Exploring the impact of methanol as an alternative, cleaner fuel for the auxiliary and support vessels within the RNLN

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Synopsis

The Netherlands Ministry of Defence has declared an ambition to reduce its dependency on fossil fuels by at least 20% by the year 2030 and 70% by the year 2050 (compared to 2010); and as the seagoing support vessels within the Royal Netherlands Navy (RNLN) approach their end of life, the RNLN seeks to exploit the opportunity to introduce an alternative fuel source and begin the journey towards reduced fossil fuel dependency. Building on previous work, this study elaborates on the use of methanol, ammonia and hydrogen. The total lifetime costs are quantitatively evaluated alongside a holistic evaluation of the societal cost of CO_2-emissions in order to determine the point at which the fuel price point of synthetically produced fuels becomes economically viable. Besides this, the impact on ship design is examined using the Ships Power and Energy Concept (SPEC) research tool. Concluding, synthetic fuels produced using renewable energy offer the greatest greenhouse gas reductions, but given their current technological maturity are not yet financially attractive. However, biofuels like bio-methanol are a feasible stepping stone to gain experience in the use of alternative fuels on ships. Additionally, as expected, the parametric approach in this study suggests the ship dimensions and displacement will increase, mostly due to the relatively low energy density of the fuels. However, further concept design is required to investigate whether the actual ship design grows, or whether additional volume for fuel is available in the design of these vessels, which are primarily driven in size by the deck space required for their operations.

Keywords: alternative fuels, methanol, ammonia, hydrogen, short sea shipping, SPEC

1. Introduction

This paper will explore a select number of energy carrier and converter combinations for consideration in the future support vessels of the RNLN. The scope of this paper is limited to assessing the basic economic (OPEX and CAPEX), environmental (CO_2 emissions) and operational viability (range, speed, payload and dimensions) of the seagoing support vessel type according to operating area. This paper will not assess all energy carriers, but a limited selection according to the overall technological readiness level (TRL) with its combined energy converter; and the predicted environmental benefit compared to the current fuel of choice in the RNLN – diesel oil. Analysis is undertaken using the proprietary Ship Power and Energy Concepts tool developed by the Maritime Research Institute Netherlands (MARIN). This paper is not intended to be a deep dive into the subject material and a number of broad assumptions are made which will be discussed accordingly. The intention of this paper is to offer an insight into the potential relative costs and benefits of alternative power concepts. This paper forms a small part of an extensive work package being undertaken on behalf of NL Defence and in line with the Green Deal on Maritime and inland shipping and Ports [Rijksoverheid, 2019] and the Defence Energy and Environment Strategy [Defensie, 2019] goal of significantly reducing the department's dependence on fossil fuels. Geertsma et al. [2019] have introduced the seagoing support vessels and given a first insight into the various energy carriers and converters; this paper will assess the impact to the parametric ship design, in terms of overall dimensions and the consequent financial implications of alternative power storage and conversion solutions. This paper begins with a short explanation of the SPEC Tool, followed by a description of the vessel type and how it was assessed, based on clearly defined input, modelling assumptions and the reasons behind the selection of the particular power concepts on which the analysis is focused. The analysis results are discussed and broad conclusions drawn followed by a brief discussion regarding the aspects of the analysis not covered and where further work is necessary to provide greater resolution to the impacts touched upon.

2. SPEC Tool

MARIN's SPEC (Ships Power and Energy Concept) tool is a software program developed for the Quaestor platform that combines multiple sub-models and offers an array of design analysis possibilities [Van Hees, 1997]. It contains a knowledge database of different energy carriers (fuels) and associated power systems (e.g. internal combustion engines (ICE), fuel cells

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etc.) which it incorporates into the ship design process. The tool generates a ship model for each combination of energy carrier and power system according to the principles shown in Figure 1 and based on input requirements such as endurance and payload.

The tool undergoes an iterative process to provide estimates for CAPEX, OPEX and lifetime CO2 emissions according to basic vessel characteristics and prioritising of variables such as speed, payload, dimensions and displacement. These calculations are indicative only and cannot be relied upon for actual ship design.

2.1. Validity of the Data

The numerical model is based on data obtained from multiple verified publications, technical data sheets and symposia. The data was checked against reference projects, and frequently updated in accordance with the latest research.

2.2. Limitations

The iterative nature and complexity of ship design is simplified and the tool is therefore intended primarily for use in the conceptual phase, when it is often a case of weeding out what will not be accepted for further development. The weight and volume of the energy and power systems is reflected in the ship's power demand and size; the resulting financial implications only consider the actual energy and power systems, whilst for example aspects such as additional steel for a larger hull are not considered. Moreover, the impact is established through parametric design, while further detail in the basic design might leave additional space for fuel tanks without driving up ship size, as discussed in Geertsma et al. [2019].

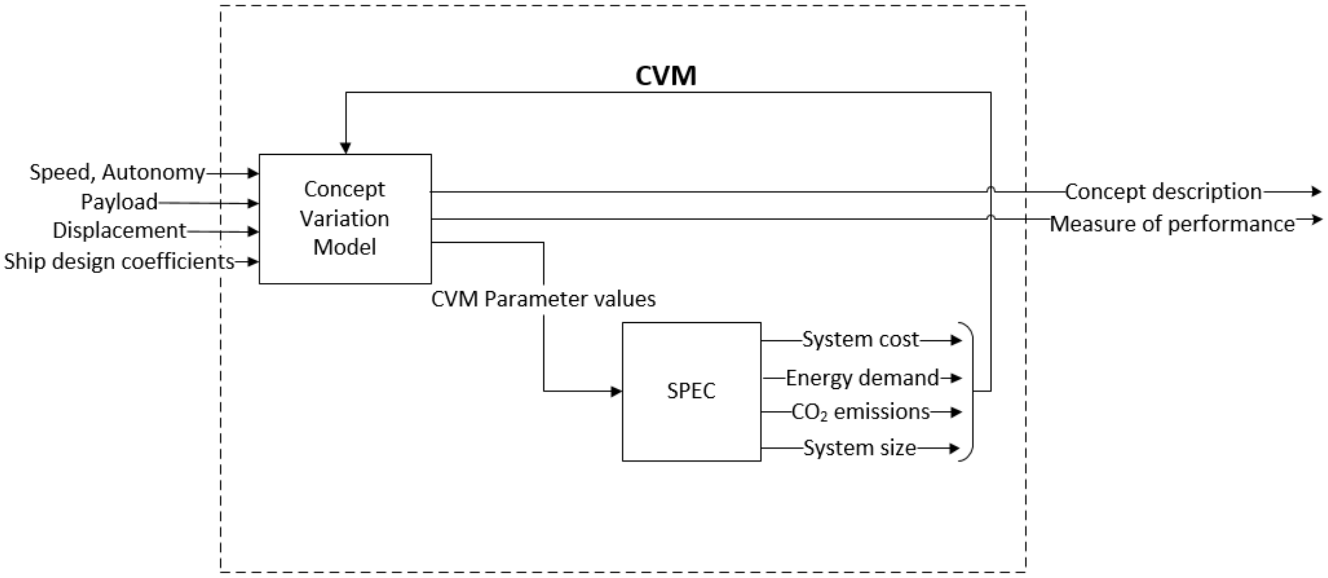

Figure 1. SPEC tool integration in the Quaestor model

3. Alternative fuels and power systems

The first support vessel is to be built for the RNLN in 2024, and therefore a high TRL is necessary to ensure applicability and feasibility of the design to meet production deadlines. The impact of three alternative fuels, already selected in previous work [Geertsma et al., 2019] is compared to a conventional diesel-electric power system baseline - methanol and ammonia both with an ICE as their respective energy converter; and hydrogen combined with a PEM fuel cell. See Table 1 for an overview. Hydrogen in combustion engines is not considered due to low energy density combined with low system-efficiency. Solutions including batteries were negated because they were simply unrealistic for the size, endurance and role of the vessels – the design became too big, too heavy and too costly to warrant further discussion. Solutions with Solid Oxide fuel cells have not been considered due to their low TRL, as is also the case for an ammonia PEM fuel cell which due to the additional step of extracting the hydrogen through cracking results in lower efficiencies than a straight hydrogen PEM fuel cell – ammonia cracking is only between 55-66% efficient [Lipman et al., 2007]. The power density of combustion engines is adjusted according to data from Wartsila's dual fuel engines [Wartsila, 2020]. Table 1 summarizes the characteristics of the energy converters and energy carriers applied in this paper.

3.1. Fuel Prices and the Cost of Carbon

The operating costs (OPEX) for each of the power systems are based on current prices and forecasts from a number of sources [Dena, 2018; De Vries, 2019; Hydrogen Europe, 2020; Lloyds Register, 2019; MethaShip, 2018; MKC, 2017; TNO, 2019]. The numbers have been aggregated into a single average value for a given period, as can be seen in Table 2 and include logistics and bunkering costs.

Table 1. Characteristics of energy converters and energy carriers

Power Concept	**Green Hydrogen PEM Fuel Cell**	**Synthetic and Bio-Methanol ICE**	**Synthetic Ammonia ICE**
Fuel Production pathway	Renewable electricity e.g. wind	Synthetic: Green hydrogen plus CO_2 from carbon capture Bio: From biomass or organic waste-streams	Green hydrogen plus captured N_2. 95 % synthetic ammonia mixed with diesel 5% (volume).
Power Conversion	Compressed (700 bar) hydrogen reacted in PEM fuel cell	Methanol combusted in Otto Cycle (spark ignition) ICE	Ammonia with diesel pilot fuel combusted in Diesel Cycle (compression) ICE
CO_2 reduction potential	100% (Well-to-Wake)	Synthetic: 92% (Well-to-Wake) Bio: 35% (Well-to-Wake)[1]	80% (Well-to-Wake)
Technical development state energy converter	TRL 7 - Demonstrated technology, expected to achieve TRL 9 within 5 years	TRL 7 - Prototypes demonstrated with dual fuel technology, manufacturers developing more effective/efficient engine solutions	TRL 5 - Laboratory phase; manufacturers performing engine tests, pilot vessel expected within 5 years

Table 2. Fuel prices.

	EURO per kWh	
	2020-2030	*2030-2050*
Diesel	0.050	0.050
Bio-methanol	0.080	0.065
Synthetic Methanol	0.198	0.098
Synthetic NH3	0.101	0.045
Green Hydrogen	0.110	0.050

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[1] Methanol Institute, 2019

The price development of diesel has been conservatively assumed to remain steady over the next 30 years. Alongside fuel costs this paper will consider carbon tax[2] and how it can affect the financial viability of the alternate power systems.

4. Vessels

All vessels of the RNLN are designed for a lifespan of 30 years, during which a mid-life update is performed. Due to equivalent requirements in terms of seaworthiness, maneuverability and control; and to optimize engineering and maintenance, a family design is preferred over specific replacements per existing vessel type. The five seagoing support vessels encompass Caribbean support, submarine support, training and two hydrographic survey vessels. The principal family design characteristics for the replacement are as mentioned in Table 3. Table 4 shows the average operational profile, from which an average power percentage of 59% can be derived, assuming a maximum speed of 15 knots.

Table 3. Principal design characteristics Seagoing Support Vessels

Parameter	Value
High speed transit	12 kts
Maximum speed	15 kts
Installed power	5000 kW
Range at transit speed	5000 nm
Displacement	2400 t
Payload	800 t
Design life	30 years
Endurance	14 days
Operational Days	200 days per year

Table 4. Operational profile of the Seagoing Support Vessels

	Type of operation	Power percentage	Time percentage	Speed
1	Low speed and station keeping	33%	15%	4 kts
2	Operations	52%	40%	6-10 kts
3	Economic transit	52%	15%	9 kts
4	High speed transit	82%	25%	12 kts
5	Maximum speed	99%	5%	15 kts

5. Methodology

The SPEC tool is used to analyse the impact of fixing or freeing the variables of speed, payload, dimensions and displacement. The results provide indicative CAPEX, OPEX, dimensions and lifetime CO_2 emissions. Alongside the aforementioned initial

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[2] The price per ton of carbon dioxide emissions

design characteristics, estimated values based on the current in-service vessels are used as input for the SPEC tool. Table 5 indicates which ship specific data is required.

Table 5. Input variables of the SPEC tool

General	Ratio	Dimensions	Performance	Time
Block coefficient	Beam / draft	Mean draft [m]	Design speed [kts]	Autonomy [d]
Displacement [t]	Length / beam	Moulded beam [m]	Admiralty coefficient	Downtime [%]
SWLight End of Life [t/m^3]		Moulded depth [m]	Total power [kW]	Lifespan [yr]
Total payload [t]		Waterline length [m]		Power Profile [%]

3.1. Design Cases

The SPEC tool offers various Design Cases, fixing and freeing the variables of *power, speed, payload, displacement* and *dimensions*:

1. *Speed Fixed – Payload Fixed – Displacement Free* - For a given speed and payload the minimum displacement is calculated.
2. *Speed Fixed – Payload Free – Displacement Fixed* - For a given speed and displacement, the dimensions are free to calculate the maximum payload.
3. *Speed Fixed – Payload Free – Dimensions Fixed* - For a given speed and dimensions, the maximum payload is calculated.
4. *Power Fixed - Payload Fixed - Displacement Free* - For a given power and payload the minimum displacement is calculated.
5. *Power Fixed - Payload Free - Displacement Fixed* - For a given power and displacement the maximum payload is calculated.
6. *Speed Free - Payload Fixed - Displacement Fixed* - For a given displacement and payload, the maximum speed is calculated.
7. *Speed Free - Payload Fixed - Dimensions Fixed* - For given dimensions and payload, the maximum speed is calculated.

The power fixed Design Cases (4 and 5) are eliminated from analysis because vessel power is a means to an end rather than a requirement. Fixing or freeing speed and payload directly affects the operations of a ship, resulting in a more interesting analysis. Speed is typically one of the greatest determining factors in ship design, particularly for naval vessels that are required to respond swiftly to emergent situations. Design Cases 6 and 7 are not assessed since there is a requirement to achieve a specific speed and no requirement to go beyond this - the higher energy density of diesel gives rise to a significantly pricier variant that can achieve unnecessarily high speeds. Besides speed, payload is another important factor which affects the vessel's capabilities and therefore the operations that can be undertaken; as such, having the desired payload is crucial. Preliminary research showed that Design Cases with a payload free condition, i.e. Design Cases 2 and 3, gave results that were not applicable - the payload decrease for the lower energy density options, e.g. hydrogen, could be as much as 100% or more, meaning that power and energy storage systems resulted in a zero or negative payload carrying capability for the vessel. Therefore, Design Cases with payload fixed conditions are necessary to derive realistic solutions. This leaves Design Case 1 which clearly shows the impact on ship design, emission and total cost of ownership for various energy carrier and converter options.

6. Results

Table 6 summarises the results from the SPEC tool with Design Case 1 (*Speed Fixed, Payload Fixed and Displacement Free)*; values are compared relative to a Diesel ICE benchmark. The results show the increase of capital expense, operational expense, ship dimensions, and ship displacement per energy and power solution. It is important to note that the results are all derived from an equivalent theoretical vessel based on aforementioned input variables and not the actual existing vessels. The results should be viewed as indicative and relative to the other power systems rather than in absolute terms and in isolation.

Table 6. SPEC results of the seagoing support vessels

	CAPEX	OPEX		Dimensions	Displacement
		2020-2030	*2030-2050*		
Bio-methanol (ICE)	+39%	+82%	+48%	+12%	+41%
Synthetic methanol (ICE)		+349%	+122%		
Ammonia (ICE)	+120%	+139%	+7%	+14%	+50%
Hydrogen (Fuel Cell)	+344%	+185%	+30%	+20%	+72%

In order to consolidate the financial data in a more useful manner and to enhance the ease with which the picture can be formed for the different power concepts, the annual CAPEX and OPEX have been calculated over the 30 year life of the vessels and broken down on an annual basis. Furthermore, an additional cost has been added in the form of carbon tax and Figure 2 derived to consolidate and highlight the financial impact of different fuel prices as per Table 2. The values shown in the chart are the diesel equivalents, e.g. for a carbon cost price of 30 EUR per ton, the cost of the bio-methanol power system is forecast to be 141% that of diesel over the period 2020-2030 and 123% for 2030-2050, based on the conservative assumption that price of diesel remains static.

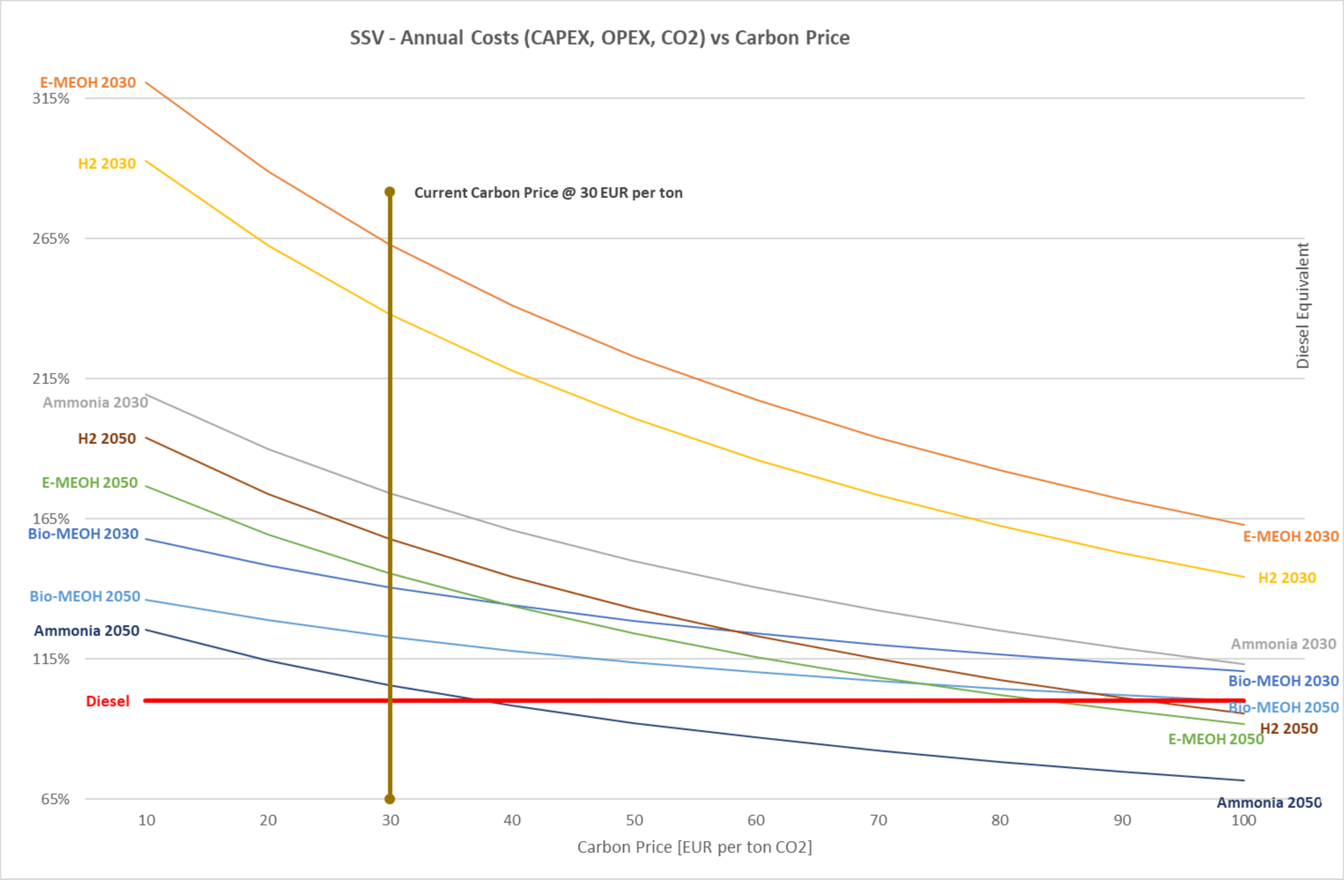

Figure 2. Diesel equivalent annual costs plotted against carbon price

For the current time period (2020-2030) the business cases for synthetic methanol[3] and hydrogen are simply not viable, even in the face of significant carbon taxation up to 100 EUR per ton; however, ammonia and bio-methanol offer a more realistic alternative. Looking further ahead (2030-2050), even with a static carbon tax of 30 EUR per ton, the business case for all options looks promising as highlighted in Table 7 below:

Table 7. Annual Costs compared to Diesel with carbon tax of 30 EUR per ton CO_2

	Diesel Cost Equivalent	
	2020-2030	*2030-2050*
Bio-methanol	141%	**123%**
Synthetic methanol	263%	**146%**
Ammonia	174%	**106%**
Hydrogen	238%	**158%**

7. Discussion

7.1. Ship design impact

As seen from Table 6 the introduction of alternate power systems requires a significantly larger ship, as with a lower energy density comes a greater volumetric requirement for storage which generates a larger vessel that needs to develop more power for a given speed and/or payload. The impact of the hydrogen fuel cell solution in particular is very large, as was also concluded in the previous study [Geertsma et al., 2019]. Furthermore, such enlarged dimensions is not simply a financial consideration, but also one of operational requirements and vessel capabilities; not only would there be an impact on the areas in which the vessel could access, transit and operate in, but also potentially the ease with which the vessel may conduct certain operations. Finally, alongside a larger CAPEX for the vessel itself, there will also be an uplift in the maintenance costs as systems and equipment are scaled up; this level of detail is beyond the scope of the SPEC tool, but should be given due care and attention when assessing the overall financial viability of the vessel.

7.2. Financial Viability

From the results above it can be seen that currently bio-methanol offers the most cost-effective solution, based on current price forecasts (2020-2030) and a carbon cost hovering around 30 EUR per ton as of July 2020. The switch to synthetic methanol (E-MEOH) in the future (2030-2050) will most likely require further carbon tax hikes towards 60-80 euros per ton, unless the production costs are significantly reduced and/or the cost of diesel rises. Both of which are not unrealistic given the ever-growing societal demand for greener ways of working and living, of course provided that appropriate national and international policies and initiatives are enacted to promote and further work in the field of alternative power concepts. As previously mentioned, the price comparisons are based on a stagnant diesel price and should carbon tax remain stable around 30 euros per ton then the RNLN should consider adopting bio-methanol as the next fuel of choice for the SSV's, with an eye to adopting synthetic methanol later down the line. The total annual costs of adopting bio-methanol for 2020-2030 and synthetic methanol for 2030-2050 in place of diesel will require a surcharge of 41% and 46% respectively. A relatively small cost for delivering carbon dioxide savings of at least 35% for bio-methanol and 92% for synthetic methanol. As the fuel production pathways develop and efficiencies are realised, the cost of bio-methanol and its carbon dioxide emissions will further improve, offering greater savings when taking carbon tax into account.

7.3. Reducing CO2 Emissions

Synthetic hydrogen offers 100% carbon dioxide emission savings and is the greenest option available; however, as discussed, the battery power concept was rejected for the SSV and the hydrogen power concept may also result in an undesirable SSV design given the indicative increase in dimensions and displacement of 20% and 72% respectively. For larger vessels, although

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[3] Synthetic methanol is referred to in the short-hand 'E-MEOH' in *Figure 2*

a hydrogen power system can offer a viable solution with prices expected to drop below that of methanol in the future, the enlarged vessel size required may either preclude it as an option for operational or financial reasons. This then begs the political question, how important is it to achieve 100% CO2 reduction versus the 92% offered by synthetic methanol?

7.4. Nitrous Oxide

The ammonia power concept offers the cheapest option over the long-term, but with carbon dioxide savings that lag behind synthetic methanol – 80% vs. 92%. For the foreseeable future, the ammonia solution offers significantly greater uncertainty than any of the other power concepts with a TRL of only 5 and there is uncertainty regarding the emissions of nitrous oxide which may reduce the greenhouse gas reduction potential significantly (Korean Register, 2020).

7.5. Methanol

The high TRL of a methanol ICE power system means that this choice is surrounded by less uncertainty than its closest rival – ammonia. Beyond the immediate technical challenges in the implementation of emerging technologies, there is the question over the ease with which an organisation can transition from one fuel source to the next. Such a discussion would need to encompass everything related to achieving a successful shift, from personnel safety to logistics; and firefighting to harbour infrastructure. Despite the difficulties related to a low flash point fuel, the challenges surrounding the use of methanol as a maritime fuel are not insurmountable as is demonstrated by existing success stories such as the ferry Stena Germanica [The Motorship, 2020], that demonstrate how to transition from conventional diesel to methanol.

8. Conclusion

Holistically, adoption of methanol ICE's will be the most straightforward solution for the SSV; it currently offers the best overall solution in terms of cost and CO2 savings for 2020-2030 and is likely to be cost-effective well into 2030-2050, while reducing the CO2 emissions by up to 92%. Given the comparable nature of the methanol and diesel power concepts, its adoption would be far less complex than hydrogen or ammonia. Bio-methanol can be introduced now to achieve immediate and significant carbon dioxide savings and the earlier it is embraced, the quicker the expertise, knowledge and experience can be developed by the RNLN to capitalise further as synthetic methanol becomes financially viable. While the 50% lower energy density potentially leads to a 40% increase in displacement, previous work has shown this increase can be limited by reducing the fuel capacity of the vessels. The approximate 70 % increase in displacement due to H_2 cannot be completely prevented and the required safety measures for hydrogen might have an even larger impact on the ship design due to its impact on the topside design of the vessel, which is already challenging for any naval vessel. Therefore, methanol appears to be the relatively mature option to meet the goals of the Operational Energy Strategy and the various green deals, thus significantly reducing the impact of operations of the RNLN on the environment. Finally, the availability of a fuel cannot be overlooked and as one of the most widely traded chemical feedstocks, methanol is available worldwide [DNV-GL, 2020]. However, most of the methanol currently available is sourced from fossil fuels and just as, if not more, polluting than diesel/HFO. Greater uptake of methanol as an alternative fuel for the maritime industry will promote greater demand and thereby enhance the prospects of the business case for bio- and synthetic methanol into the future, but this will not only require governmental backing through policies and initiatives, but commercial investment supported by research into more efficient and effective means of fuel production and energy conversion.

9. Recommendations

Whilst the future fuel of choice for energy converters in stationary applications is expected to be dominated by fuel cells and green hydrogen, the lower energy density of hydrogen limits its use on board ships needing to operate independently for more than two weeks. Therefore, the maritime community needs to investigate alternative, more energy dense bio- and synthetic fuels, such as methanol and ammonia. With an energy density half that of conventional marine gas oils and a significantly lower flash point the application of these fuels undoubtedly brings technical challenges. However, the urgent need to significantly reduce CO_2 and NOx emissions combined with the potential to retrofit existing diesel internal combustion engines warrants further research into the application of methanol and ammonia in the short term.

Despite the drawbacks of the ammonia power system, related predominantly to its low TRL and at a present limited research concerning N_2O emissions[4], it would be wise to monitor its development, as it has the potential to compete with methanol both on price and its carbon dioxide emissions.

Further research is needed for methanol and its mixing with water and/or the use of a Selective Catalytic Reduction to reduce NOx emissions. Moreover, the true impact on the displacement and design of the vessels needs to be established with further design activities. These activities also need to further investigate the impact of safety measures required due to the low flashpoint of methanol, a particularly acute challenge for any naval vessel.

These activities are expected to provide a feasible short-term solution for which the increase in CAPEX and OPEX is easily offset by the societal cost of CO_2 emissions.

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[4] Nitrous oxide is far more damaging to the environment than carbon dioxide.

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