., fuel consumption for main propulsion and for auxiliary systems, respectively. Therefore, LSMGO is consumed in each condition as the auxiliary engine and boilers are powered by it across all types. The different vessels for which fuel consumption is calculated are HFO, VLSFO, LNG and methanol (MeOH) vessels. Further, the fuel consumption is calculated and shown in metric ton of fuel consumed for each trip by considering the operating profile of the vessel, obtained from AIS, which is consistent with the methodology followed for previous research by the research group.

The fuel consumption results show that methanol vessels have the highest consumption in metric ton per trip. This is primarily due to the low LHV of methanol when compared to conventional marine fuels. Thus, despite assuming similar efficiency for the engine, the fuel quantity needed is higher for methanol to provide the same energy. Thus, it is important to note that although the quantity of fuel consumed is higher, the energy consumed by the vessel is in the same range. To understand this, the fuel consumption was converted into fuel energy using the LHV of the fuels and obtained in tera joules (TJ) for each trip and shown in Fig. 3 (b).

It was observed that the fuel energy consumed from primary and secondary fuels are similar in range for the vessel types indicating a similar range of efficiency for the energy converters across the vessel types. In case of the trip to Japan, the LSMGO consumption for the HFO

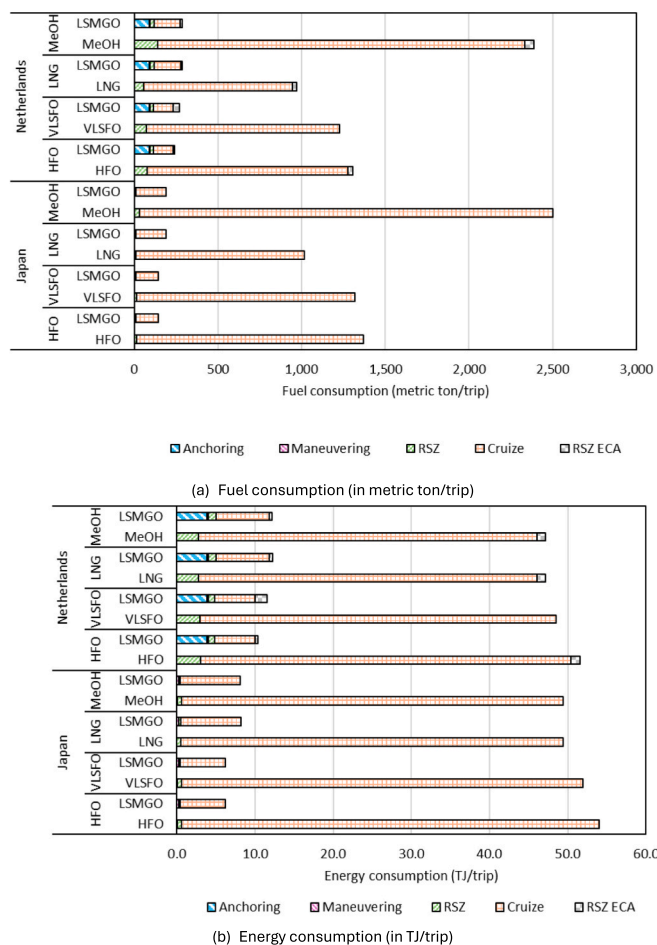


Fig. 3. Fuel and energy consumption per trip.

vessel is similar to the VLSFO vessel, while for the methanol vessel it is similar to the LNG vessel as both involves added pilot fuel injection. However, for the trip to Netherlands, although the LNG and methanol vessels have similar LSMGO consumption, the VLSFO vessel had higher consumption than HFO. This was because of the switching to 100 % LSMGO for VLSFO vessels during ECAs.

#### Life cycle GHG analysis

The life cycle GHG analysis is carried out separately for the two hydrogen pathways, i.e., solar and wind. The results for the base case, from SB and WB methanol are shown in Fig. 4 for the two trips, together with results for HFO, VLSFO and LNG vessels. Since methanol could potentially be produced and bunkered at the destination regions (Japan or Europe) as well as Saudi Arabia, that aspect was included in the analysis, while production and bunkering of conventional fuels was limited to Saudi Arabia. The total GHG emissions, after accounting for the GHG emissions credit from the feedstock stage, are calculated for the vessel's operation during its lifetime in MMT and shown as a thin gray bar and numeric value in the middle of each stacked bar.

It can be observed that the gray methanol emits the highest GHG on a lifecycle basis among all regions. However, renewable-based methanol has the lowest GHG emissions mainly due to the feedstock GHG emissions credit from carbon capture. This helps in offsetting combustion related emissions from methanol use and ultimately results in significantly reduced life cycle GHG emissions. Further, when comparing the solar and wind-based results, it can be observed that the wind-based methanol has lower GHG emissions in EU and KSA. That can overall be related to the lower embodied emissions associated with the wind

based renewable systems. But in case of Japan the wind-based results were higher than solar due to the lower electricity yield or efficiency of the wind based renewable system in countries like Japan. Thus, it is important to understand which source of renewable energy can be used in different regions across the globe for efficient energy generation to meet the demands. In this study, it was also found that in terms of lifetime WTW GHG emissions, both gray and renewable-based methanol produced in KSA had the lowest value as compared to production in destination regions. This was due to low carbon intensity of natural gas in the region for gray methanol and high renewable electricity yield in the kingdom for the renewable-based methanol.

#### Life cycle cost analysis

The LCC results are shown for SB and WB methanol in Fig. 5. Renewable-based methanol is bunkered at the origin and destination region, separately. For fossil fuels, the production and bunkering location is taken to be in KSA only. The life cycle cost is calculated by combining all the CAPEX (in blue shades) and OPEX (in brown shades) for the vessel across its lifetime and then adding an interest rate of 10 %. Based on the different variations in the cost of the fuel, the fuel cost varies significantly for each vessel type and is thus the main driver for the change in LCC across the vessel types. Also, scrubbers are only applicable to HFO vessels that need additional  $\text{SO}_x$  removal.

It can be observed that the cost for wind-based methanol is higher than solar based methanol production in the EU and Japan. But that's not true for KSA as the results do not change significantly for SB to WB methanol. This is due to the high yield for both renewable sources in KSA annually. In Japan and EU, the wind-based methanol has much higher cost than solar based methanol, due to low annual energy yield from wind based renewable systems. Thus, KSA could be a good candidate for methanol production for international shipping from both solar and wind based renewable sources due to lower LCC but also low GHG emissions for both cases of renewable sources.

#### Sensitivity analysis

A sensitivity analysis was performed for the WTW life cycle GHG emissions and life cycle cost results by varying the hydrogen source and  $\text{CO}_2$  source with respect to each region. For the cost results, the plant size (in MW) was also varied. The main results for the sensitivity analysis are shown in Fig. 6 for both solar (on the left) and wind (on the right) based methanol for (a) Lifetime WTW GHG emissions and (b) life cycle cost. The results are shown only for the renewable-based methanol powered vessel for both the trips in the base, best and worst cases. Further, a dotted gray line in Fig. 6 (a) represents approximately 50 % GHG reduction compared to the reference HFO vessel, while in Fig. 6 (b) represents the LCC of the HFO. Similarly, the red dotted line represents approximately a 75 % reduction in GHG compared to the HFO vessel in Fig. 6(a), while a life cycle cost twice as the HFO vessel in Fig. 6(b). Thus, with the sensitivity analysis it was evaluated if the bars reach closer to the red dotted line for the renewable-based methanol cases in Fig. 6(a). In Fig. 6(b), the intent was to avoid the red dotted line and be closer to the gray dotted line to ensure cost parity.

The results of the WTW life cycle GHG emissions from the sensitivity analysis show that in the worst case, the maximum possible reduction of lifecycle GHG emissions was less than 50 % (gray dotted line) in all cases for solar as well as wind-based methanol. However, the 75 % reduction (red dotted line) was observed only for wind-based methanol produced in KSA, for both the trips, but only in the best-case scenario. Thus, in KSA, with wind-based hydrogen methanol can provide more than 75 % reduction in GHG emissions relative to HFO, which can help in meeting the IMO future GHG reduction targets. Overall, it was observed that methanol from solar had lower GHG reduction potential than wind, except in Japan, due to poor wind energy availability in that region. It is important to note that this study considers the embodied emissions

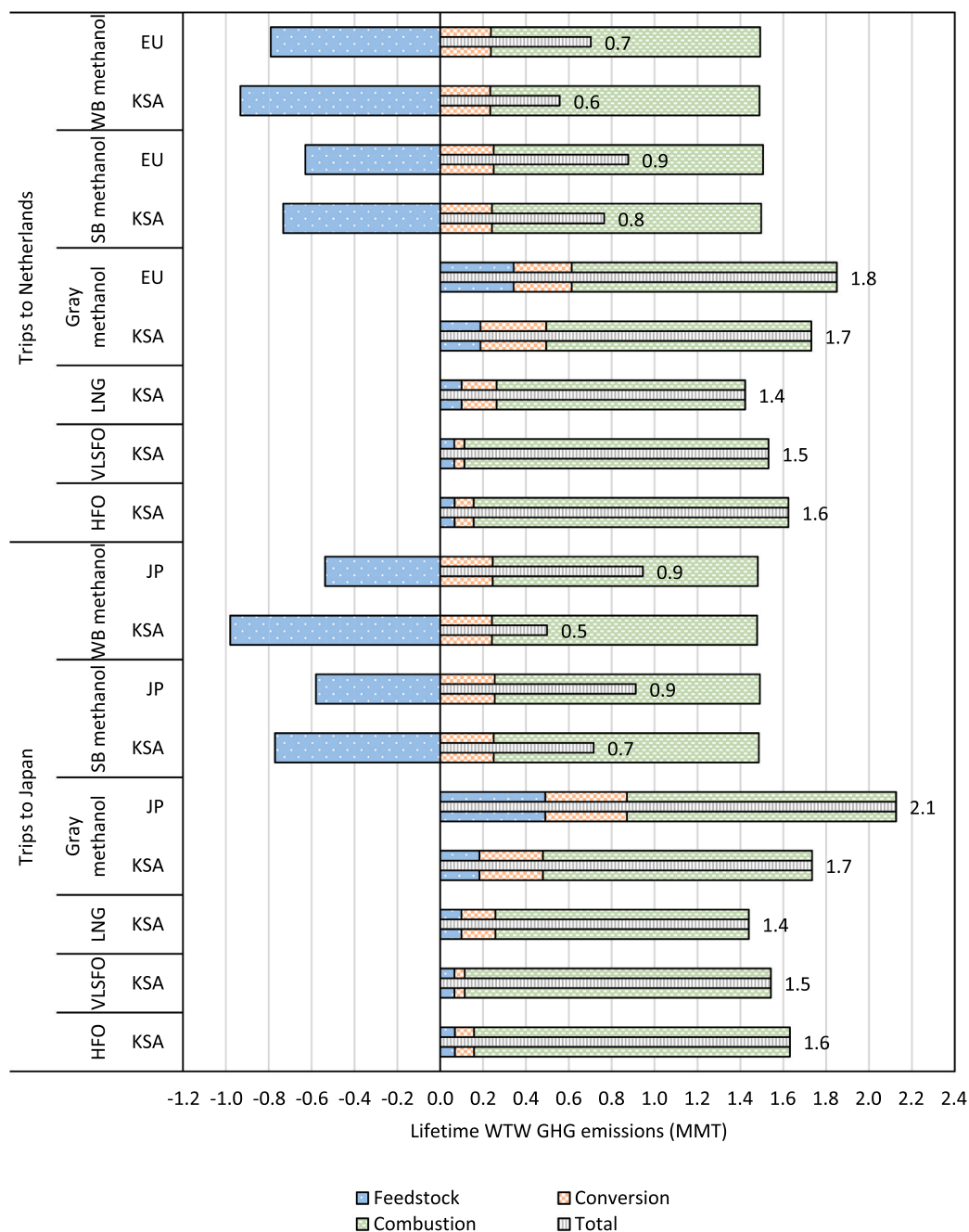


Fig. 4. Lifecycle GHG analysis results by life cycle stage for the two trips with SB and WB methanol produced at both the trip origin and destination locations and conventional fuels.

associated with renewable-based methanol.

However, the IMO LCA methodology for renewable fuels (such as methanol) has not been fully established, and it is not clear if embodied emissions associated with the production of renewable methanol will be included. This work demonstrates that embodied emissions can have a significant impact on the WTW GHG emissions of international shipping. In the case that the embodied emissions are not accounted for, the WTW GHG emissions results would drop to a near-zero value since only the emissions associated with the pilot fuel combustion would remain. In such a case, renewable methanol will be very helpful in reaching the IMO GHG emissions reduction targets. However, the real-world total GHG emissions associated with international shipping would be underestimated and the effect of the location of fuel production would be ignored. Thus, this paper demonstrates the importance for the IMO to

consider the embodied emissions aspect of their future LCA guidelines by accounting of life cycle GHG emissions and reaching their GHG emissions reduction targets.

Further, the life cycle cost sensitivity analysis results show that methanol from wind had higher costs than methanol from solar, except for the best case. This can be mainly related to the cost of hydrogen considered in these cases. While the best cases for both solar and wind consider the lowest cost for hydrogen of \$1/kg, the hydrogen cost for the base and worst cases are higher for the wind-based hydrogen than solar based. It can be concluded that only in the best case, with hydrogen cost of \$1/kg, renewable-based methanol can reach cost parity with the conventional HFO vessel. However, in the worst case, the cost can be as high as twice the HFO-powered vessel. Moreover, JP can be identified as an unsuitable region for methanol production having the highest cost

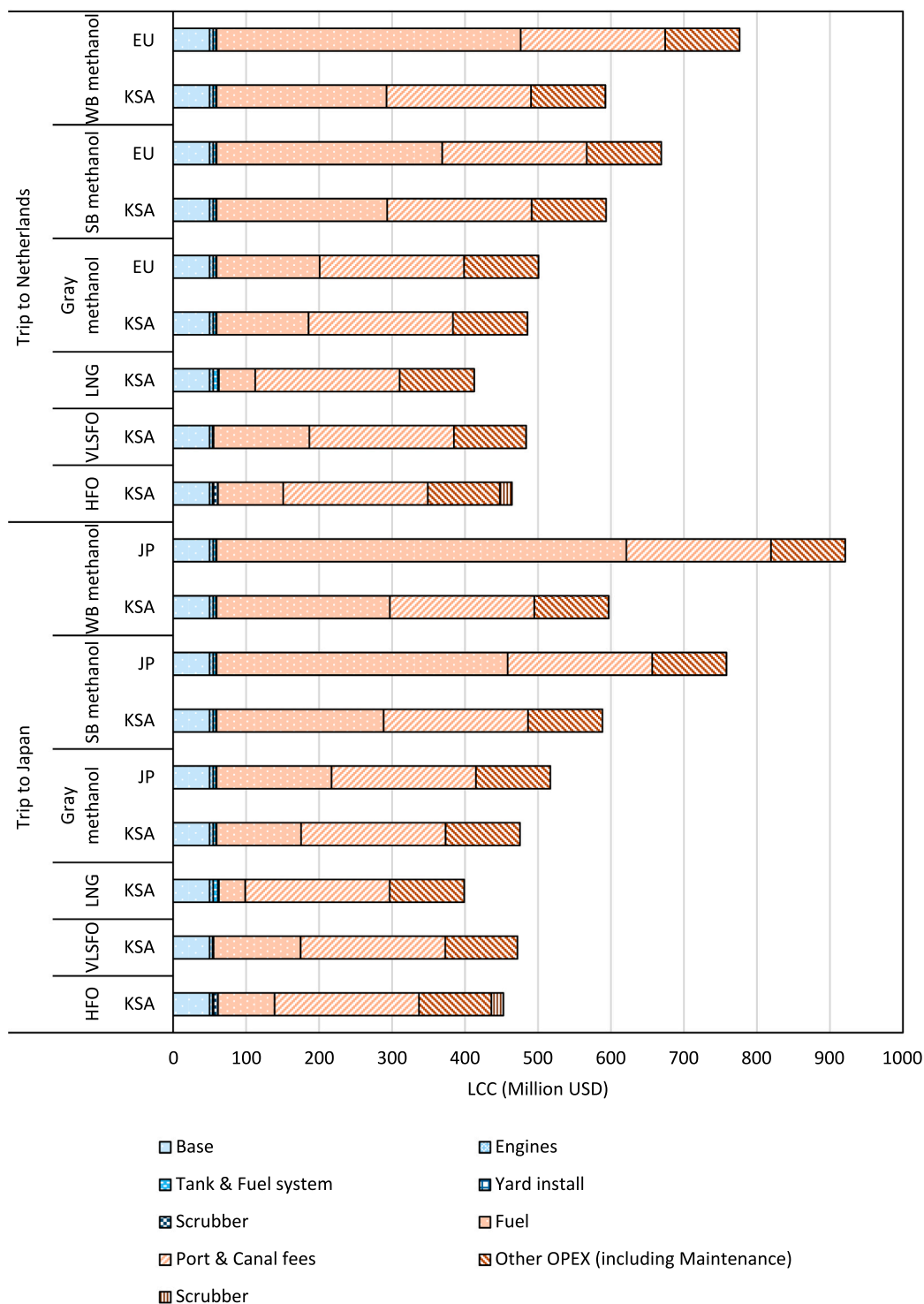


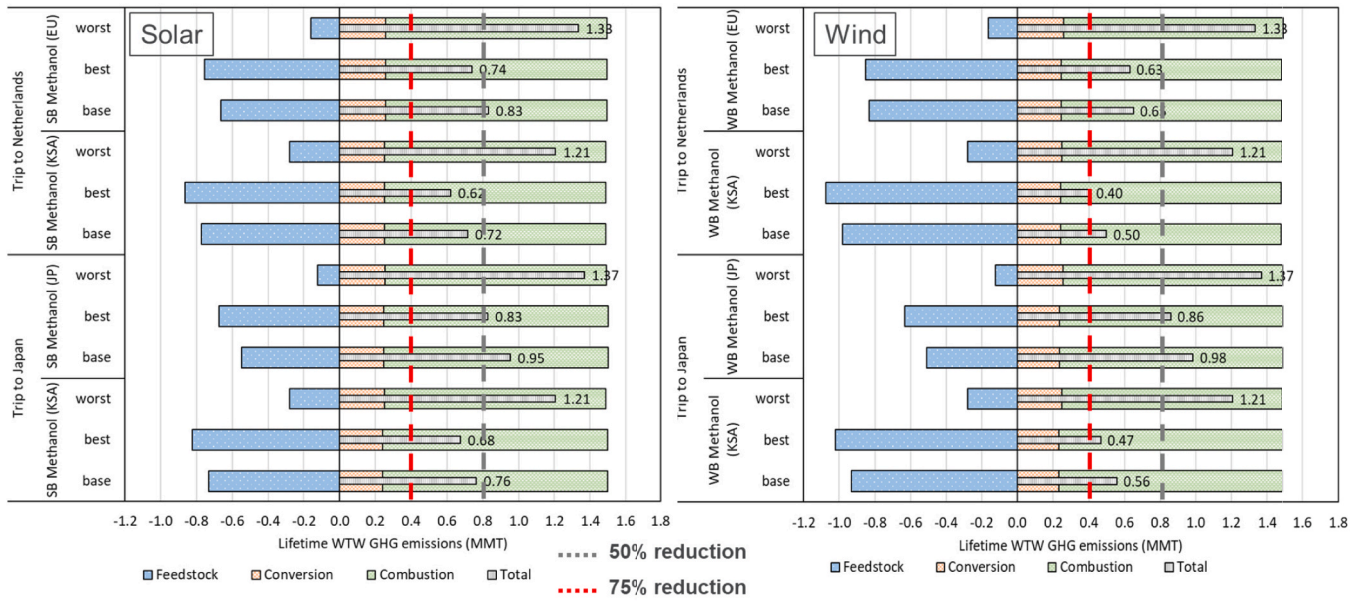
Fig. 5. Life cycle cost analysis results for the two destinations with fuel bunkered at different locations for methanol from solar and wind-based hydrogen and other conventional fuels.

among the three regions, especially from wind, while KSA is found to be the most suitable location based on the lowest cost as well as GHG emissions.

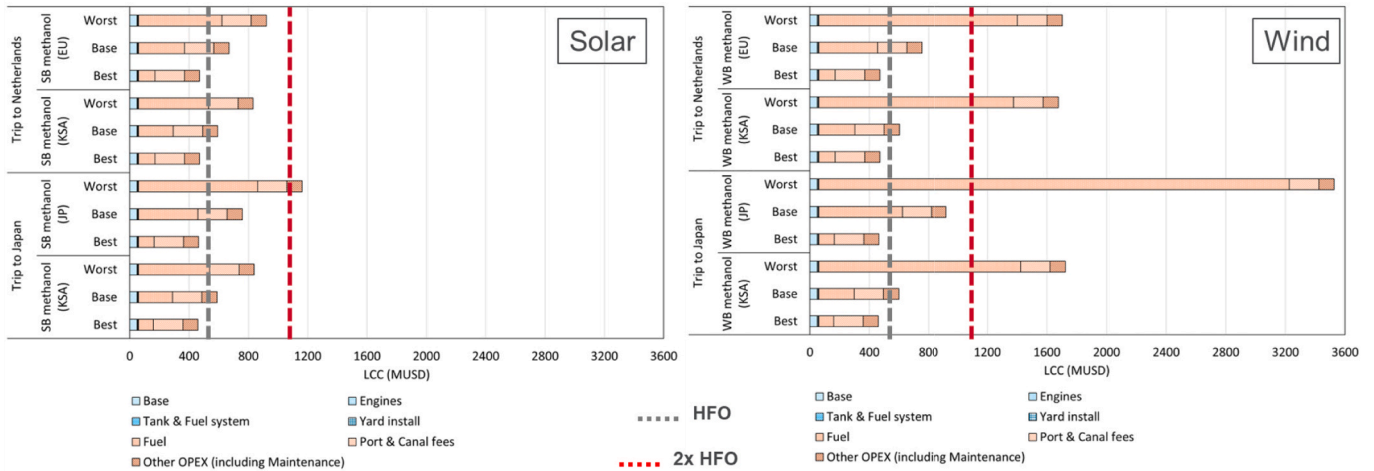
*Cost of carbon abatement*

The cost of carbon abatement (CCA) results is shown for the SB and WB methanol in Fig. 7. Since there was no carbon abatement by gray methanol, it was not considered for the CCA calculation. Thus, the

results are shown for LNG, VLSFO and renewable-based methanol for different sensitivity analysis cases, i.e., base, best and worst. Further, as observed earlier, the cost for the worst-case results were almost twice the reference HFO vessel, therefore the CCA for that can be very high. Thus, the worst-case results are about five times higher for the SB methanol and by 10 times for the WB, to have results for the base, best and worst cases on the same scale. The results are then compared to identify the changes from SB methanol to WB methanol in terms of the associated cost of carbon abatement with its use in a SUEZMAX tanker.



(a) Lifetime WTW GHG emissions (MMT)



(b) Life cycle cost (in MUSD)

Fig. 6. Results for sensitivity analysis with solar based hydrogen on the left and wind based on the right for (a) WTW life cycle GHG emissions and (b) life cycle cost.

The CCA results show that for the solar based methanol, if it is produced at its origin, i.e., KSA, the CCA will be very similar for both the trip destinations (EU and JP). However, when it is produced at the destination, the trip to EU has lower CCA due to lower cost of renewable-based methanol in EU than JP. Similarly, the wind-based results were observed to have the highest CCA among all conditions for the two trips. However, the main observation made about renewable-based methanol was that it can provide carbon abatement at a negligible cost in the best case, i.e., when hydrogen prices reach a rock-bottom \$1/kg in the future. While LNG from KSA, due to its very low cost in KSA, has lower WTW GHG emissions as well as lower LCC, resulting in a negative CCA. This negative CCA means that there is a cost saving as well as GHG reduction while operating with LNG. This is not the case for renewable-based methanol, as despite providing higher GHG reduction, due to the cost being higher and LHV almost half than HFO, there are very low chances for the LCC to go negative. Thus, even in the best case, the renewable-based methanol CCA becomes close to zero but not negative.

### Conclusions

This study focused on assessing the life cycle GHG emissions on a WTW basis and the cost of a SUEZMAX tanker operating on renewable-based methanol and conventional fuels for two different trips, from KSA to JP and KSA to NL. Saudi Arabia was taken to be the default origin based on current energy transport. The conventional fossil fuels were assumed to be produced and bunkered at the origin (KSA) only. However, for methanol the production and bunkering were also considered at the destination. Thus, the production of methanol was considered in the destination regions of Japan and Europe (trip to NL) along with the origin region, KSA. The gray methanol produced from natural gas was initially evaluated and was found to emit more lifecycle GHG than the conventional HFO-powered vessel. This can be attributed to the WTT GHG emissions due to the use of natural gas for the fuel production process, consistent with past studies using gray methanol [54]. Even for the life cycle cost results, due to the high fuel consumption (in metric ton/trip) the life cycle cost was higher for gray methanol vessels than conventional vessels, despite having similar cost per metric ton. This too

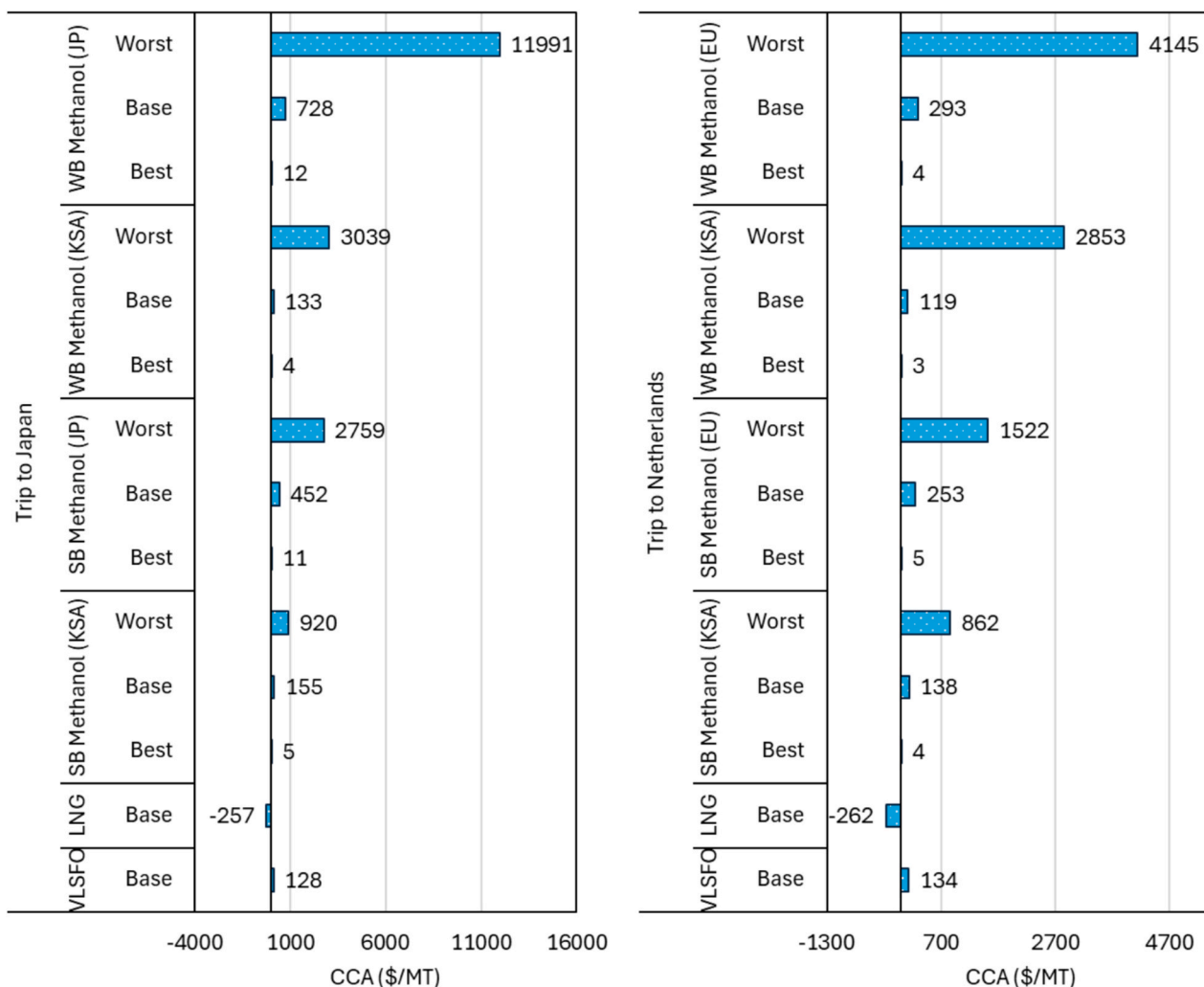


Fig. 7. Cost of carbon abatement of the two trips for methanol produced from solar and wind based hydrogen and other conventional fuels when compared to HFO vessel.

is consistent with previous related works on gray methanol.

However, renewable-based methanol, produced from electrolysis hydrogen (from solar or wind electricity) and captured CO<sub>2</sub>, showed significant lifecycle GHG reduction compared to the reference HFO vessel, in each region [57]. This was largely due to the involvement of carbon capture in the fuel production process that is counted as a GHG emissions credit. Therefore, for the final GHG, the high combustion GHG emissions are offset by the captured CO<sub>2</sub>, which is needed as feedstock for fuel production [58]. The CI of renewable-based methanol varied based on the CI of hydrogen production from wind or solar in each region, as well as the sources of CO<sub>2</sub> considered for carbon capture based on the top GHG contributing sectors in each region. It was observed that methanol production from both wind and solar had the lowest GHG emissions when produced in KSA, while JP was higher than the EU. Further, due to the lower embodied emissions associated with wind renewable systems, the GHG emissions were lower for KSA and EU for wind. This was due to the poor wind availability in JP resulting in very low annual yield of renewable energy that can be used for methanol production. In terms of LCC, methanol production in KSA had the lowest cost for methanol vessels across both the trips with solar as well as wind-based hydrogen. It was also found that the LCC for solar based methanol and wind-based methanol was similar for both the trips when produced in KSA. However, for EU and JP the cost is higher for wind-based methanol due to the high cost of hydrogen from wind than solar in these regions. Overall, LNG vessels had the lowest LCC, even lower than

the renewable-based methanol produced in KSA, but did not offer nearly as much of an absolute reduction in lifecycle GHG emissions.

Further, a sensitivity analysis is also performed for WTW life cycle GHG emissions and LCC by considering the best and the worst case in addition to the base case. Where best case considers hydrogen cost of \$1/kg and minimum CI over a year from the hydrogen modeling, as well as CO<sub>2</sub> capture from ammonia plants replacing Cement/Steel plants for the manufacturing sector's source of CO<sub>2</sub> emission. And the worst case considers the maximum cost and CI of hydrogen from the hydrogen modelling, while CO<sub>2</sub> captures from DAC only in all three regions. The sensitivity analysis results showed that for the worst cases, GHG emission reduction of 50 % was not achieved in any of the cases, while only in the best case for wind based renewable-based methanol that is produced in KSA, a 75 % GHG reduction could be achieved. This is consistent with other studies as well [59]. It was also concluded that methanol produced in KSA from solar or wind has the lowest GHG emissions across the three regions. Further in terms of LCC, it was observed that in the best case, with a hydrogen cost of \$1/kg, a cost parity with HFO vessel can be achieved. However, in the worst case it can be as high as twice the HFO vessel, and even more so in the case of wind-based methanol. This is mainly due to the high cost of hydrogen in the worst scenario and even higher cost for the wind-based scenario. However, in the case of KSA, the LCC for the wind-based methanol was still much lower.

Based on these sensitivity analysis results the cost of carbon

abatement was also calculated to observe that the methanol from wind and solar can provide carbon abatement at a negligible cost in the best case, but in the worst, it can be higher than 5 times for solar based methanol, and 10 times for wind-based methanol. While LNG showed negative CCA due to both, GHG saving as well as cost saving. Thus, this study shows that KSA can be a potential location for producing methanol from both solar as well as wind sources, when compared with EU and JP. This is due to the large availability of wind and solar sources in KSA, as evaluated in this study. Further, it was observed that Japan may not be the right location for methanol production from wind or solar energy due to the high cost and GHG emissions associated with it. The reduced availability of solar and wind energy in Japan is the main cause for this, while the EU is between KSA and Japan. Hence, it is important to note that despite KSA being historically a global leader in oil production, it can also be a potential location to use its wind and solar energy resources for producing and exporting renewable fuels, such as renewable-based methanol.

### CRedit authorship contribution statement

**Shashwat Tripathi:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher P. Kolodziej:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Farhad Masum:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Loiy Al-Ghussain:** Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Zifeng Lu:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Data curation. **Daniel De Castro Gomez:** Supervision, Resources, Project administration, Funding acquisition, Data curation. **Xin He:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation. **Enze Jin:** Resources, Investigation, Data curation. **Jessey Bouchard:** Validation, Supervision, Resources, Project administration. **Troy Hawkins:** Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Michael Wang:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

### 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.

### Acknowledgements

This work was supported by the Aramco Services Company under an agreement through U.S. Department of Energy Contract No. DEAC02-06CH11357.

### Data availability

Data will be made available on request.

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