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Shipping decarbonization: E-fuels as a potential solution and the role of resources

Elias Yfantis[1, *], *Kleanthis* Kleanthous[2], *Angelos* Ktoris[3], *George* Mallouppas[4], *Sofia* Damianou[5], *Constantina* Ioannou[6], *Dimitris* Shiali[7], and *Ioannis* Nikolaou[8]

[1]Cyprus Marine and Maritime Institute, Larnaca 6023, Cyprus; elias.yfantis@cmmi.blue
[2]National Technical University of Athens, School of Mechanical Engineering, Zografou 15772, Greece; mc17608@mail.ntua.gr
[3]Cyprus Marine and Maritime Institute, Larnaca 6023, Cyprus; angelos.ktoris@cmmi.blue
[4]Cyprus Marine and Maritime Institute, Larnaca 6023, Cyprus; george.mallouppas@cmmi.blue
[5]Cyprus Marine and Maritime Institute, Larnaca 6023, Cyprus; sofia.damianou@cmmi.blue
[6]Cyprus Marine and Maritime Institute, Larnaca 6023, Cyprus; constantina.ioannou@cmmi.blue
[7]National Technical University of Athens, School of Naval Architecture and Marine Engineering, Zografou 15772, Greece; nm19711@mail.ntua.gr
[8]Aristotle University of Thessaloniki, School of Mechanical Engineering, Thessaloniki 54124, Greece; nikolaouis@meng.auth.gr

Abstract. The scope of this paper is to examine proposed e-fuels (e-hydrogen, e-ammonia, e-methanol) as alternative maritime fuels. A techno-economic analysis is conducted considering the current energy demand of the shipping sector, the solutions for decarbonisation that are based on e-fuels, and the projections and scenarios regarding the energy mix towards 2050, to meet the IMO targets. According to the current preliminary study, apart from the barriers related to technological maturity levels, applicability and safety, there are barriers related to (a) the Well-to-Wake characteristics of e-H_2, e-NH_3, and e-CH_3OH, (b) the existing infrastructure that utilises Renewable Energy Sources and the current and projected percentage of RES in the global energy mix, and (c) the availability of resources required for the development of the infrastructure to support e-fuels' utilisation. Estimated fuel prices in 2050 that include production and distribution costs, indicate that alternative fuels are expected to be uncompetitive. Though they become relatively competitive when carbon-price is added to production and distribution costs of fossil fuels, the Well-to-Wake Analysis of biofuels and e-fuels proves that a significant RES rump-up is required, which further requires huge capital investment costs and raw materials. Ultimately, a re-prioritisation is proposed targeting decarbonisation of "easier-to-abate" sectors before decarbonising "hard-to-abate" sectors such as shipping and aviation.

1 Introduction

On the context of research, alternative fuel implementation and assessment is an already discussed topic for transport industries, yet the binding of a common path towards decarbonisation and GHG emission mitigation accelerates the need for an effective solution on a multidisciplinary problem, both quantitatively and qualitatively.

Utilization of alternative fuels in the maritime sector is equally crucial and demanding to achieve since seaborne transport representing most of the global trade by volume, stands out for the predominant use of fossil fuels, and constitutes a major driving force and actuator on the Drivers Pressures State Response Impact (DPSRI) feedback loop.

The present paper aims to quantify and to assess the adequacy of prospect maritime alternative fuels [1], namely e-hydrogen, e-ammonia, and e-methanol, also considering a variable mixture of the three to meet the projected needs by mid-century. More specifically, supposing no future use of fossil fuels, three main scenarios concerning the breakdown of the maritime energy mix of 2050 are considered, out of which the quantity of electro-fuels (e-fuels) is calculated, also accounting for the projected evolution of energy needs. The respective energy requirements for primary energy are then calculated, by reviewing the stages of the predominant methods of the e-fuels' production. Furthermore, assuming their production is solely by RES (solar and wind energy), the land requirements are examined both onshore and offshore. A diagrammatic comparison and review of future projections and respective requirements strongly suggests the use of e-hydrogen.

This techno-economic approach does not only test the feasibility of e-fuels, but also the validity of future scenarios and projections, and serves as a strong indicator for the attenuation of the desired sustainability, while elucidating the path forward.

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[*] Corresponding author: elias.yfantis@cmmi.blue

2 Detailed Analysis

This paper will conduct techno-economic analysis for the transition of the shipping sector in using e-fuels (synthetic fuels that are produced using captured carbon dioxide or carbon monoxide and hydrogen derived from sustainable electricity sources), involving the assessment of the applicability and feasibility of the proposed e-fuels, namely e-hydrogen, e-ammonia and e-methanol, as potential maritime alternative fuels. In this regard, the analysis is based on DNV scenarios and projections regarding the energy mix towards 2050, as described in the "Decarbonization by 2050" plan [2], as well as the financial conditions for each scenario that support specific types of fuels. Three scenarios were obtained and are presented in Table 1.

The first scenario of 2050's fuel mixture set by DNV comprises fuel shares of e-fuels and biofuels (fuels derived from biomass feedstock) at the percentages of 76% and 24% respectively. The second scenario consists of 100% e-fuels, while the third scenario includes 3% e-fuels, 83% biofuels and 14% blue fuels (fuels that are produced through carbon-neutral processes).

Table 1. DNV scenarios of 2050's fuel mixture.

Scenario	Fossil Fuels	Electro fuels	Bio fuels	Blue Fuels
1	0%	76%	24%	0%
2	0%	100%	0%	0%
3	0%	3%	83%	14%

2.1 E-fuels quantity requirements

To further enhance technical analysis, various sub-scenarios are generated for the electro fuels and scenarios of Table 1. Each sub-scenario consists of different e-fuels along with different shares at 0%, 25%, 50%, 75% and 100% respectively as seen in Table 2.

Table 2. E-fuels at different shares in the generated sub-scenarios.

Sub-scenario	e-hydrogen	e-ammonia	e-methanol
1	0%	0%	100%
2	0%	25%	75%
3	0%	50%	50%
4	0%	75%	25%
5	0%	100%	0%
6	25%	0%	75%
7	25%	25%	50%
8	25%	50%	25%
9	25%	75%	0%
10	50%	0%	50%
11	50%	25%	25%
12	50%	50%	0%
13	75%	0%	25%
14	75%	25%	0%
15	100%	0%	0%

The energy demand of the shipping sector in 2050 is expected to remain the same as the energy demand in 2021 (conservative scenario) whilst [3] it is estimated that it reaches approximately 8.7 exajoules (EJ) entirely generated from fossil fuels. Therefore, the required energy demand for each fuel category in Table 3 is calculated using the estimated 8.7 EJ with each scenario for each fuel category in Table 1.

Table 3. Energy demand calculated for each fuel category of the forecasted scenarios.

Scenario	Fossil Fuels [EJ]	Electro fuels [EJ]	Bio fuels [EJ]	Blue Fuels [EJ]
1	0.000	6.612	2.088	0.000
2	0.000	8.700	0.000	0.000
3	0.000	0.261	7.221	1.218

In this regard, projections for each fuel category are made for scenarios 1, 2 and 3 respectively. For example, for the electro-fuels at Scenario 1 (of 6.612 EJ total energy share), 15 projections are made to calculate the energy demand of each e-fuel and are presented in Table 4. Table 5 and Table 6 show the corresponding energy demand for the electro-fuels category of the other two scenarios.

Table 4. Energy demand of each e-fuel calculated for scenario 1 (total e-fuels energy demand equals to 6.612 EJ).

Sub-scenario	e-hydrogen [EJ]	e-ammonia [EJ]	e-methanol [EJ]
1	0	0	6.612
2	0	1.653	4.959
3	0	3.306	3.306
4	0	4.959	1.653
5	0	6.612	0
6	1.653	0	4.959

7	1.653	1.653	3.306
8	1.653	3.306	1.653
9	1.653	4.959	0
10	3.306	0	3.306
11	3.306	1.653	1.653
12	3.306	3.306	0
13	4.959	0	1.653
14	4.959	1.653	0
15	6.612	0	0

Table 5. Energy demand of each e-fuel calculated for scenario 2 (total e-fuels energy demand equals to 8.700 EJ).

Sub-scenario	**e-hydrogen [EJ]**	**e-ammonia [EJ]**	**e-methanol [EJ]**
1	0	0	8.7
2	0	2.175	6.525
3	0	4.35	4.35
4	0	6.525	2.175
5	0	8.7	0
6	2.175	0	6.525
7	2.175	2.175	4.35
8	2.175	4.35	2.175
9	2.175	6.525	0
10	4.35	0	4.35
11	4.35	2.175	2.175
12	4.35	4.35	0
13	6.525	0	2.175
14	6.525	2.175	0
15	8.7	0	0

Table 6. Energy demand of each e-fuel calculated for scenario 3 (total e-fuels energy demand equals to 0.261 EJ).

Sub-scenario	**e-hydrogen [EJ]**	**e-ammonia [EJ]**	**e-methanol [EJ]**
1	0	0	0.261
2	0	0.06525	0.19575
3	0	0.1305	0.1305
4	0	0.19575	0.06525
5	0	0.261	0
6	0.06525	0	0.19575
7	0.06525	0.06525	0.1305
8	0.06525	0.1305	0.06525
9	0.06525	0.19575	0
10	0.1305	0	0.1305
11	0.1305	0.06525	0.06525
12	0.1305	0.1305	0
13	0.19575	0	0.06525
14	0.19575	0.06525	0
15	0.261	0	0

In order to calculate the required fuel quantity of e-hydrogen, e-ammonia and e-methanol for each simulated sub-scenario, the energy demand (calculated in Tables Table 4, Table 5 and Table 6) is divided with the energy density of each e-fuel in Table 7.

Table 7. Energy density of proposed e-fuels [4].

Fuel Type	**Energy density [MJ/kg]**
e-hydrogen (e-H_2)	120
e-ammonia (e-NH_3)	18.8
e-methanol (e-CH_3OH)	19.9

2.2 E-fuels production methods and energy requirements

In the case of e-hydrogen, favourable production pathways are through water electrolysis, specifically Alkaline and Proton Exchange Membrane (PEM) electrolysis technologies [5]. Therefore, the energy consumption to produce a Mt of e-hydrogen is assumed to be approximately the average energy amount required for the aforementioned production methods. Table 8 presents the energy requirements per produced Mt of e-hydrogen (in units of TWh/Mt) for each production method, which is calculated by dividing the energy consumption per cubic meter (minimum and maximum values obtained by [6]) with its density in normal conditions (which equals to 0.08 kg/m^3) [5], [6]. The total average energy demand for the production of e-hydrogen equals to 57.19 TWh/Mt.

Table 8. Energy requirements for the production of e-hydrogen.

Production Method	**Min [TWh/Mt]**	**Max [TWh/Mt]**
Alkaline Electrolysis	53.75	58.75
PEM Electrolysis	56.25	60.00
Total average energy demand	57.19	

E-Ammonia is synthesized mainly using high-pressure, medium-pressure or absorbent enhanced Haber-Bosch technology, which in turn in this paper is assumed to be the ideal production pathway for e-ammonia [7]. This production method takes place through several main and auxiliary processes, including water desalination, electrolysis, Pressure Swing Absorber (PSA), ammonia synthesis and ammonia storage, with different energy requirements.

Table 9 shows the energy consumption for each stage of the Haber-Bosch process for e-ammonia production. The total energy consumption required for the production of e-ammonia is estimated at 13.9 TWh/Mt and is expected to cover all the renewable electricity demands of a typical ammonia plant [7].

Table 9. Energy requirements for the production of e-ammonia.

Stages of e-ammonia production	**Energy demand [TWh/Mt]**
Water desalination	0.013
Electrolysis	8.73
PSA	0.35
Ammonia Synthesis	4.57
Ammonia Storage	0.22
Total average energy demand	13.9

Table 10 shows that approximately 10 to 11 MWh of renewable electricity are required to produce a tonne of e-methanol according to [8] and [9]. It is worthwhile to mention that the largest proportion of energy is used for electrolysis.

Table 10. Energy requirements for the production of e-methanol.

	Min [TWh/Mt]	**Max [TWh/Mt]**	**Average [TWh/Mt]**
Total average energy demand	10	11	10.5

Lastly, Table 8, Table 9, and Table 10 accentuate that e-hydrogen has the highest total average energy demand to be produced.

2.3 Land requirements

In addition to the projected energy consumption, the required land that needs to be dedicated for their production is also important when examining the applicability of e-fuels as potential maritime fuels. This paper considers that renewable electricity for e-fuels production is generated exclusively by solar (i.e., solar farms) and wind sources (i.e., offshore and onshore wind farms).

The capacity density for solar farms is assumed to be approximately 20 MW/km^2 [11] while the average capacity density of offshore wind farms is estimated at 5.94 MW/km^2 [12] (through a weighted average of the capacity densities of offshore wind farms in various European countries) and according to [13], the capacity density of onshore wind farms is estimated to be 9 MW/km^2.

Table 11 shows the capacity density of each renewable energy source that is transformed into energy density by utilising the capacity factor, obtained from [14], [15] and [16].

Table 11. Capacity factor and energy density of solar and wind sources.

	Capacity factor [%]	**Energy density [TWh/km^2]**
Solar farms	17.2	30134.40
Offshore wind farms	43	22367.01
Onshore wind farms	34	26805.60

The projected energy share of solar and wind renewable energy in 2050 in the total non-fossil generated energy mix, is 15% and 13% respectively, and thus it is assumed that the share of solar and wind energy equals to ratios of 15/28 and 13/28.

The projected wind capacity by mid-century is expected to reach approximately 6 TW, of which 1.8 TW corresponds to the offshore fixed-foundation wind turbines and 289 GW to the offshore floating wind turbines [17], hence the remaining amount of wind capacity, equals to 3.911 TW and is generated by onshore wind turbines. The projected solar energy capacity is estimated at 9.5 TW [10]. The energy capacities are summarized in Table 12.

Table 12. Energy capacities of solar and wind energy sources.

Renewable Source	**Energy Capacity [TW]**
Solar energy	9.5

Offshore wind energy	Fixed-Foundation wind turbines	1.8	2.089
	Floating wind turbines	0.289	
Onshore wind energy		3.911	

The dedicated area of land (in km^2) for the production of e-fuels can be estimated by the following equation, which combines the solar and wind energy percentage with the energy densities of each renewable source:

$$Land\ [km^2] = E_{d_{sce}}\left[\frac{15}{28}\left(\frac{1}{E_{d_{sol}}}\right)+\frac{13}{28}\left(\frac{2.089}{6}\left(\frac{1}{E_{d_{off}}}\right)+\frac{3.911}{6}\left(\frac{1}{E_{d_{on}}}\right)\right)\right] \quad (1)$$

where:

$E_{d_{sce}}$ indicates the energy demand of each sub-scenario [in TWh], $E_{d_{sol}}$ indicates the solar energy density [in TWh/km^2], $E_{d_{off}}$ indicates the offshore wind energy density [in TWh/km^2], and $E_{d_{on}}$ indicates the onshore wind energy density [in TWh/km^2].

3 Results

The required fuel quantities (in Megatonnes) of e-hydrogen, e-ammonia, and e-methanol to cover the energy demands described in each simulated scenario (presented in Section 2.1) are presented in Figure 1, Figure 2 and Figure 3.

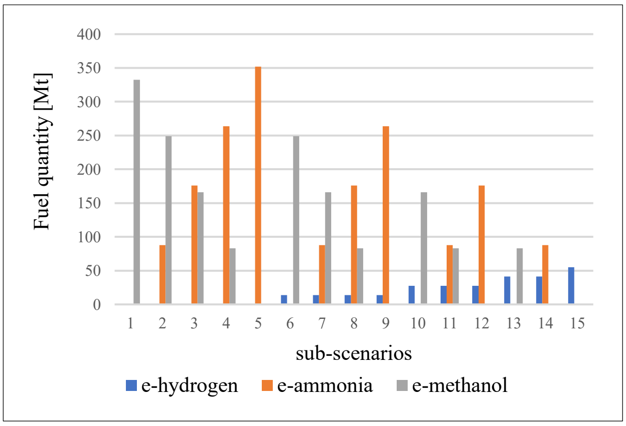

Figure 1. E-fuels quantity requirements for Scenario 1.

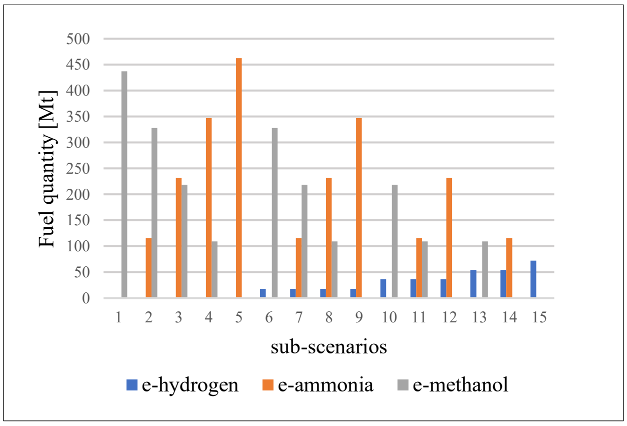

Figure 2. E-fuels quantity requirements for Scenario 2.

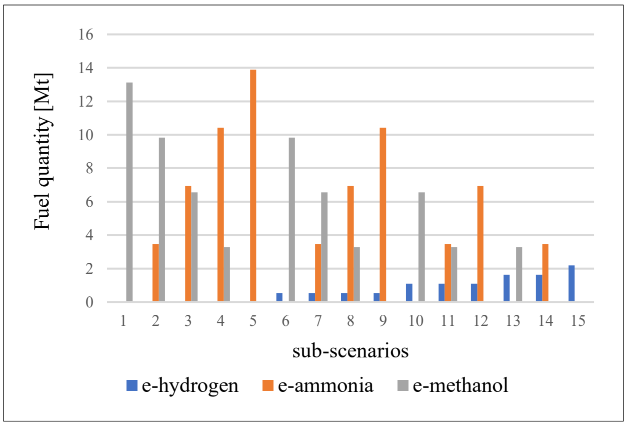

Figure 3. E-fuels quantity requirements for Scenario 3.

Moreover, the renewable energy requirements for the production of e-hydrogen, e-ammonia and e-methanol (presented in Section 2.2) to calculate the amount of energy needed (in TWh) to cover the demands for each foreseen scenario is illustrated in Figure 4, Figure 5 and Figure 6.

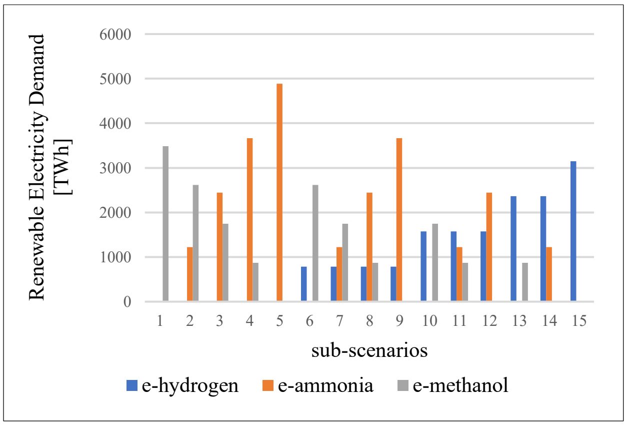

Figure 4. Renewable electricity demand for Scenario 1.

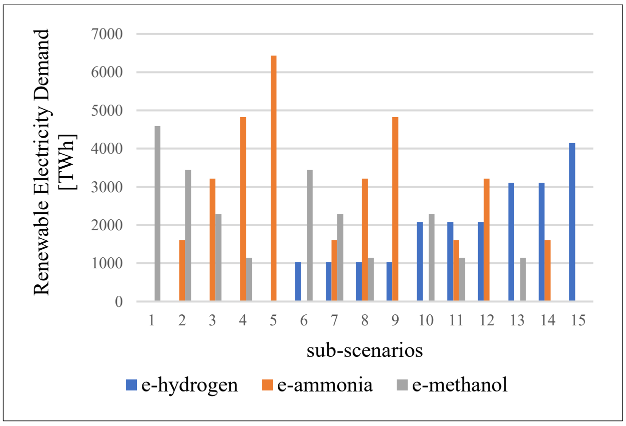

Figure 5. Renewable electricity demand for Scenario 2.

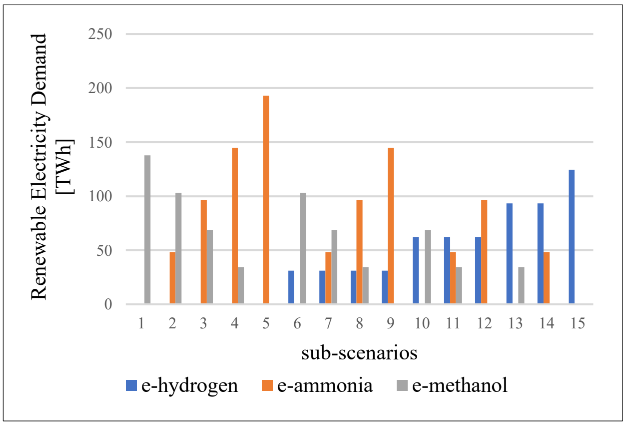

Figure 6. Renewable electricity demand for Scenario 3.

Solar and wind energy are projected to share 15% and 13% respectively of the total non-fossil generated energy in 2050, which is estimated to reach approximately 315 EJ [10], resulting in 24500 TWh available renewable energy. The energy required for e-fuels production can also be presented in the form of percentages (%) with respect to the estimated energy capacity of renewable energy by 2050 and therefore Figure 7, Figure 8 and Figure 9 indicate the source of renewable energy (solar or wind) that contributes to the production for each e-fuel.

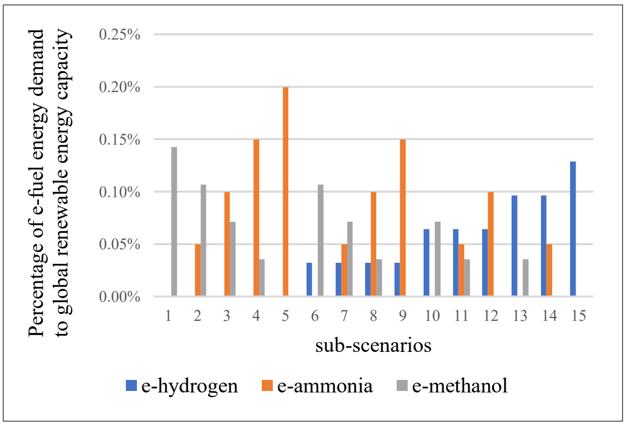

Figure 7. Energy demand percentages of e-fuels w.r.t. the global renewable energy capacity for Scenario 1.

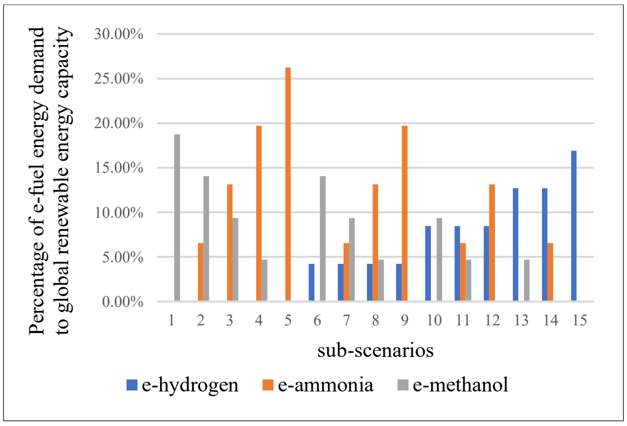

Figure 8. Energy demand percentages of e-fuels w.r.t. the global renewable energy capacity for Scenario 2.

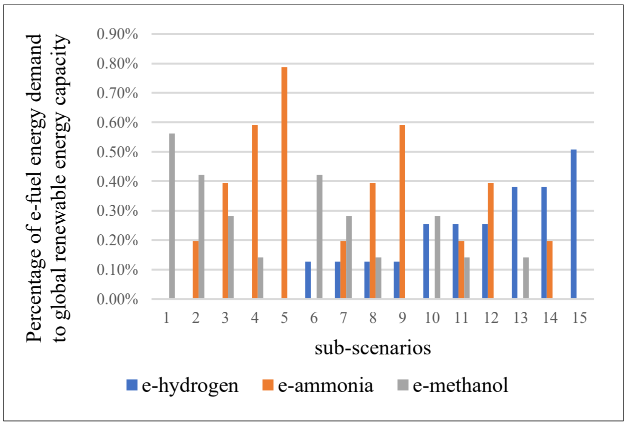

Figure 9. Energy demand percentages of e-fuels w.r.t. the global renewable energy capacity for Scenario 3.

The calculations indicate that for each scenario the e-fuel mixture providing the minimum and maximum projected energy consumption are sub-scenarios 15 and 5, which correspond to 100% utilization of e-hydrogen and 100% utilization of e-ammonia, respectively.

Moreover, the results calculated through Equation (1) are plotted in Figure 10, Figure 11 and Figure 12.

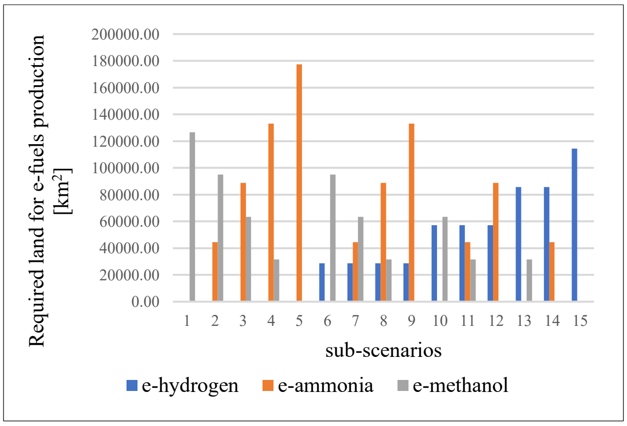

Figure 10. Land requirements of Scenario 1.

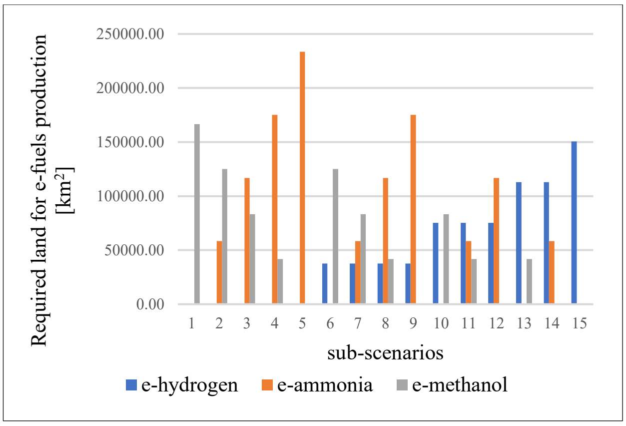

Figure 11. Land requirements of Scenario 2.

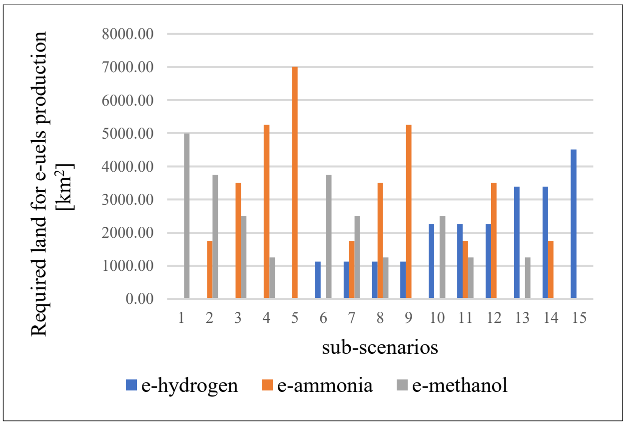

Figure 12. Land requirements of Scenario 3.

4 Discussion

This techno-economic analysis demonstrated the quantities of e-fuels required to cover global energy demands of projected DNV scenarios regarding the energy mix towards 2050 [2]. The renewable energy demand to produce such fuels and the resources and land required for the development of an appropriate infrastructure to support their production and utilisation is also analysed. This paper indicates that economic resources, are yet to be developed, to enable the utilisation of e-fuels.

The presented results indicate that for each scenario, the 15th projection for each sub-scenario which refers to 100% e-hydrogen production requires the least amount of energy demand and thus land.

Although an electrolysis plant for e-hydrogen production requires considerable amounts of electricity, the ratio of the energy demand for e-hydrogen production to its gravimetric energy density is the lowest of the respective ratios compared to other e-fuels. On the contrary, the highest energy demand is illustrated in sub-scenario 5 (100% e-ammonia) since the respective ratio for e-ammonia is the highest. The low energy density of e-ammonia, in conjunction with other issues related to safety, for instance e-ammonia's high toxicity, and applicability due to constraints on board the vessel, restricts its suitability for combustion in marine engines.

5 Conclusions

To sum up, the current analysis favours the utilisation of e-hydrogen for generating 100% of the global energy demand in 2050, out of all the projected scenarios set by DNV [2]. Ultimately, the production of e-hydrogen constitutes the most effective path for the development of e-fuels and their deployment as potential alternative fuels in the shipping sector, nonetheless significant capital investment costs, amounts of raw materials and land required for the development of an appropriate infrastructure are necessary for RES utilisation, and hinder valorisation of green renewable sources to cover the needs of increasing global energy demands.

Further research should be conducted to build a better understanding of the e-fuel production technologies and implications in terms of efficiency, greenhouse gases (GHG) emissions, technology readiness level, environmental impact, investment costs and demand that can have a potential role in the decarbonisation of these fuels to also build the appropriate regulations and eventually curb climate crisis.

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