Forecasted hydrogen demand from vessels required to serve floating offshore wind in the Celtic Sea.

GENERIC REPORT

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PREFACE

ORE Catapult is the UK's flagship technology innovation and research centre for offshore wind, wave and tidal energy. ORE Catapult is playing a leading role in the delivery of the offshore wind sector deal (partnership between UK Government and offshore wind industry), including the Offshore Wind Growth Partnership, focused on enhancing the competitiveness of UK supply chain companies for supplying into the domestic and export markets. ORE Catapult has developed and actively maintains technology roadmaps to co-ordinate R&D funding and activity across agreed industry priorities. This provides ORE Catapult with a unique broad and objective perspective on the UK and global offshore wind industry.

We are an independent, not-for-profit business that exists to accelerate the development of offshore wind, wave and tidal technologies. Our team of over 300 people has extensive technical and research capabilities, industry experience and track record.

Through our world-class testing and research programmes, we work for industry, academia and government to improve technology reliability and enhance knowledge, directly impacting upon the cost of offshore renewable energy. We organise our activities around key areas for future innovation and developing local Centres of Excellence that will support the transformation of our coastal communities. These areas include:

- Floating wind
- Marine energy
- Testing and demonstration
- Operations and maintenance

These Centres of Excellence champion innovation in robotics, autonomous systems, big data and artificial intelligence, balance of plant – especially foundations – and next-generation technologies.

To date, we have supported more than 800 SMEs, contributed to 328 active and completed research projects, and supported over 180 companies in their product development.

CONTENTS

NOMENCLATURE

FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
ORE	Offshore Renewable Energy
O&M	Operations and Maintenance
PoMH	Port of Milford Haven

1 INTRODUCTION TO HYPR: HYDROGEN PORT RE-FUELLING PROJECT

As Wales seeks to de-carbonise and meet future green energy targets, the Welsh Government have supported the assessment of technologies which could support the objectives of the Welsh Hydrogen Pathway Report. The HyPR project seeks to explore the utilisation of hydrogen as a marine fuel for powering the Floating Offshore Wind (FOW) vessel fleet in the Celtic Sea in the short, medium and long term. The Offshore Renewable Energy (ORE) Catapult's involvement in the project looks to identify the vessel types and quantities required for servicing FOW in the Celtic Sea with a view to estimating the capacity of a hydrogen facility required at the Port of Milford Haven (PoMH) to service the FOW vessel fleet.

This report outlines work carried out to estimate the hydrogen required for different fuel adoption scenarios to service the predicted future Celtic Sea FOW vessel fleet. Hydrogen demand estimations were made in the short (up to 2030), medium (2030 - 2040) and long term (2040 - 2050) future using a unit energy conversion method which is presented in Section 4. The vessel types and numbers estimated to make up the Celtic Sea FOW fleet were presented in the HyPR Work Package 2 report [1], a summary of which is shown in Table 1.

Table 1: Estimated vessel years required per vessel type used in 5-year periods

Period	**Total Vessel Years Required for Estimated FOWT Unit Deployment Numbers**													
	Survey Vessel	Semi-submersible	Heavy Lift Cargo Vessel	ODC	Coaster	CLV	OCV <200t crane capacity	OCV 200-400t crane capacity	OCV >400t crane capacity	AHTS bollard pull <200t	AHTS bollard pull >200t	Tug	SOV	CTV (from mother SOV)
Up to 2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2026 – 2030	2.14	0.55	1.50	0.95	0.95	1.11	1.66	1.19	0.55	2.06	1.98	0.87	2.14	0.40
2031 – 2035	8.90	2.29	6.21	3.92	3.92	4.57	7.18	4.90	2.29	8.65	8.49	3.75	10.09	2.03
2036 – 2040	10.47	2.61	7.08	4.47	4.47	5.22	9.45	5.59	2.61	10.50	10.94	4.91	16.56	3.89
2041 – 2045	13.72	3.35	9.10	5.75	5.75	6.71	13.18	7.19	3.35	14.02	15.09	6.83	25.40	6.29
2046 - 2050	18.24	4.40	11.95	7.55	7.55	8.81	18.24	9.44	4.40	18.87	20.76	9.43	37.11	9.43
Totals	**53.47**	**13.21**	**35.85**	**22.64**	**22.64**	**26.42**	**49.71**	**28.30**	**13.21**	**54.10**	**57.26**	**25.80**	**91.29**	**22.04**

2 INTRODUCTION TO THE PORT OF MILFORD HAVEN

The UK's largest energy port

The Port of Milford Haven is the UK's largest energy port, delivering around 30% of the annual UK gas demand. A deep-water port with the ability to handle vessels with up to 22m drafts, the Port of Milford Haven is a leading UK shipping gateway handling liquid, bulk, break bulk and heavy lift cargoes, with high-capacity gas and oil pipelines and electricity connections to the centre of the UK. Sited on the Milford Haven Waterway, the Port currently serves Valero Refinery and Valero Pembrokeshire Oil Terminal, Puma Energy, South Hook LNG and Dragon LNG, and is home to Europe's largest gas-fired power station, Pembroke Power Station, built by RWE nPower. The Port's operational interests include Pembroke Port, Milford Marina, Milford Fish Docks, Haven's Head Retail Park and Pembroke Dock Ferry Terminal. It also has a diverse commercial property portfolio covering light and heavy industrial units, office and retail spaces and warehousing.

Over the last decade the Milford Haven Waterway has attracted new innovative collaborations and green technologies including wave, tidal and floating wind. The port delivers proximity to natural energy sources, access to a high-skill energy and engineering supply chain developed around the established energy sector, and the existing energy infrastructure. Projects such as the £60m Swansea Bay City Deal funded Pembroke Dock Marine[1] project are helping ensure the region's facilities are suited to this fast-paced sector. The Port is transforming to maximise the opportunity. 17,000sqm of laydown space is being created, as is a new enlarged slipway, new workboat pontoons, and new offices and workshop spaces. These facilities are an important first step in meeting changing industrial demand and help developers maximise operational efficiency and reduce associated development and operations costs. It is anticipated that all current works will be complete by the end of 2023.

Hydrogen is a high potential next step for the Port, supporting of the potential of Floating Offshore Wind to decarbonise existing industry in the region. Over the last 18 months, existing major energy companies such as RWE, Valero, PUMA and Dragon LNG have helped the Port deliver the transformative, 30 year Haven Waterway energy vision with Hydrogen showcased as the "missing link" to deliver Net Zero. Building on this, the Celtic Freeport will accelerate the delivery of Wales' net zero ambition with the Haven a major UK Hydrogen generation, use and innovation hub with the ambition of delivering 20% of the UK Government's low carbon hydrogen production by 2030.

Future Energy Vision

Projects such as Milford Haven: Energy Kingdom have played important foundational roles in increasing regional expertise. This project was a partnership between Pembrokeshire County Council, ORE Catapult, Wales and West Utilities and Riversimple, supported by Arup and the Energy Systems Catapult. The project investigated and reported on the opportunity for a renewables and hydrogen based future for the Haven Waterway and the implications for this on the supply of clean electricity

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[1] Pembroke Dock Marine is a partnership project between the Port of Milford Haven, Offshore Renewable Energy Catapult, Marine Energy Wales, and Celtic Sea Power. It will create a world class centre of marine energy and excellence centred around the Milford Haven Waterway. It is funded by UK Government, the Welsh Government, and the public and private sectors. It is also part funded by the European Regional Development Fund through the Welsh Government.

and fuel for the region. Useful demonstrators were also undertaken including the installation of a hydrogen electrolyser and refueller paired with two prototype Riversimple hydrogen fuel cell electric cars. The Port also designed, installed and tested a world-first smart hydrogen hybrid heating system and the first hydrogen boiler to be retrofitted into a commercial building. HyPR is a complementary deep dive to explore how the demand for clean fuels will increase alongside the development of the floating wind industry, and the range of vessels it will utilise from pre-construction, through construction, operations and maintenance. The Port is positioning itself to be a clean energy hub and to ensure it is able to serve this market as the need arises.

The Port of Milford Haven is collaborating actively with industry, regulators and governments to find the right solutions and ensure the Milford Haven Waterway is at the forefront of the clean energy drive.

3 FUEL & DRIVETRAIN USAGE

3.1 Fuel Types

Currently, the majority of vessels used for offshore wind activities use crude oil distillates, such as Marine Gas Oil, as their fuel source along with internal combustion engines to power the ship propulsion systems. However, alternate fuels are expected to be increasingly deployed as the FOW vessel industry seeks to decarbonise. Many of these fuels can be synthesised from hydrogen, and to ensure they are net zero would require a source of green hydrogen, such as FOW. Key future fuel types, some of which are currently utilised, are listed below.

3.1.1 Baseline Fuels

Marine Gas Oil

Marine Gas Oil (MGO) is a type of diesel, composed of a variety of distillates from crude oil. It is different to the diesel that is used on land in cars but is combusted in a similar way through the use of a compression ignition internal combustion engine. Unless created as an e-fuel, i.e. by combining hydrogen and CO2 from carbon capture, this is not a net zero fuel.

Marine Fuel Oil / Heavy Fuel Oil / Residual Marine Fuel Oil

Marine Fuel Oil (MFO), Heavy Fuel Oil (HFO) and Residual Marine Fuel Oil (RM) are the heavy yields from the refining process of crude oil and are considered low-quality fuels. These fuel types have high emissions associated with them, producing large amounts of smoke when burned. As with MGO, these fuels are not net zero unless produced via a carbon negative process.

3.1.2 Immediate Alternatives

Biodiesel

The most common form of biofuel, biodiesel is produced from biomass and biomass residues that are converted to liquid or gas for fuel. Biodiesel is used in internal combustion engines to power vessels and can be used in standard diesel engines with no changes to the engine necessary. Although biofuels can theoretically be carbon neutral, there are some concerns as to the environmental effects of scaling up biofuel production.

3.1.3 Near to Market Changes

Methanol

Methanol contains the highest amount of hydrogen and lowest amount of carbon of any fuel that can be carried as a liquid without compression or cooling. It is currently predominantly produced using fossil fuels as this is the lowest cost method of producing it, but can be produced using sustainable methods. It has lower emissions compared to diesel and produces less smoke. Methanol can be burned to produce power in typical internal combustion engines or run through fuel cells to power electric motors.

Liquid Natural Gas (LNG)

LNG for use in vessel engines is similar in chemical composition to that used in industrial power generation and domestic heating. Comprised predominantly of methane, LNG is collected from gas wells and cooled to assume a liquid state. It produces less carbon when burned than MGO or MFO and is used in gas turbines onboard typically larger vessel types.

3.1.4 Zero Carbon Fuels

Ammonia

Ammonia, with the chemical formula NH3, contains no carbon atoms and therefore emits no CO2 during combustion. Taking a liquid form at temperatures below -33C, it does not have to be stored in cryogenic tanks or at high pressure. There are however, challenges related to Ammonia toxicity and it’s potential impact on crew and environment in the event of a release. Ammonia has roughly half the energy density of MGO and is more difficult to burn, requiring specialised engines. It can be synthesised from hydrogen and nitrogen using the Haber-Bosch process.

Hydrogen

Hydrogen, although predominantly currently produced using steam methane reforming, can also be produced through the electrolysis of water. It is a colourless, odourless and non-toxic gas that can be transformed into a liquid at extremely low temperatures. As a fuel for vessels, it can be used in different ways, for example:

- Used in a hydrogen fuel cell to produce electricity to power electric motors.
- Used in an Internal Combustion Engine (though currently requiring the addition of some diesel as a pilot fuel.

Hydrogen contains three times more energy per unit mass compared to diesel, however is challenging to store as its unit energy per volume is significantly higher than that of other typical vessel fuels. For this reason, cryogenic liquid hydrogen, which has a better volumetric density, is typically being investigated for larger vessels.

Electricity

Electricity can be used to directly power electric vessel drivetrains, being stored in battery form on board the vessel. However, the mass of batteries required to store sufficient electrical energy for vessels for extended periods is challenging, making batteries alone unlikely to be adopted for vessels travelling large distances unless offshore or infield charging becomes available.

3.2 Energy Content of Fuels

To convert quantities of fuels currently utilised by FOW vessels into calorific equivalent quantities of alternative fuels, the energy content of each fuel type must be known. Table 2 presents the energy content per kilogram of each fuel type mentioned [2] including an equivalent lithium-ion battery value [3].

Table 2: Energy content for different fuel types [2], [3] .

Fuel	Specific Energy (MJ/kg)	Energy Content (kWh/kg) @ Lower Heating Value
Ammonia	22.50	6.25
Hydrogen	119.88	33.30
Methanol	19.94	5.54
LNG	48.60	13.50
Biodiesel	37.80	10.50
Electricity (battery stored Li-ion)	0.90	0.25
Marine Gas Oil (MGO)	42.80	11.89
Heavy Fuel Oil (HFO)	38.99	10.83

3.3 Current Fuel Utilisation

Until 2020, larger vessels typically utilised HFO whilst smaller vessels used distillate fuels, such as MGO. However, with the introduction of new shipping regulations in 2020, lowering the maximum allowable sulphur content of fuels utilised by all vessels from 3.5% to 0.5%, vessel operators have had to switch to utilising MGO and Ultra-Low Sulphur Fuel Oil (ULSFO) [4]. With fuel types utilised by vessel varying for different vessels of the same category, as a simplification to aid the analysis procedure in this report, it was assumed that all FOW vessels considered utilise MGO as their fuel type. This approach is thought to be accurate and is unlikely to significantly change the final conclusions drawn.

3.4 Powertrain Types

The fuel types discussed can be utilised with different types of powertrain to power vessels. Each combination of fuel and powertrain produces a typical powertrain efficiency, affecting the volume of fuel required to propel a vessel by a unit distance using each fuel type. The fuel and powertrain type, along with their powertrain efficiency are presented in Table 3 ([5], [6]). The powertrain efficiency values presented are indicative of a typical powertrain of each type.

Table 3: Vessel powertrain types and compatible fuels ([5], [6])

Powertrain Type	Typical Powertrain Efficiency	Fuel Type
Internal Combustion Engine (ICE) with Mechanical Propulsion	40%	Ammonia
		Biodiesel
		LNG
		Methanol
		MGO
		MGO & Hydrogen
Generator with Electric Propulsion	50%	Ammonia
		Biodiesel
		LNG
		Methanol
		MGO
Generator with Electric Propulsion & Battery[2]	90%	Ammonia & Electric
		Biodiesel & Electric
		LNG & Electric
		Methanol & Electric
Fuel Cell (PEMFC) & Battery	62%	Ammonia
		Hydrogen
Battery with Electrical Propulsion	98%	Electric

3.5 Selection of Fuel/Powertrain Combination for Calculation

From the list of fuel and powertrain combinations, four were selected for analysis in this report. Each choice is shown below with justification for their selection discussed. Some fuel and powertrain combinations from the list in Table 3 are more likely to be adopted by the FOW vessel fleet than others for various reasons. Based on current evidence of market support the longlist was down selected to the ’future-fuels’ deemed most likely to be utilised at the PoMH in the short to medium

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[2] Primary energy source assumed to be from batteries with existing charge prior to operations.

term future and ensure the results presented are as clear as possible to inform further work in sizing a hydrogen facility at the PoMH.

- Ammonia with ICE – when synthesised using green hydrogen, ammonia has no associated carbon emissions as no carbon is released in its combustion. A relatively high energy density, along with it not needing to be cooled to extreme temperatures to achieve a liquid state makes ammonia a good possibility for future adoption in FOW vessels.
- Hydrogen with fuel cell and battery – losses are introduced when using hydrogen to produce other fuels. Direct use of the green hydrogen produced at the PoMH, rather than using it to produce other fuels, represents the option with least associated losses. Along with the high powertrain efficiency of a hydrogen fuel cell, use of hydrogen as a fuel in this setup is a highly efficient energy use. However, with the complexities of storing hydrogen, along with its low volumetric energy density, hydrogen will present a challenge to be utilised in larger vessels unless converted to liquid.
- Methanol with ICE – with the capability of current diesel engines to run on methanol with only minor modifications, the introduction of this fuel would cause little disruption to current vessels, making it a highly attractive option from a practical standpoint. Furthermore, with its high energy density and ability to be produced using hydrogen and captured carbon, methanol has strong potential for adoption as a future maritime fuel. As a result, Ørsted, RWE and others have ordered renewable powered e-methanol ICE vessels to support offshore operations at their wind farms [7].
- Hydrogen and MGO mix with ICE – some current vessels, such as the Hydrocat 48 CTV utilise a mix of hydrogen and MGO in a standard diesel engine [8]. This combination reduces the MGO fuel usage by up to 80%, whilst allowing the vessel to maximise its availability by allowing it to fall back on using 100% MGO if hydrogen is unavailable. With the huge task of decarbonising vessels in the FOW and wider maritime sector and the challenges associated with introducing new fuels, this fuel combination approach is likely to gain traction whilst minimising risk for vessel operators.

4 FUEL CONSUMPTION CALCULATION METHODOLOGY

For each of the vessel types a reference vessel was identified to provide the installed power, Table 4. The power demand was then calculated using operational window estimates available internally at ORE Catapult.

Table 4: Vessel Installed Power

Vessel	Installed Power (kW)
Survey Vessel [9]	12960
Cable Laying Vessel [10]	12330
AHTS Bollard Pull <200t [11]	8702
AHTS Bollard Pull >200t [12]	12000
Tug Boat [13]	1656
OCV <200t Crane Capacity [14]	15824
OCV 200-400t Crane Capacity [15]	16680
OCV >400t Crane Capacity[3]	26170
Heavy Lift Cargo Vessel [16]	35660
Semi-Submersible [17], [18]	21360
Open Deck Carrier [19]	5976
Coaster [20]	1725
SOV [21]	10674
CTV [22]	2734

The vessel years required, shown in Table 1, Section 1, were used to estimate the proportion of a year that each vessel would be operating.

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[3] Figures were estimated by interpolating reference data for the OCV 200-400t Crane Capacity and Heavy Lift Cargo Vessels

4.1 Power Requirements for Vessels at Different Operating Modes

The operational power requirements for a reference SOV were available internally within ORE Catapult with the totals shown in Table 5. These were made up of a range of power draw sources including:

- Navigation and safety systems
- Auxiliary and main engine services
- Walk to work gangway and offshore deck crane
- Ventilation
- Galley, refrigeration and laundry
- Lighting and sockets
- Entertainment

The percentage of installed power required for each operational mode was calculated. Given these were known power requirements, these percentages were applied across the other vessels to give an estimate of their power requirements for each mode of operation (Table 6). The assumption has been made that operation of the walk to work gangway and offshore deck crane operations on the SOV are equivalent to the operation of specialist equipment on the other vessels, for example the operation of the jacks and offshore cranes on an offshore construction vessel.

Table 5: Reference SOV Operational Power Requirements

Category	Harbour Mode	At Anchor	Maneuvering	Transit 10 Knots	Standby Offshore	DP W2W Operations (Diesel)	DP W2W Operations (ESS)
	(kW)						
Total Loads	564	800	1561	1961	837	4263	4184
% of installed SOV Power	5%	7%	15%	18%	8%	40%	39%

Table 6: Estimated Vessel Power Requirements

Vessel	Required Power at Each Operational State (kW)						
	Harbour Mode	At Anchor	Manoeuvring	Transit 10 Knots	Standby Offshore	DP W2W Operations (Diesel)	DP W2W Operations (ESS)
Survey Vessel	685	971	1895	2381	1016	5176	5080
Cable Laying Vessel	652	924	1803	2265	967	4924	4833
AHTS Bollard Pull <200t	460	652	1273	1599	682	3475	3411
AHTS Bollard Pull >200t	634	899	1755	2205	941	4793	4704
Tug Boat	88	124	242	304	130	661	649
OCV <200t Crane Capacity	836	1186	2314	2907	1241	6320	6203
OCV 200-400t Crane Capacity	881	1250	2439	3064	1308	6662	6538
OCV >400t Crane Capacity	1383	1961	3827	4808	2052	10452	10258
Heavy Lift Cargo Vessel	1884	2673	5215	6551	2796	14242	13978
Semi-Submersible	1129	1601	3124	3924	1675	8531	8373
Open Deck Carrier	316	448	874	1098	469	2387	2342
Coaster	91	129	252	317	135	689	676
SOV	564	800	1561	1961	837	4263	4184
CTV	144	205	400	502	214	1092	1072

4.2 Time Spent in Each Operational Mode

As with the required power for operational modes above, information regarding each vessel type was not readily available. As such the reference SOV’s operational profile was utilised across all vessels given this was a known profile. It was noted this would not give a true representation of the fuel burn profiles for each vessel; however, this was deemed a more reliable approach than estimation as it was traceable to a reference source.

The operational profile for the reference SOV was given over a 14-day period and is shown in Table 7.

Table 7.

Table 7: Reference SOV 14 Day Operational Profile

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Port Call	12	-	-	-	-	-	-	-	-	-	-	-	-	3	15
Transit (10Knots)	6	-	-	-	-	-	-	-	-	-	-	-	-	6	12
W2W DP Operations	-	4	4	4	4	4	4	4	4	4	4	4	4	3.4	51
Inter-field Transits	-	4	4	4	4	4	4	4	4	4	4	4	4	3.4	51
Standby	-	6	6	6	6	6	6	6	6	6	6	6	6	4	76
At Anchor or Moored	6	10	10	10	10	10	10	10	10	10	10	10	10	4	130
Total Hrs.	24	24	24	24	24	24	24	24	24	24	24	24	24	24	336

4.3 Calculation of kWh for Each Vessel

Knowing the power consumption of each vessel across a range of different operating states and the time spent at each state over a 14-day period, the energy required for each vessel over that period was calculated using Equation 1.

$$\begin{aligned}&Total\ Energy\ Required\ per\ Vessel\ Year\\&\quad = \sum (Time\ Spent\ at\ Operational\ Mode * Installed\ Power\\&\quad * \%\ of\ installed\ power\ required\ in\ operational\ mode)\end{aligned}$$

Equation 1: Calculation of kWh per Vessel Year

This was then multiplied out to give the total energy consumption (at output) of each vessel per vessel year ,Table 8.

Table 8: Total Energy Consumption per Vessel year per Vessel

Vessel	Total Energy per Vessel Year (kWh)
Survey Vessel	22,475,446
Cable Laying Vessel	21,382,890
AHTS Bollard Pull <200t	15,091,152
AHTS Bollard Pull >200t	20,810,598
Tug Boat	2,871,863
OCV <200t Crane Capacity	27,442,242
OCV 200-400t Crane Capacity	28,926,732
OCV >400t Crane Capacity	45,384,446
Heavy Lift Cargo Vessel	61,842,161
Semi-Submersible	37,042,865
Open Deck Carrier	10,363,678
Coaster	2,991,523
SOV	18,511,027
CTV	4,741,348

4.4 Calculation of Fuel Consumption

The mass of fuel required for each of the powertrain options was calculated using Equation 2.

$$Fuel\ Mass = \frac{\frac{Total\ Energy\ Required\ per\ Vessel\ Year}{Powertrain\ efficieny}}{Fuel\ Specific\ Energy} * Vessel\ Years$$

Equation 2: Fuel Mass Required per Vessel per Deployment Period

For the Mechanical (ICE) with H2 mix powertrain, there is an up to 80% reduction in MGO usage. The power output is supplemented by the hydrogen which is injected into the system. As such, the mass of hydrogen required must offset the lost energy potential of the MGO. This was calculated using Equation 3.

$$Supplementary\ H2\ Mass = \frac{MGO\ Specific\ Energy}{H2\ Specific\ Energy} * 0.8 * Standard\ MGO\ Fuel\ Mass$$

Equation 3: Supplementary H2 Mass Required in MGO, H2 mix Powertrain

Error! Reference source not found. shows the fuel requirements as calculated for the reference SOV. The remaining vessels are presented in Appendix 1 .

Table 9: SOV Fuel Requirements

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement					
					Up to 2025 (kg)	2026-2030 (kg)	2031-2035 (kg)	2036-2040 (kg)	2041-2045 (kg)	2046-2050 (kg)
SOV	Marine Gas Oil	Mechanical (ICE)	40%	3,892,142	0	8,329,184	34,640,063	40,750,726	53,400,188	70,992,669
	Ammonia	Mechanical (ICE)	40%	7,404,411	0	15,845,439	65,899,257	77,524,182	101,588,517	135,056,454
	Methanol	Mechanical (ICE)	40%	8,353,352	0	17,876,172	74,344,829	87,459,591	114,607,984	152,365,133
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	900,221	0	1,926,474	8,011,970	9,425,318	12,351,037	16,420,038
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	778,428	0	1,665,837	6,928,013	8,150,145	10,680,038	14,198,534
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,111,773	0	2,379,195	9,894,783	11,640,268	15,253,531	20,278,747

4.5 Greenhouse Gas Emissions Avoided

Based on the required masses of fuels calculated, calculations were performed to quantify the greenhouse gas emissions that could be offset by the use of these fuels in the Celtic Sea FOW fleet in place of the currently used diesel fuels.

Of the fuel types considered, various assumptions were made as to how the fuels would be produced. These assumptions directly affect the emissions associated with each fuel.

- Ammonia – produced using green hydrogen and renewable electricity. Storage infrastructure powered using renewable electricity. Zero carbon fuel as a result.
- Methanol - produced using green hydrogen and air carbon capture powered by green electricity. As a result, net zero emissions are achieved carbon is captured from the atmosphere at the same rate as is emitted during combustion.
- Hydrogen – produced using electrolysis, powered by renewable electricity. Storage infrastructure is powered using renewable electricity.
- MGO – production emissions were not considered due to lack of available data. Combustion emissions were considered only.

Current production of ammonia, methanol and hydrogen generally utilises fossil fuel based energy sources as they provide the lowest cost method of production. However, it is anticipated that in future these methods will be gradually replaced by green methods, utilising renewable electricity as it becomes more abundant and costs reduce. Thus, the greenhouse gas emission calculations performed assumed the use of green energy sources in the production and use of the alternative fuels as the resulting estimates will likely prove more suitable in an increasingly green economy. This scenario is deemed plausible given that fuelling of FOW support vessels will be taking place in areas experiencing a significant growth in the renewable power supply needed to synthesize these fuels.

With the assumptions discussed applied, in order to calculate the carbon emission offset that could be achieved by adopting the alternative fuels, the carbon emissions of powering the Celtic Sea FOW using MGO was calculated. The universally used unit of greenhouse gas emissions is the carbon dioxide equivalent (CO_2e). This unit accounts for carbon dioxide, along with other greenhouse gases converted to the equivalent amount of carbon dioxide to achieve the same greenhouse effect. This unit, supplied as CO_2e per kilogram of fuel, was multiplied by the mass of MGO calculated to service the Celtic Sea FOW vessel fleet to produce an overall value of CO_2e for each time period. The results of these calculations are shown in Table 10. A CO_2e per kilogram value of 3.25 was used in the calculations [23].

Table 10 Carbon dioxide equivalent emissions from the use of MGO for the Celtic Sea FOW vessel fleet by time period

Fuel	CO_2e emissions up to 2025 (tonnes)	CO_2e emissions 2026-2030 (tonnes)	CO_2e emissions 2031-2035 (tonnes)	CO_2e emissions 2036-2040 (tonnes)	CO_2e emissions 2041-2045 (tonnes)	CO_2e emissions 2046-2050 (tonnes)
MGO	0	467,776	1,945,425	2,288,607	2,999,015	3,987,029

Evidently, with utilising green fuels to power the Celtic Sea FOW vessel fleet, there is an opportunity to offset an enormous mass of greenhouse gases, as shown by the emission forecast from the continued use of MGO. For context, the combined mass of CO_2e for Celtic Sea FOW vessels up to 2050 is predicted to be greater than that of the entire UK construction industry in 2021 [24].

4.6 Considerations

4.6.1 Fleet Proportion Serviced by PoMH

This report presents estimations of hydrogen quantities required to service the entire fleet of FOW vessels likely to be deployed in the Celtic Sea for different fuel usage scenarios. In the short term, it is likely that the PoMH will service a large proportion of the overall vessel fleet due to its size and capability as a port. However, in the medium and long-term future, it is likely that the FOW vessel fleet will require the use of other Celtic Sea ports for fuelling services due to the size of the fleet and demand that that will impose on fuel and docking space provision. It is unknown what proportion of the overall fleet will utilise the PoMH for fuel supply as the development of port infrastructure, amongst many other factors, will play a large part in influencing this. Due to this uncertainty, the proportion of the vessel fleet that will use the PoMH was not considered in the calculations. The results presented only estimate the overall fuel demand of the entire FOW vessel fleet.

4.6.2 Seasonality

Seasonality will likely have a considerable influence on peak fuel demand seen at the PoMH from FOW vessels. Many offshore operations require calm seas and favourable weather which is far more common in summer months in the UK than in the winter. As a result, FOW vessel activities will be at their most numerous and intensive over the summer period and at their fewest in the winter, resulting in a peak fuel demand in the summer and less demand in the winter. The estimates presented in this report consider average fuel demand across 5-year periods neglecting to include estimates of the effects of seasonality on fuel demand due to complexity and scope considerations.

4.6.3 Offshore Wind Farm Hydrogen Production

In the upcoming Celtic Sea FOW leasing round, the Crown Estate intends to include offshore hydrogen production and offtake in the Technical Design Envelope for the leasing sites [25]. If developers pursue offshore or onshore hydrogen production in their bids, a sizeable amount of hydrogen could be available in the Celtic Sea region directly from the FOW farms installed. This should be considered by the PoMH as access to this supply of hydrogen could augment a production facility built in the port.

5 CONCLUSION - FOW VESSEL HYDROGEN DEMAND

Table 11 below shows the hydrogen demand in the short (up to 2030), medium (2030 – 2040) and long (2040 – 2050) term taken from the mass of fuel required for each vessel type over these time periods. The values presented are for all vessels across the fleet, assuming they are operating and fuelled out of PoMH.

It is possible to synthesise ammonia and methanol using hydrogen. In order to produce one tonne of each, 177kg [26] and 200kg [27] of hydrogen are required respectively. As such, the values presented within Table 10 refer to the mass of hydrogen required to produce these fuels, not the total mass of fuel required.

Table 11: Hydrogen demand for proposed fuel types in the short, medium and long term

Fuel	Powertrain Type	Total Mass of H2 Required for Short Term (Up to 2030) (kg)	Total Mass of H2 Required for Medium Term (2030 - 2040) (kg)	Total Mass of H2 Required for Long Term (2040 - 2050) (kg)
Ammonia	Mechanical (ICE)	48,465,000	438,679,000	723,810,000
Methanol	Mechanical (ICE)	61,781,000	559,209,000	922,681,000
Hydrogen (liquid)	Fuel Cell (PEM) and Battery	33,290,000	301,323,000	497,176,000
Hydrogen (liquid)	Mechanical (ICE) with MGO/H2 mix	41,113,000	372,134,000	596,864,000

The results presented above will feed into further work on the HyPR project. This work will look to estimate the size of a hydrogen-based fuel production facility required to service the FOW fleet in the Celtic Sea.

It should be noted that as the FOW vessel fleet adopts alternative fuels, it is expected that different fuels and drivetrain combinations will be adopted by different vessel types, resulting in a varied fuel demand. For example, the O&M fleet may be made up of battery electric CTVs and methanol SOVs due to the different operational requirements of these vessel types, resulting in a reduced hydrogen demand when compared with a purely methanol fuelled CTV and SOV fleet. However, due to the current lack of visibility as to the fuel and drivetrain combinations that will be adopted in the short, medium and long term for FOW vessels, no analysis was carried out looking at scenarios where multiple fuel types were adopted across the fleet. The data presented offers insight into the broad scale of hydrogen quantities that would likely be required for some key fuel and drivetrain combinations, and can be used to compare the relative effect on hydrogen quantities required by adoption of the different combinations. As the adoption of alternative fuels develops in the future, the methodology presented in this report should be re-visited with the fuel and drivetrains used applied to the calculations to provide more accurate overall estimates of hydrogen demand. It is anticipated that fuel and drivetrain selection will converge in the comping years as FOW demand increases and technologies converge.

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APPENDIX 1 VESSEL FUEL CONSUMPTION

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Survey Vessel	Marine Gas Oil	Mechanical (ICE)	40%	4,725,704	0	10,113,006	42,058,762	49,478,116	64,836,653	86,196,833
	Ammonia	Mechanical (ICE)	40%	8,990,178	0	19,238,982	80,012,588	94,127,168	123,345,248	163,980,855
	Methanol	Mechanical (ICE)	40%	10,142,349	0	21,704,628	90,266,909	106,190,397	139,153,033	184,996,452
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,093,018	0	2,339,058	9,727,856	11,443,893	14,996,200	19,936,640
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	945,141	0	2,022,601	8,411,752	9,895,623	12,967,331	17,239,367
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,349,877	0	2,888,736	12,013,902	14,133,208	18,520,308	24,621,750

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Cable Laying Vessel	Marine Gas Oil	Mechanical (ICE)	40%	4,495,982	0	9,621,401	40,014,239	47,072,930	61,684,871	82,006,709
	Ammonia	Mechanical (ICE)	40%	8,553,156	0	18,303,754	76,123,087	89,551,542	117,349,299	156,009,563
	Methanol	Mechanical (ICE)	40%	9,649,318	0	20,649,541	85,878,934	101,028,364	132,388,649	176,003,569
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,039,885	0	2,225,353	9,254,974	10,887,593	14,267,218	18,967,497
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	899,196	0	1,924,280	8,002,848	9,414,586	12,336,974	16,401,342
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,284,258	0	2,748,311	11,429,893	13,446,177	17,620,015	23,424,859

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
AHTS Bollard Pull <200t	Marine Gas Oil	Mechanical (ICE)	40%	3,173,077	0	6,790,384	28,240,381	33,222,112	43,534,611	57,876,917
	Ammonia	Mechanical (ICE)	40%	6,036,461	0	12,918,026	53,724,502	63,201,745	82,820,243	110,105,046
	Methanol	Mechanical (ICE)	40%	6,810,087	0	14,573,586	60,609,772	71,301,608	93,434,390	124,215,982
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	733,907	0	1,570,562	6,531,775	7,684,009	10,069,208	13,386,469
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	634,615	0	1,358,077	5,648,076	6,644,422	8,706,922	11,575,383
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	906,376	0	1,939,644	8,066,742	9,489,752	12,435,472	16,532,289

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
AHTS Bollard Pull >200t	Marine Gas Oil	Mechanical (ICE)	40%	4,375,651	0	9,363,894	38,943,298	45,813,071	60,033,938	79,811,882
	Ammonia	Mechanical (ICE)	40%	8,324,239	0	17,813,872	74,085,730	87,154,785	114,208,563	151,834,125
	Methanol	Mechanical (ICE)	40%	9,391,064	0	20,096,877	83,580,471	98,324,442	128,845,401	171,293,011
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,012,053	0	2,165,794	9,007,274	10,596,198	13,885,371	18,459,852
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	875,130	0	1,872,779	7,788,660	9,162,614	12,006,788	15,962,376
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,249,886	0	2,674,756	11,123,983	13,086,304	17,148,433	22,797,917

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Tug Boat	Marine Gas Oil	Mechanical (ICE)	40%	603,840	0	1,292,217	5,374,175	6,322,204	8,284,683	11,014,040
	Ammonia	Mechanical (ICE)	40%	1,148,745	0	2,458,314	10,223,831	12,027,360	15,760,782	20,953,109
	Methanol	Mechanical (ICE)	40%	1,295,967	0	2,773,369	11,534,105	13,568,773	17,780,665	23,638,435
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	139,663	0	298,880	1,243,004	1,462,275	1,916,181	2,547,460
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	120,768	0	258,443	1,074,835	1,264,441	1,656,937	2,202,808
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	172,484	0	369,116	1,535,110	1,805,910	2,366,484	3,146,112

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
OCV <200t Crane Capacity	Marine Gas Oil	Mechanical (ICE)	40%	5,770,026	0	12,347,855	51,353,229	60,412,169	79,164,753	105,245,269
	Ammonia	Mechanical (ICE)	40%	10,976,897	0	23,490,559	97,694,382	114,928,110	150,603,025	200,218,599
	Methanol	Mechanical (ICE)	40%	12,383,683	0	26,501,082	110,214,781	129,657,164	169,904,135	225,878,384
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,334,561	0	2,855,960	11,877,592	13,972,853	18,310,176	24,342,391
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	1,154,005	0	2,469,571	10,270,646	12,082,434	15,832,951	21,049,054
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,648,183	0	3,527,111	14,668,826	17,256,473	22,613,067	30,062,853

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
OCV 200-400t Crane Capacity	Marine Gas Oil	Mechanical (ICE)	40%	6,082,156	0	13,015,813	54,131,184	63,680,168	83,447,173	110,938,516
	Ammonia	Mechanical (ICE)	40%	11,570,693	0	24,761,282	102,979,164	121,145,152	158,749,903	211,049,434
	Methanol	Mechanical (ICE)	40%	13,053,579	0	27,934,660	116,176,855	136,670,975	179,095,107	238,097,285
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,406,754	0	3,010,454	12,520,111	14,728,715	19,300,665	25,659,194
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	1,216,431	0	2,603,163	10,826,237	12,736,034	16,689,435	22,187,703
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,737,341	0	3,717,910	15,462,337	18,189,963	23,836,322	31,689,104

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
OCV >400t Crane Capacity	Marine Gas Oil	Mechanical (ICE)	40%	9,542,567	0	20,421,092	84,928,842	99,910,671	130,924,013	174,056,413
	Ammonia	Mechanical (ICE)	40%	18,153,779	0	38,849,086	161,568,629	190,070,061	249,069,842	331,124,921
	Methanol	Mechanical (ICE)	40%	20,480,346	0	43,827,940	182,275,078	214,429,221	280,990,345	373,561,508
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	2,207,119	0	4,723,236	19,643,363	23,108,541	30,281,679	40,257,860
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	1,908,513	0	4,084,218	16,985,768	19,982,134	26,184,803	34,811,283
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	2,725,793	0	5,833,196	24,259,554	28,539,048	37,397,874	49,718,457

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Heavy Lift Cargo Vessel	Marine Gas Oil	Mechanical (ICE)	40%	13,002,978	0	27,826,372	115,726,500	136,141,175	178,400,852	237,174,310
	Ammonia	Mechanical (ICE)	40%	24,736,864	0	52,936,890	220,158,094	258,994,971	339,389,780	451,200,408
	Methanol	Mechanical (ICE)	40%	27,907,112	0	59,721,221	248,373,301	292,187,467	382,885,582	509,025,731
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	3,007,485	0	6,436,018	26,766,616	31,488,367	41,262,693	54,856,525
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	2,600,596	0	5,565,274	23,145,300	27,228,235	35,680,170	47,434,862
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	3,714,244	0	7,948,482	33,056,771	38,888,134	50,959,426	67,747,809

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Semi-Submersible	Marine Gas Oil	Mechanical (ICE)	40%	7,788,660	0	16,667,731	69,319,070	81,547,266	106,860,409	142,065,150
	Ammonia	Mechanical (ICE)	40%	14,817,146	0	31,708,692	131,872,599	155,135,518	203,291,242	270,264,742
	Methanol	Mechanical (ICE)	40%	16,716,094	0	35,772,442	148,773,239	175,017,507	229,344,813	304,901,559
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	1,801,455	0	3,855,113	16,032,948	18,861,232	24,715,960	32,858,536
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	1,557,732	0	3,333,546	13,863,814	16,309,453	21,372,082	28,413,030
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	2,224,797	0	4,761,065	19,800,691	23,293,621	30,524,211	40,580,292

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Open Deck Carrier	Marine Gas Oil	Mechanical (ICE)	40%	2,179,074	0	4,663,219	19,393,762	22,814,909	29,896,901	39,746,317
	Ammonia	Mechanical (ICE)	40%	4,145,471	0	8,871,308	36,894,693	43,403,083	56,875,864	75,613,394
	Methanol	Mechanical (ICE)	40%	4,676,750	0	10,008,245	41,623,075	48,965,572	64,165,010	85,303,919
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	504,003	0	1,078,565	4,485,622	5,276,906	6,914,915	9,193,006
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	435,815	0	932,644	3,878,752	4,562,982	5,979,380	7,949,263
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	622,443	0	1,332,028	5,539,744	6,516,979	8,539,920	11,353,362

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
Coaster	Marine Gas Oil	Mechanical (ICE)	40%	629,000	0	1,346,060	5,598,099	6,585,629	8,629,879	11,472,958
	Ammonia	Mechanical (ICE)	40%	1,196,609	0	2,560,744	10,649,824	12,528,500	16,417,481	21,826,155
	Methanol	Mechanical (ICE)	40%	1,349,965	0	2,888,926	12,014,693	14,134,139	18,521,526	24,623,370
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	145,483	0	311,333	1,294,796	1,523,203	1,996,022	2,653,604
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	125,800	0	269,212	1,119,620	1,317,126	1,725,976	2,294,592
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	179,671	0	384,496	1,599,073	1,881,156	2,465,087	3,277,201

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
SOV	Marine Gas Oil	Mechanical (ICE)	40%	3,892,142	0	8,329,184	34,640,063	40,750,726	53,400,188	70,992,669
	Ammonia	Mechanical (ICE)	40%	7,404,411	0	15,845,439	65,899,257	77,524,182	101,588,517	135,056,454
	Methanol	Mechanical (ICE)	40%	8,353,352	0	17,876,172	74,344,829	87,459,591	114,607,984	152,365,133
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	900,221	0	1,926,474	8,011,970	9,425,318	12,351,037	16,420,038
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	778,428	0	1,665,837	6,928,013	8,150,145	10,680,038	14,198,534
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	1,111,773	0	2,379,195	9,894,783	11,640,268	15,253,531	20,278,747

Vessel	Fuel	Powertrain Type	Power train Efficiency (%)	Mass of fuel required per vessel year (kg)	Fuel Requirement Up to 2025 (kg)	Fuel Requirement 2026-2030 (kg)	Fuel Requirement 2031-2035 (kg)	Fuel Requirement 2036-2040 (kg)	Fuel Requirement 2041-2045 (kg)	Fuel Requirement 2046-2050 (kg)
CTV	Marine Gas Oil	Mechanical (ICE)	40%	996,919	0	2,133,407	8,872,581	10,437,745	13,677,732	18,183,807
	Ammonia	Mechanical (ICE)	40%	1,896,539	0	4,058,594	16,879,199	19,856,765	26,020,518	34,592,875
	Methanol	Mechanical (ICE)	40%	2,139,597	0	4,578,739	19,042,417	22,401,585	29,355,277	39,026,258
	Hydrogen (liquid)	Fuel Cell (PEM) and Battery	62%	230,579	0	493,440	2,052,157	2,414,167	3,163,550	4,205,770
	Marine Gas Oil	Mechanical (ICE) with H2 mix	40%	199,384	0	426,681	1,774,516	2,087,549	2,735,546	3,636,761
	Hydrogen (liquid)	Mechanical (ICE) with H2 mix	40%	284,766	0	609,398	2,534,414	2,981,496	3,906,985	5,194,125

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