Net Zero Oceanographic Capability - Scoping Study

WP3: Future Ship Technologies

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In 2019, UKRI (NERC) commissioned the National Oceanography Centre to identify the options for developing a world-class oceanographic capability with a reduced carbon footprint by presenting a range of options for transitioning to low or zero carbon capabilities. 6 work packages were initiated to examine the science and policy drivers for a future research capability and the various technologies that could enable the capability. The findings of the 6 work packages and a number of independent reports commissioned under the NZOC banner were combined in the NZOC Summary Report that provides more information about the project.

This report covers the detailed findings of Work Package 3: Future Ship Technologies.

Executive Summary

Next Generation Research Ships: emerging & future technology in research ship design

This third work package (WP3) in the Net Zero Oceanographic Capability scoping project has considered emerging & future technology in research ship design for the Next Generation Research Ships. This is initially focussed on the 2035 timescale which coincides with a number of critical inflection points in the development of emerging technologies necessary to deliver the transformative change in the maritime operating environment to achieve the low to zero emission goals proposed by the Natural Environment Research Council (NERC). This time period is also pivotal for the adoption of autonomous technologies and their support infrastructures which can change the way UK marine science, survey and monitoring programmes can be organised and delivered in the coming decades.

The Next Generation Research Ship work package seeks to assess the emerging opportunities and challenges for a low to zero GHG emission oceanographic research ship infrastructure that aligns with the objective of becoming a net zero organisation by 2040. It looks to:

- Review the technology and infrastructure developments in emerging fuels, ship propulsion and power systems and research ship design to enable low to zero GHG emission operations.
- Assess the changing and developing science and technology landscape that will influence research ship design and more broadly fleet structure focussed on the timescale of the RRS James Cook replacement.
- Consider the options for science delivery in the context of a changing research fleet structure, and collaborative arrangements both within the UK and internationally.

This report does not provided original research, but is a study carried out using publically available information. In the project timescale only a limited section of the vast amount of information publicly available relating to emerging fuel and energy options for the commercial shipping sector, future generation research ship design and developments in research ship equipment was reviewed. The report has identified clear emerging themes on the direction and viability of emerging fuel and energy sources, their barriers for market entry and the constraints to adoption by research ships. The report's intent is to provide an overview of the emerging landscape and technology opportunities potentially available for marine science delivery, and to identify the core areas which will need to be further investigated as technology and support infrastructure develops over the next one and two decades.

The report comprises three main sections;

N Operational energy technology options for reduced carbon/GHG emissions from research ships
N Capability demand & utilisation; current to 2035 replacement ship
N Options for collaboration and consolidation

The section on ***energy technology options for reduced Carbon/GHG emissions*** primarily considers low to zero carbon and Green House gas (GHG) emissions *at operation* (Scope1[1]), but reference is

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[1] As defined by *Greenhouse Gas Protocol* – **Scope 1** defined as emissions from activities of an organisation or from that under their control. **Scope 2** is defined as indirect emissions from supplied electricity and its

made to the broader issue of emissions due to fuel production and other indirect activities (Scope2, Scope3). Any detailed evaluation of Scope2 and 3 emissions would form part of follow-up studies.
The chapter reviews future options, and the potential market uptake of low/zero carbon fuels. It also considers the impacts of a range of Energy Efficiency Measures (EEM) that will form an integral part of emerging alternative fuel use and carbon emissions reduction.

Understanding the timescales for market uptake and the associated costs will be the central issues facing all operators looking to adopt zero carbon operations so these are discussed along with the risks and opportunities of the matching technologies needed to enable their use. This area highlights that technology appears to not be the limiting factor, rather that availability of future zero carbon fuel options will be the limiting factor for transition to zero carbon fuels, particularly for international and trans-ocean operations.

The study has highlighted there will be different transition rates between 'Short Sea Shipping' (coastal and regional operations), and 'deep sea shipping' operations, as well as different optimum fuel and machinery options for each scenario. Coastal/regional operations have closer proximity to ports and lower range and fuel storage demand, deep sea operations require greater range and greater fuel storage demand. The reduced energy densities of zero carbon fuels have major impacts on vessel design for these two scenarios. For this reason, and linked with the potential rapid emergence of autonomous shipping particularly for coastal/regional operations, the report explores some of the different options low/zero fuels and autonomy may present to change the way UK marine science can be delivered in the coming decades, and how a broader UK wide focus could bring greater efficiencies of scale and enhanced delivery to the UK communities.

As noted above regional availability and regional variability of zero carbon fuels will be a significant constraint for deep sea operations as markets progress to full uptake of these technologies. Based on research available for this study, 2035 looks to be at an early point in this process. This presents constraints and options for fleet development. These range from delaying the RRS James Cook replacement and applying carbon reduction technologies to the current vessel to reduce emissions, then replacing the ship as market uptake of emerging fuel options reach further maturity, to progressing the replacement at 2035 adopting mixed fossil/zero carbon fuel technology with a view to transition to fuel zero carbon fuel later in the ships life. These timing uncertainties and considerations are explored within the report.

The section on **capability demand & utilisation** considers the past development of the fleet, the operational and science community drivers that influenced past ship designs, and assesses the mode of operation of vessels in response to the requirements and programming criteria of the NERC Marine Facilities programme (MFP). The section explores development of the NERC fleet and the drivers of ship designs to understand the context of why NERC currently operates multi role research ships, and why the fleet structure is as it is today.

As noted above the rapidly changing technology landscape around zero carbon fuel developments and autonomy present an opportunity to review the approach to the fleet renewal programme and the way the NERC and the UK wide fleet is structured. The section considers how future delivery capability and infrastructure can continue to innovate to not only equal that of our current

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production. **Scope 3** are all other indirect emissions from activities of the organisation, occurring from sources that they do not own or control – e.g. from areas such as business travel, procurement, waste and water. [1]

capabilities, but continue to evolve and expand on these capabilities in response to the changing needs of the science community in a sustainable and innovative way.

Part of the remit of the NZOC project is to assess the potential options for collaboration with other partners both within the UK and internationally with a view to enhance capability and develop areas for operational efficiency across the operating landscape. The final section on ***options for collaboration*** considers how the NERC fleet renewal programme, and the changing technology landscape around zero carbon fuel developments and autonomy presents opportunities to look more holistically at the future NERC fleet structure and operating concept with a view to collaboration and coordination.

On a national UK basis there is considerable opportunity for collaboration across the diverse monitoring, survey and science activities currently carried out by the various UK organisations and their associated assets. UK government agencies operate a range of research, survey and monitoring vessels to support UK obligations for deep sea marine science, environmental monitoring, survey, fisheries stock assessment and coastal navigation aids. This extended fleet operates from coast to shelf edge and globally for deep water research.

Over the past decade there have been a number of reviews and reports which looked at the multiple vessel operators, fleet utilisation, collaboration and cost/programming efficiency. Three of these reports are referred to in this study as they show clear correlation in their observations and recommendations with the NZOC report. They collectively propose options for UK collaboration, in areas such as common scheduling systems, asset sharing, and potentially efficiencies of scale through joint evaluation of fleet renewal plans and adoption of autonomy. On the international front, there are options to enhance collaboration through international forums such as OFEG[2], ERVO[3] and IRSO[4]. These are discussed in more detail within this third section of the report.

Conclusions and recommendations based on the NZOC study can be found at the end of each chapter, with the overarching points noted below;

Timing the markets for such a transformational process such as global shipping moving to zero carbon fuels comes with high uncertainty. The projections outlined in this report are assessments based on today's market intelligence. Continuous review of the market is critical over the coming decade to calibrate the timelines for market maturity and inform on the optimum approach to ship and fleet renewal strategies.

Increasingly the technology and engineering solutions for emerging fuels and machinery transitions are not seen to be the limiting factors. The major manufacturers of Internal Combustion Engines (ICEs) have, or are in the process of developing solutions that can burn a range of fuels, either in a single, dual or multi-fuel system. Many of these systems are already available, with others still in development. There is less certainty around the development rate and costs of fuel cells, which

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[2] OFEG – Ocean Facilities Exchange Group www.ofeg.org

[3] ERVO – European research Vessel Operators https://www.ervo-group.eu/

[4] IRSO – International Research Ship operators https://irso.info/

would enhance efficiency and reduce carbon emissions (and of other non-GHGs such as NOx and SOx) for a sub-set of alternative fuels.

It will more likely be issues of global availability and supply chain resilience of fuels that will slow the transition rates from fossil to zero carbon fuels, particularly for international and trans-ocean operations. During the 2020s' it will be beneficial to develop and maintain touch points with key suppliers, ship designers and other research ship operators to share lessons learnt, information and experience of design and technology developments to inform on ship design options as technology and supply chains mature.

It is likely there will be significant variation in the availability of different fuels regionally, and in their costs and production methods, and hence carbon intensity during the 2030's and 40's. The impact of this diversified but immature alternative fuels market for most ships built in the early 2030's may result in the need to build in fuel flexibility. This may be in the form of operating with multiple fuel capability (including the use of dual or multi-fuel ICEs) or through flexibility in design to allow upgrades and additions to support alternative fuels later in life. This may result in designs that can operate on a range of gaseous fuels, or on a mix of diesel and a gaseous fuel to ensure world-wide operation is possible, irrespective of local alternative fuel supply constraints.

Zero carbon operations requires zero carbon fuel adoption, but combining Energy Efficiency Measures (EEMs) along with operational efficiency measures can be a medium term strategy for *current ships* to achieve IMO carbon reduction measures during the 2020s' & 2030s', moving to full zero carbon fuels at replacement as international fuel markets mature. To de-risk international operations for early adopter operators seeking carbon reduction measures in advance of maturing zero carbon fuel markets, progress to meet international targets can be made through the adoption and retrofit of EEMs to existing ships, and delaying new builds until fuel markets mature; however the potential benefit and most suitable mix of EEM technologies for a research vessel is currently poorly understood and needs further research and assessment.

All alternative fuel options have lower energy densities than diesel fuels impacting both future ship design and hosted science capabilities. These impacts are amplified by the additional Size, Weight and Power (SWaP) needs of the systems needed by some fuel options to manage fuel storage and safety.

The main UK operators considered in this report as part of an evaluation of options to collaborate across different organisations, manage UK obligations for marine science research, environmental monitoring, survey, fisheries stock assessment, and marine navigation management. These operators collectively operate around 15 different vessels, and initial review of the fleet suggests significant potential for collaboration. The fleet age profile shows most vessels will be at or beyond a typical replacement design age at the 2035 NZOC timeframe. If there was a serious intent to coordinate, rationalise and/or integrate across the UK fleet to maximise efficiency of operations, initiating a fleet wide review process at the earliest opportunity would ensure the minimal number of ship replacement designs are progressed in isolation resulting in lost opportunities to include them within a broader strategic collaborative UK fleet renewal process. An integrated approach would need significant ground work for funding alignment, project administration and organisation, but the downstream benefit for cost effectiveness and efficiency could be significant once structures are in place. An integrated national fleet renewal plan also has potential for substantial long term engagement with UK industry.

The emergence of un-crewed autonomous shipping and progress in marine autonomous systems presents future opportunities for the development of a mixed surface fleet model providing a step change in capability, flexibility and collaboration for marine survey, and research programme delivery on a broad UK collaborative scale. Evaluating the adoption of autonomy as a central part of a UK fleet renewal strategy to augment/replace existing activities during the current and next decade could present options to enable the development of a mixed fleet operating model and enhance the potential of cross organisation exchange.

On the international scale, collaboration has brought significant benefits to marine science in the previous decades and there is potential to further progress existing partnerships and collaborations such as OFEG, IRSO and ERVO. These can include; enhanced OFEG collaboration and review of new areas of cooperation; taking a lead role initiating a review of collaborative options via the IRSO forum to assess the appetite for more formal arrangements between IRSO partners via bi-lateral arrangements, or other arrangements that may be determined through a formal approach across the IRSO community, with particularly focus on the adoption of emerging technologies such as zero carbon fuels, EEMs and autonomous shipping; review NERCs limited engagements with ERVO with a view to higher levels of engagement, which is highly relevant to the UK small, medium vessel operators potentially providing benefits to both UK and EU partners.

Key points:

Transition to zero carbon fuels

- Timing the markets of global shipping moving to zero carbon fuels comes with high uncertainty. Review of the market is critical over the coming decade to calibrate timelines for market maturity and influence fleet renewal strategies.
- Technology and engineering solutions for emerging fuels and machinery transitions are not seen as limiting factors to move to zero carbon fuels for research ship operations.
- Global availability and supply chain resilience of fuels will likely slow transition rates to zero carbon fuels in the shipping sector, particularly international and trans-ocean operations.
- Implementing Energy Efficiency Measures (EEMs) can be a medium term strategy for *current ships* to achieve IMO carbon reduction measures during the 2020s' & 2030s', moving to full zero carbon fuels at replacement as international fuel markets mature.

Fleet renewal, collaboration and uptake of autonomy

- The main UK operators considered in this report collectively operate around 15 different vessels. The fleet age profile shows most vessels will need replacing within the 2035 NZOC timeframe.
- Rapid development of un-crewed autonomous ship technology presents opportunities to develop a mixed surface fleet model providing a step change in science delivery, capability and flexibility on a UK wide collaborative scale.
- A fleet wide renewal strategy would provide;

  - significant cost savings,
  - cross organisational interoperability,
  - integration of un-crewed ships and MAS,
  - benefits to UK industry through a coordinated approach to fleet design, build, operating and maintenance policies.
- Adoption of autonomous ships should form a central part of an integrated UK wide fleet renewal strategy enabling UK cross organisation engagement.
- The UK/EU regions are leaders in zero carbon fuel projects and likely to achieve maturity earlier in global realignment to zero-carbon fuel adoption than some other regions. This provides potential for faster development of zero-carbon fuel, and autonomous shipping uptake for coastal and regional operations.
- Looking forward to 2035 there are technology and operational developments likely to significantly change research ship design and the way operations are managed;
  - Automation, remote management and monitoring of ship fitted science systems
  - Telepresence and high speed data transfer
  - Integrated/semi-autonomous handling systems for MAS, ROV and other deployed tethered science platforms.
  - Advances in remote monitoring and management of bridge and engine room operations
  - Further integration of Marine Autonomous Systems (MAS) into programme delivery
  - Adoption of MASS/USVs (un-crewed autonomous ships) as force multipliers alongside crewed multi role research ships, also operating independently within their own programmes.

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1 Low to zero carbon operational emissions - technology options

The design and operation of any future research ship will have a significant influence on the overall net carbon and wider Greenhouse Gas (GHG) emissions of the UK research enterprise. Carbon emissions will be a result of the entire life-cycle of any new, or retrofitted research vessel, emanating from design, build (or modification), operation and final disposal.

This section reviews the current market, academic and industrial view on the current and emerging technology options that will influence the operational carbon emissions of a future research ship (i.e. GHG Scope 1 – direct emissions)[5]. Ships such as the RRS James Cook (and the RRS Discovery) will represent the primary source of carbon and wider GHG emissions from the marine research enterprise. Operational emissions are a key area in which a ship operator/owner can have influence through initial specification and through-life operational choices, as well as the implementation of alternative non-ship approaches, such as the increased use of autonomy.

The section is based on data from an open-source literature review and discussions with marine systems and vessel design subject matter expertise in this area.

1.1 Study scope

Operational emissions of a ship will be influenced by its design, the systems installed, how it is operated and the energy sources and fuels it uses.

While design, operational profiles and systems can all be changed to reduce carbon emissions, only changing the fuel or energy source used can achieve zero operational carbon emissions.

This report therefore focuses on a range of alternative energy sources and fuels that support reduced or zero carbon operational (Scope 1)[1] emissions – often described as Tank-to-Propeller (TTP) emissions. This includes transitional fuels and energy sources needed to step towards zero carbon operational emissions. The impact of these alternatives on fuel storage, processing, safety and the power systems required to use them is captured. While not a focus, wider supply-chain carbon emission issues (Well to Tank emissions (WTT)) and the operational risks of alternative fuels and sources are also noted (I.e. a Mix of GHP Scope 2 and 3 issues). Current and emerging Energy Efficiency Measures (EMMs) are also summarised because of their potential ability to reduce operational carbon emissions, or to mitigate the use of lower energy density alternative fuels.

The expected maturity and availability of these technologies in the 2030's is assessed, as is their expected impact to ship design, hosted science capabilities, and to crew and science staff. Carbon emissions have to be considered independently from other environmental issues, so any impacts on wider GHG emissions or on pollutants such as NOx, SOx and particulates are also noted.

The section does not consider in detail the carbon emission impacts of design, build and disposal of a new ship, or the secondary impacts to carbon emissions of design or operational choices, e.g. the exchange of carbon emissions from sea to air to fly crews to operational areas (i.e. Scope 3

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[5] As defined by *Greenhouse Gas Protocol* – **Scope 1** defined as emissions from activities of an organisation or from that under their control. **Scope 2** is defined as indirect emissions from supplied electricity and its production. **Scope 3** are all other indirect emissions from activities of the organisation, occurring from sources that they do not own or control – e.g. from areas such as business travel, procurement, waste and water. [1]

emissions). It also does not consider the fuel and energy requirements and hence carbon emission impacts of any on-board hosted and deployed off-board systems.

Discussions are based on the assumption that there will be a continuing need for a research vessel, but that its size, performance and operating areas may be significantly different from todays and highly influenced by outputs from other work packages in this study. The likely fuel and energy source options are relevant to a vessel/ship of broadly comparable scale to the current classes – namely a global class long range research ship. The discussion is therefore agnostic, but cognisant of the expected future science delivery and operational options also being investigated in the other work packages of this study.

1.2 Operation carbon emissions reduction pathways

Achieving carbon emissions reduction for ship operation can be achieved via two distinct but connected energy management pathways. Only the use of alternative zero carbon fuels or energy sources can achieve zero operational carbon emissions, but the use of EEMs to reduce demand or mitigate growth can still provide useful carbon emission reductions.

1. ***Use of low to zero carbon energy sources/ fuels*** [**managing energy sources & supply**] – the use of alternative fuels or energy sources (and matching power systems) that have a significant lower or zero carbon footprint in use and/or in production. This includes secondary energy sources exploited directly on-board a ship, such as wind, solar or thermal.

    - I.e. consider options that reduce or remove carbon emissions during operational (TTP emissions) use, but also potentially in the supply chain to a ship Well To Tank (WTT emissions).

    - NOC/NERC will need to select energy sources/fuels based upon local or global availability and technology readiness of both fuels and the matching power systems. I.e. will be subject to same market forces as other commercial operators, but likely to have low levels of influence on the market due to its limited fuel demand compared to other larger operators/ sectors.

    - The same fuel type may have very different levels of carbon emissions associated with its production in different geographical areas. E.g. depending on whether it is produced or synthesised with green energy or fossil fuel derived energy.

    - UK government can influence availability of certain marine fuels in the UK, and support wider world-wide use politically. Policy can also influence the use of green energy to produce these fuels and hence overall carbon intensity.

    - Alternative fuel options are likely to impact the net capability of a future research vessel through reduced performance and the impacts to design of reduced fuel energy density. These impacts are likely to need mitigation via energy efficiency measures or will likely result in larger ship designs to maintain the same capabilities.
2. ***Influencing energy demand*** **[Managing Energy Use]** – achieving energy and hence carbon emissions reduction through an influence on the vessel's efficiency and its operation, through design, optimisation and selection of suitable technologies and design features.

- I.e. Carbon reduction by maximising vessel efficiency.
  NOC/NERC have a significant influence through requirements setting, and through optimising how a platform is used and operated, but will (or their designers will) need to undertake cost vs. benefit assessments to select the optimal mix of technologies based on the required operating profile.

- These efficiency measures cannot achieve zero carbon operational emissions without the additional use of low or zero carbon fuels or energy sources.

- These measures will not always be universally suitable, with some technologies matched to specific operating regimes, speeds, power systems or prime mover choices. I.e. there is a link between the fuel considered and the applicable efficiency measures.

- These measures can mitigate the ship design impacts of low or zero carbon fuels – e.g. the impact of using a lower energy density fuel (Compared to Diesel) on overall platform size, or the impact of rising or more volatile fuel prices.

These pathways may also include the use of transitional energy sources, fuels or technologies – i.e. the move to net zero may be through several transitions reflecting that future energy sources, fuels and systems will mature and become available at different points in time, and the fact that these transitions will continue to occur through the life of any vessel built in the next 20 years.

There is an industry wide acceptance that during a transition period it is likely that commercial ships will operate on a more diverse mix of fuel options than found today. It is also widely discussed that ships will need to be able to operate with a mix of fuels during this transition period to mitigate the variability in availability, costs and infrastructure around the world. Most engine manufacturers are therefore developing multi-fuel engines to support this, able to support a range of fossil, low and zero carbon fuels, both in liquid and gaseous states. The external study commissioned to support this work [19] shows these potential intermediate steps as shown in Table 1.

Initial point			First Transition			Second Transition		
Machinery	Fuel	Availability	Machinery	Fuel	Availability	Machinery	Fuel	Availability
4SD	MDO	2021	4SD	Methane	2021	4SD	NH3	2025
						4SD	H2	2030
						PEMFC	NH3/H2	2025
						SOFC	NH3/H2	2035
			4SD	Methanol	2021	4SD	NH3	2025
						4SD	H2	2030
						PEMFC	NH3/H2	2025
						SOFC	NH3/H2	2035
			4SD	LPG	2021	4SD	NH3	2025
						4SD	H2	2030
						PEMFC	NH3/H2	2025
						SOFC	NH3/H2	2035
			4SD	NH3	2025			
			4SD	H2	2030			
			PEMFC	NH3/H2	2025			
			SOFC	NH3/H2	2035			

Notes to table 1:

4SD	4-stoke diesel	MDO	Marine Diesel Oil
PEMFC	Proton Exchange Membrane Fuel Cell	SOFC	Solid Oxide Fuel Cell
LPG	Liquid Petroleum Gas	NH3	Ammonia
H2	Hydrogen		

Table 1 - transitional fuels and machinery with their expected availability [19]

1.3 Alternative marine fuels - Discussion

1.3.1 Background

A range of alternative fuels and energy sources have, or are expected to become available for marine use, all with the aim of moving the marine industry towards reduced carbon and GHG emissions.

There are a significant number of discussions, papers and reports being produced by governments, marine suppliers, operators and trade organisations attempting to address a roadmap towards net-zero shipping. These address both the 50% reduction by 2050 proposed by International Maritime Organisation (IMO) in their draft strategy, and a range of more ambitious targets towards net zero. There is some indication in reviewing this public domain information that much of it is based on a much more limited, but high-quality sub-set of fuel trend predictions produced by organisations such as UCL’s energy institute in support of the IMO.

While there is some certainty around the types of fuel that could be available in 2035, there is significant uncertainty around the levels of availability, the costs and the maturity of the matching infrastructure both at local and world-wide level. It is also hard to judge the relative carbon intensity and cost of each of these fuels, at each supply location, as the supply chains and power sources used to support them are currently immature. Equally there is very low certainty around the pace of alternative fuel up-take by individual operators. These risks make specifying a suitable fuel for a ship in 2035 complex and subject to a wide range of risks. Fuel options and availability is also likely to change through the typical life of a ship of between 25 and 35 years.

The consideration of a 2035 build, however, is widely considered to coincide with an expected inflection point in the development and availability of these fuels presenting both opportunities and risks to procuring a new vessel in this timeframe. These can be summarised as:

Opportunities:

- An opportunity to move to lower carbon/ GHG emitting fuels for what is, for many organisations, their biggest source of Scope 1 carbon emissions (ship operations).
- Can offer potential access to new sources of energy – e.g. links to locally available waste streams or energy sources that could reduce the supply chain's overall carbon footprint.
- Some proposed fuels are near 'drop-in' replacements to existing fuels minimising changes to ship design and matching platform systems, and offering the opportunity to use current fuels when availability issues arise in early years of operation.
- Should minimise future risks of additional taxation (costs), negative publicity or even denied access to certain environmental sensitive or protected areas due to perceived or real emissions of a ship.

Risks:

- A need to 'second-guess' which fuels become dominant and widely available – a risk in becoming an early adopter of a fuel that fails to find a large enough market to be sustainably produced or supplied in operational areas throughout a ship's life.
- A risk that fuel types diversify in type and to differing degrees around the world making world-wide operation on a single fuel type more complex. This potentially drives operators to adopt more flexible solutions able to operate on multiple fuels.
- Risks from moving to new power system technology required for certain fuel options leading to greater uncertainty around cost, availability, reliability and support implications.
- Equally a risk to maintaining use of current diesel based fuels if net levels of use decline, impacting availability, quality and cost of both the fuel and the systems that use it.
- Some synthetic fuels are energy intensive to produce and are likely to be produced by different methods and feed-stocks in different locations world-wide. This raises risks around moving carbon emissions responsibility down into the supply chain, or abroad, and making it hard to trace actual carbon footprint of a given fuel type at the operator level.
- It will become potentially more complex to assess fuel quality and chemistry due to a diversification in source and supply chain – this could generate availability, reliability and maintainability risks in the ship's systems as well as generating an additional testing burden.

1.3.2 Fuel & energy source options

The following fuels and energy sources are considered in this report and represent the mostly widely discussed options currently being debated within the marine industry.

Type	Variant	Sub variants/ descriptor	Matching Technology need
Carbon based Primary fuels	Diesels and Heavy fuel (Oil based)	MDO/MGO HFO	Internal Combustion engines (ICE) – direct mechanical, hybrid or electric drive, plus exhaust after treatment systems.
	Synthetic Diesels	Hydro-C-derived Bio-derived	ICE – direct mechanical, hybrid or electric drive, plus exhaust after treatment systems.
	Natural Gas	LNG CNG	ICE – direct mechanical, hybrid or electric drive. Potential future Fuel Cell options
	Liquefied Petroleum Gas	LPG	ICE – direct mechanical, hybrid or electric drive.
	Methanol	Methanol Dimethyl Esther (DME)	ICE – direct mechanical, hybrid or electric drive. Potential future Fuel Cell options (methanol)
Non-carbon based primary fuels	Hydrogen	Grey Green (inc. Bio-derived) Blue	Fuel Cells matched to electric drive and energy storage. Potential for direct use in ICE match to any power system.
	Ammonia	Grey Green (inc. bio-derived) Blue	Re-conversion into Hydrogen for use by fuel cells; research looking at direct use in ICE, but limited to large slow speed ICE currently
Electrical energy	Stored Electricity	Closed Batteries Flow Batteries	Considered here as a primary energy source but can also offer hybrid options with any other fuel. Battery technology and matching Systems design (cooling, safety etc.) – Electrical drive-trains
Nuclear	Nuclear	Fission reactors Atomic batteries	Range of core/ reactor designs; matching steam and electrical systems & drive trains.
Secondary energy sources	Solar	Solar cells	Solar cell technology and Integrated electrical systems – also likely to drive need for matching energy storage systems
	Wind	Sails Kites Rotors	Range of sail, kite and rotor technologies both mature and developing – limited integration into primary systems – propulsion only. Will need other fuel options and systems to support additional propulsion and hotel loads.

Table 2 - the Range of fuels/energy sources considered

Notes to Table 2:

MGO/MDO & HFO	marine fuel grades – Marine Diesel Oil/ Marine Gas Oil and Heavy Fuel Oil
LNG/ CNG	Liquefied Natural Gas and Compressed Natural Gas
LPG	Liquefied Petroleum Gas
ICE	Internal Combustion Engine
Grey fuels	Produced from fossil fuels and generally carbon intensive
Blue fuels	Grey fuels, but using carbon capture to mitigate impact of production
Green fuels	Fuels produced with Green energy and hence offer a lower carbon impact

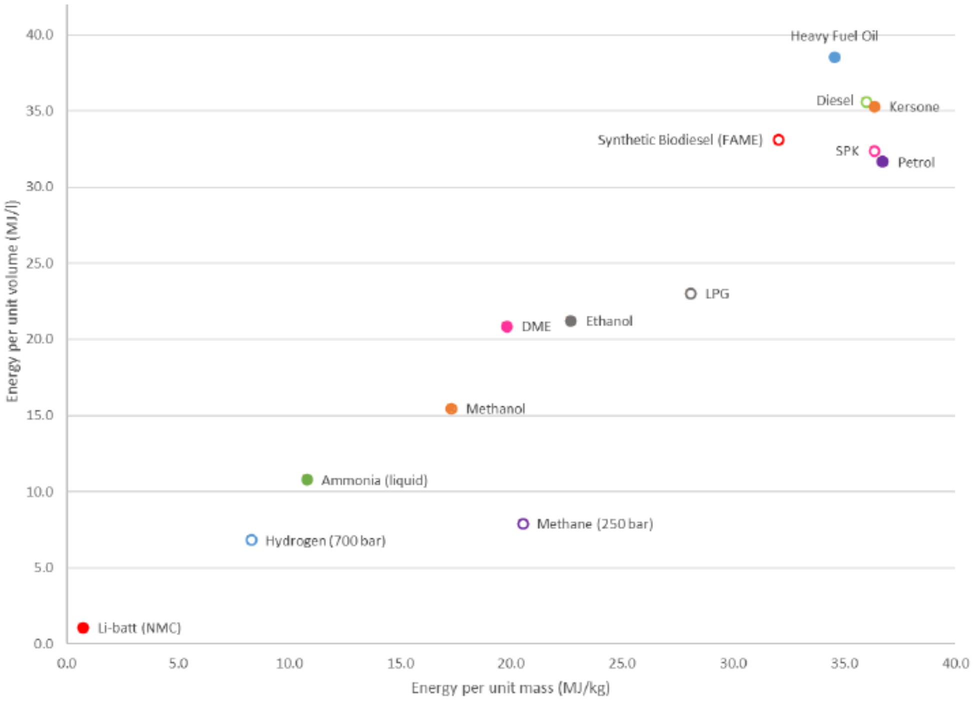
Note: Each of the fuels listed in Table 2 is considered in more detail and compared to the use of Marine diesel within this report across a range of comparison factors. These individual fuel sections are then summarised in section 1.3.6.

It is likely that other fuels and variations will emerge, based on alternative production methods, feed stocks and/or the maturing of enabling power system technologies than could use them. This will mean that fuels will see variation, with time and location, in their composition, quality, availability and cost, and critically in their carbon intensity. Local fuel solutions for short-sea shipping (coastal and regional operations) are likely to become more common.

Public and user perceptions of these fuels will also change with time in areas including, their expected environmental impact (with respect to carbon emissions and wider) and their safety. These perceptions will alter with experience, familiarity and use.

Although certain energy and fuel pathways look more resilient than others from the perspective of asset longevity, fuel price is likely to be dominant factor. The evolution from the 2020s, up to 2050 means that different zero-carbon fuel options will be more competitive in different decades and there is not one option which is the most competitive from today to 2050. Managing uncertainty will drive towards the need for as much flexibility as possible to ensure operational and cost resilience. It is therefore highly likely that operators may use transitional fuels as a stepping stone to longer term solutions, and that for many operators the ability to use multiple fuels, and in particular combinations of fossil and alternative fuels on a single ship will also be important.

While all fuel options need to be considered against a range of parameters as discussed in more detail in section 1.3.5, energy density is perhaps the most significant difference between them and the current diesel fuels. It is therefore a key influencer on ship design, due to its potential impact on required storage volume, and hence resulting availability of science operating space, cargo capacity, range and endurance. The following figure gives an idea of wide variation in energy density for a range of marine fuel options. It also shows the high levels of diesel based fuels and the fact almost all alternative options are significant less energy dense than diesel.



SPK Synthetic Paraffinic Kerosene; **Li-batt (NMC)** Lithium Nickel Manganese Cobalt Oxide Battery;
LPG Liquid Petroleum Gas; **DME** Dimethyl Ether; **FAME** Fatty Acid Methyl Esters

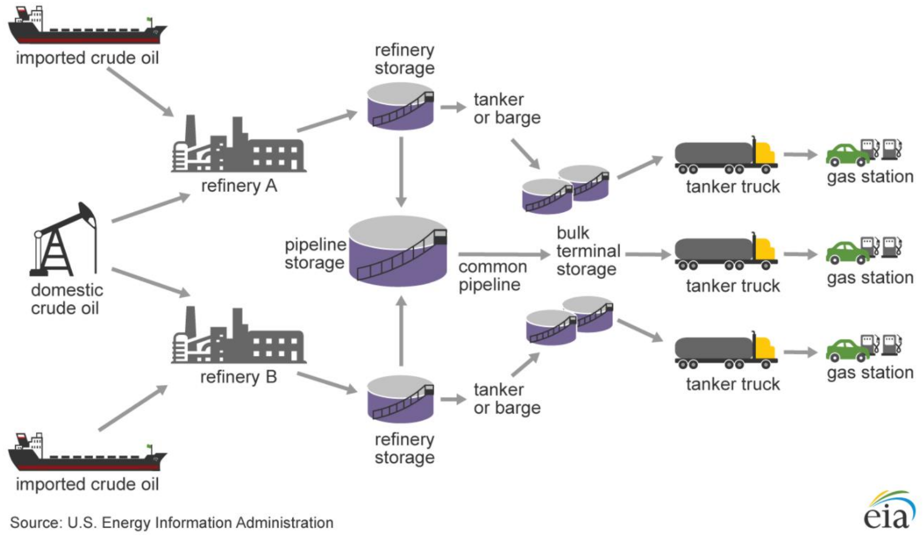
Figure 1 - Energy densities of a range of fuel sources being considered for Marine applications [13]

1.3.3 Alternative fuels supply chain - wider carbon context

The focus for this report is on potential impacts of fuel options on the operational TTP carbon emissions of future ships, but it is important to understand and be aware of the carbon intensity of the supply chain (WTT) that may support a specific selection of operational fuel. A good choice from an operational perspective may translate to higher carbon outputs within the matching supply chain. Understanding these issues also influences other incentives and cost models being considers (e.g. carbon off-setting and trading), as well as helping to understand potential political or public domain arguments or perceptions, whether real or perceived.

A simple example to consider is a traditional WTT process for oil based automotive fuel in cars (Figure1). A car driver (the owner) can make a range of choices that influence their scope 1 (Tank-to-Wheel) carbon output, from managing their driving style, to their selection of the size of car and engine, through to the time and distance they use it. The driver has significantly less influence or even visibility of the supply network and its corresponding energy consumptions and carbon footprint. Substantial energy is needed to extract, refine, store, pump, transport and deliver the fuel to the car driver, and the sources, and hence carbon footprint of that energy are often not clear, and are likely to vary from location to location, process to process.

This figure also highlights the differences between the GHG emissions scope definitions. In this case the car converts chemical energy in the fuel (Petrol or diesel) into mechanical energy via combustion in an ICE – i.e. the car owner’s direct emissions under scope 1 definitions. Extraction, transportation, refining and processing of this fuel requires additional external energy sources, typically other fuels (diesel in the ships and road tankers) or electricity in the extraction and refining process. In-direct emission sources (Scope 2) will include electricity which can be produced by a range of fuels or alternative energy sources, hence there can, and will be, a mix of energy sources and fuels used throughout the supply chain, each with their own carbon intensity. In addition there will additional carbon emissions associated in setting up, building, supporting and disposing of the vehicles and infrastructure required to support this supply chain (Scope 3).



Source: U.S. Energy Information Administration

Figure 2 - ‘Well to tank’ flow for traditional oil based fuels

In the broadest terms, most fuel types (i.e. as defined by their chemical composition) can be generated from fossil-fuel sources (oil & gas), biological sources (plants and waste streams) or generated through a combination of hydrogen and CO_2, and potentially Nitrogen through electrically powered processes including Electrolysis. These methods are described in the following sections as fossil fuels, bio-fuels and synthetic, electro or E-Fuels. It is worth highlighting that all synthetic or e-fuels are reliant on Hydrogen production as the critical production link.

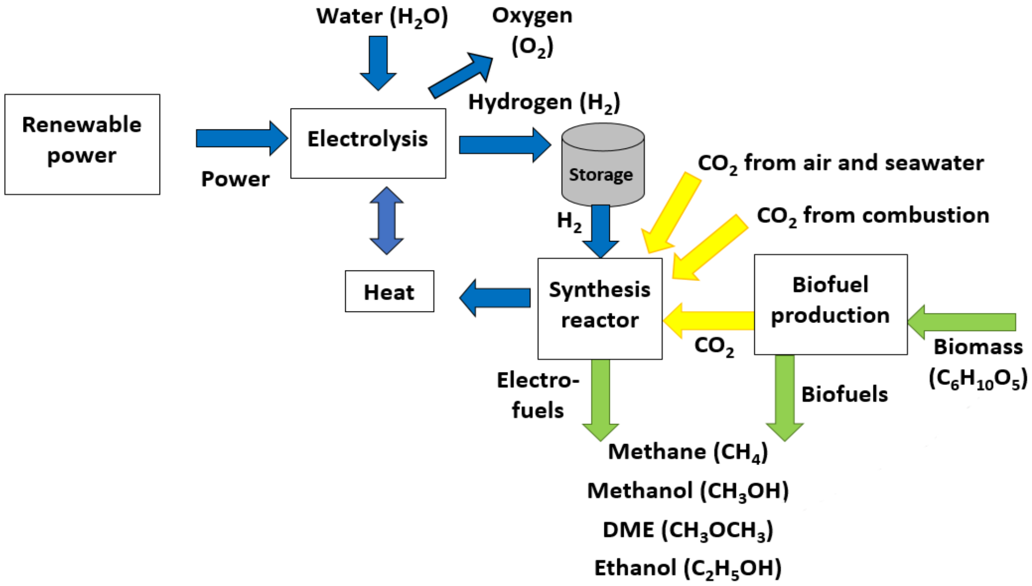


Figure 3 - high-level overview of alternative fuel production processes [18]

It can also been seen from the above figure that many non-fossil fuel derived fuel synthesis processes can produce a mix of fuels. This will drive a desire to make efficient use of these secondary 'by-product' fuels, potentially leading to their use in the maritime for predictable short-sea shipping routes such as ferries. The figure also highlights that these plant locations will be based on ease of access to local energy sources, the sea, and potentially feedstock's such as bio-mass. Hence the location of synthetic fuel plants may be different from those currently used for fossil fuels potentially shifting and favouring alternative bunkering locations. Finally it shows the multiple steps required to generate synthetic carbon based fuels; this equates to significant process energy demands and would represent a significant rise in renewable energy production. This fact is also reflected in the current costs of these fuels, which are typical 3-5 times that of equivalent carbon based fuels.

The use of Grey, Blue and Green terms are also widely used in industry, but often inconsistently, and muddled further by a range of additional colours. The following are high-level descriptions, but show the challenge of interpreting the terms without understanding the specifics and carbon intensity of a production facility, its feedstock's and the power it uses to support production.

Grey fuels – produced from fossil fuels and generally carbon intensive

Blue fuels – Grey fuels, but using carbon capture to mitigate impact of production

Green fuels – Fuels produced with Green energy and hence a lower carbon impact

1.3.4 Alternative fuels - Matching on-board systems & technologies

The carbon benefit of any alternative fuel considered cannot be considered in isolation from the matching systems and technologies needed to load, store and use it safely on a ship.

Different fuels will directly influence the available options and the selection, and performance of, matching generators, propulsion engines, power distribution and propulsion systems, and auxiliaries. Each of these connected systems and equipment can have differing efficiencies and hence will influence the net carbon intensity of the ship.

While in theory a zero carbon fuel reduces concerns over net system efficiency, efficiency will influence a ships overall size, range and endurance, and will directly impact operational costs. For fuels that only reduce carbon emissions, the selection of matching systems could reduce or negate the theoretical carbon benefit compared to a tradition system, through for example increasing the size of the matching ship.

Alternative fuel and energy options will also need a range of different sub-systems to support safe fuel and energy bunkering, storage, processing, use and after-treatment to meet a range of both safety and environmental requirements. Each additional system, or increase in capacity of existing systems creates ‘parasitic’ power demands, which when summed together could reduce the net carbon benefit of a given fuel. These parasitic loads could include, but are not limited to additional systems to provide cooling, cryogenic cooling, pressurisation, filtration, safety and exhaust after-treatment.

The selection of both primary and secondary systems matched to a specific fuel will also influence the availability and applicability of a range of Energy Efficiency Measures (EEMs). An example of this would be waste heat recovery (WHR) systems, which are often optimised to high exhaust temperatures, potentially unachievable with certain fuel options.

The impacts of transient performance should also be considered in a system level analysis. An ICE operating on different fuels will use differing combustion cycles, resulting in the same engine block seeing different pressures, injection patterns, temperatures and power outputs. This results in, for example, varying rates of acceleration, differing maximum power outputs and changes to start-up and shut-down procedures for different fuels. This can impact net efficiency, net emissions and potential carbon outputs when operating at part powers. Equally the use of fuel cells will drive the need to include electrical energy storage within the power system to mitigate their limited transient performance.

Many of the engine manufacturers are predicting an interim period where operators use multiple fuels. While the technology for dual or multi-fuel engines is rapidly maturing, and is already available for many fuels, this approach has Size, Weight and Power (SWaP) impacts to the host ship as a result of the duplication of key fuel and storage systems and impacts net performance of a fuel flexible ICE.

1.3.5 Alternative marine fuels – comparison factors

In order to compare different future ship fuel and energy options a range of comparison factors can be used. At this stage it isn’t possible to fully compare these fuels in several areas, with operating costs in particular being highly uncertain. Equally the true impact of these fuels on ship and power systems design is not fully understood at this point in time, due to immaturity (or non-existence) of matching regulations, classification society rules and design and operating experience. Additionally, generic comments against the use of these fuels in shipping as a whole may not fully capture the unique design implications on a specialist vessel design such as a Research Vessel. *It is worth noting that to this point there is limited research completed on the specific operating profiles of research ships as there is for commercial sector ships which is a key piece of future follow up work to this report*. Modelling for Offshore Supply Vessels (OSV) can be applied but OSVs still have different operating profiles to deep sea research ships. A study of research ship operating profiles needs to be completed as a key next step to matching fuel, machinery and efficiency measures to both existing ships and future designs. The UCL energy institute is well placed to carry out this study as a key area of information development.

Comparisons and assessments made within this report are made against the following factors. These factors are used in the comparison tables and discussion for each individual fuel options provided in the report and summarised in section 1.3.6.

a) **Sources of the fuel** – High-level assessment of the potential feed-stocks/ basis chemicals and energy supply options for the fuel and their associated carbon intensity. Also considers if the fuel's production can produced by green forms of energy.

b) **Availability & costs** – Based on current evidence, providing an indicative indication of the current availability of the fuel or energy source and the likely availability in 2035 and 2050 along with a general indication of expected cost trends.

c) **GHG/ Carbon impact** – An indication of the relative operational carbon impact of the use of the fuel on a ship.

d) **Energy density** – Noting the density both in terms of energy per unit volume and per unit mass. This impacts the quantity needed to achieve required work output, but also the size and scale of on-board fuel storage required and hence the overall size, range and performance of the ship.

e) **Matching power system technology** – Providing an overview of the availability and maturity of the matching power system's architectures and generators needed to convert the fuel into propulsion and electrical power on-board in the most efficient and carbon neutral way. This includes comments on these systems maturity and availability now, in 2035 and beyond. Also considers additional systems needed to manage current and future legislation such as the requirement for exhaust after treatment for NOx reduction.

f) **Storage requirements** – While the energy density of a fuel gives an indication of storage requirements on-board, additional factors such as the need to use pressurised or cryogenic tanks and additional systems to provide human and system safety, or to provide specific handling systems will all reduce energy density still further, hence these issues are addressed under this category.

g) **Applicability** – This category considers practical limitations of the fuel and its supporting systems that result in that fuel being unsuitable for certain types of ships, certain sizes and operating areas.
h) **Size, Weight & Power implications (SWaP)** – this category highlights in general terms the expected impact on a ship design of incorporating the fuel, its storage and matching power system, assuming no other changes to a ship design or capabilities.

i) **Wider emissions & risks** – this category highlights the wider impacts of the fuel with respect to other emissions and environmental risks.

The Maritime Industry Decarbonisation Council describes a triangle of requirements that need to be in place to support the practical use of a specific alternative fuel. It captures some of the issues above, as well as the need for secure supply chains and a matching level of production:

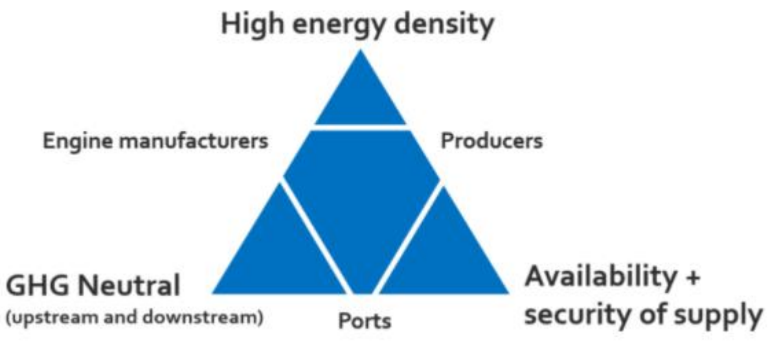


Figure 4 - MIDC's fuel triangle [18]

1.3.6 Alternative marine fuels options – Comparison table of characteristics

Fuel/ energy source		Marine availability			Carbon/ GHG Impact		Energy density	Matching technology	Key ship design impacts	Wider environmental
		Now	2035	2050	On ship	Supply chain	Gravimetric [MJ/kg] (Volumetric) [MJ/L]			
Carbon based primary fuels	1/ Marine Diesels	Widely	Widely	Reducing	High	High	42 (38.6)	ICE [MATURE]	Known – fire and pollution aspects manageable. Current designs reflect diesel use.	High NOx; PMs etc. SOx – reducing with time. Pollutant if spilled.
	2/ Synthetic/ Bio diesels	Growing, but volumes potential limited to blending percentages			High	Medium to high (depends on energy & feedstock)	Varying but similar to diesel	ICE [MATURE]	Known – additional on-board testing may be needed to manage varying blends and quality.	High NOx, PMs; reduced or zero SOx. Pollutant if spilled
	3/ Natural Gas	Growing	Location specific/ limited		High (lower than Diesel)	Medium to high (depends on energy used)	53.6 (0.04) [Gas] (22) [LNG] (9) [CNG]	ICE [MATURE] SOFC Fuel-cells [IMATURE]	**Upper & working decks** – often stored in Cryogenic/ pressurised Cylindrical tanks on upper decks. **Existing tank spaces** not required - Potential space inefficiency. **Range/ endurance** – more tank volume needed for same range.	Lower NOx, PMs than diesel; reduced or zero SOx. Methane loss (slip) – a very high potency GHG (~84 × CO_2)
	4/ LPG	Limited	Widely	Limited		Medium to high (depends on energy & feedstock)	49.3 (26.5)	ICE [MATURE]	**Upper & working decks** – stored in pressurised Cylindrical tanks on upper decks. **Existing tank spaces** not required - Potential space inefficiency. **Range/ endurance** – more tank volume needed for same range	Very low SOx and particulates; 20% reduction in NOx
	5/ Methanol/ DME	Location specific/ limited			High	Medium to high (depends on energy used)	19 (15) [Meth.] 28.5 (19) [DME]	ICE [MATURE, but limited availability] H_2 Fuel-cells [MATURING]	**Upper & working decks** – Methanol – no impact; DME needs pressurised Cylindrical tanks **Tank spaces** – Can be used for Methanol, but not for DME. **Range/ endurance** – more tank volume needed for same range.	Significantly lower NOx, PMs than diesel; reduced or zero SOx. Methanol has toxicity issues.
Non-carbon primary fuels	6/ Hydrogen	Low	Limited	Widely	Near Zero	Low to high (depends on energy used & source)	120 (0.01) [Gas] (8.5) [Liquid] (4.5) [690bar]	ICE [MATURING] H_2 Fuel-cells [MATURING]	**Upper & working decks** – often stored in Cryogenic/ pressurised Cylindrical tanks on upper decks. **Existing tank spaces not required** - Potential space inefficiency. **Range/ endurance** – significantly more tank volume needed.	No emissions if used in Fuel cells. Limited PMs, but NOx produced if used in ICEs
	7/ Ammonia	Low	Limited	Widely	Near Zero	Low to high (depends on energy used & source)	18.6 (12.6)	ICE [IMATURE but developing] H_2 Fuel-cells [MATURING]	**Tanks & upper decks** – limited pressurisation/ cooling needed to liquefy – not clear how large scale ship tanks would be configured. **Range/ endurance** – significantly more tank volume needed for same range	No emissions if used in Fuel cells. Limited PMs, significant NOx produced if used in ICEs – requires exhaust treatment.
8/ Stored Electricity		Limited I.e. access to shore electrical connectivity	Widely	Widely	**Zero**	Low	<1 (<6)	Batteries [Varying maturity] Electric system [MATURE]	**SWaP** – low density of battery systems would require significant volumes for even small ranges. **Range/ endurance** – Existing endurance unachievable with anticipated technologies in 2035. **Life** – batteries likely to need replacement in life of vessel. Performance degrades through life.	No emissions – however fire, safety and chemical risks depending on cell chemistry. Disposal/ recycling methods immature.
9/ Nuclear		Limited – cost and availability of systems. SMRs may change paradigm in longer term			**Zero**	High	81M (1.5B) [U235]	Reactors & Steam systems [Varying technology maturity; limited types at sea]	**SWaP** – current Nuclear system are over-sized for research vessel – SWaP need for rector, steam systems and shielding. SMRs may change this – shown to fit in larger commercial ships in studies **Power system** – likely to need secondary sources for emergency; steam systems – limited supplier and experience.	Significant risks and pollution if accident occurs. Majority of issues around disposal/ re-processing of spent fuel. Political & public opinion highly variable.
Secondary Sources	10/ Wind, wave, solar	N/A – harvested at point of use dependant on variable environmental conditions			**Zero**	Low - Limited to system build only	N-A	Sails, Kites, foils etc. [Varying maturity & availability]	**Upper & working decks** – All wind and solar methods require upper deck space – potential limit to operations/ or sail size. **Power system** – likely to be only a secondary source so still needs fuel based generators. Energy storage likely to be needed to manage unpredictability of supply.	No additional issues other than limited impacts of loss of system elements at sea.

Table 3 - summary of tables 1-9 for comparison of fuel option

1.4 Alternative marine fuels – Detailed descriptions of options

The following section provides additional information and discussion on the individual emerging fuel options discussed in the previous table providing context on potential applications and availability.

1.4.1 Marine Diesels and fuel oils (crude oil-based)

Marine distillate diesels (MDO/MGO) and residual oil fuels (HFO) are discussed here as a baseline to other fuel options and represent the current dominant fuels in marine use, as they have done for many decades. They are currently available world-wide and in a limited and well understood range of grades offering operators the ability to balance between cost and performance. With the introduction in sulphur caps under IMO regulations, operators are increasingly using either Ultra-Low (UL) sulphur derivatives of these fuels, or using post treatment systems to manage SOx.

Matching ship and power systems and associated technologies are highly mature, widely available and relatively low cost, and based on Internal-Combustion Engine (ICE) technology. Due to the long life of ships, many diesel based ships built across the next 10 years are likely to be still operational beyond 2060 unless restricted by the availability and/or cost of diesel or via legislative instruments and international political pressure. Diesel is also often required as a pilot fuel for some of the other alternative fuels discussed in this section.

Diesel based solutions for future research ship capability cannot be fully discounted at this stage, as designing for oil based diesels should allow the ship and its systems to operate on a range of semi and fully synthetic and/or bio derived diesel-like fuels as they became available with minimal impacts to systems and processes (see next section) and current ship design approaches.

1/	**Marine Diesel (oil-derived) [MDO/MGO/HFO]** {$C_{12}H_{23}$ – $C_{15}H_{28}$}			Carbon based fuel derived from Crude oil – liquid hydrocarbons. Already blended with a fraction (<10%) of bio-derived fuel; likely fuel will continue to see reductions in Sulphur and increases in blending with bio or synthetically generated diesels.
Availability & cost	Now	Widely		Currently available world-wide at relatively low costs.
	2035	Widely		Hard to assess, likely to be still widely available due to large numbers of legacy diesel based ships still operating – costs potentially rising. UCL study [11] predicts HFO will still be 47-66% of market in 2030.
	2050	Reducing		Availability & quality may be reducing & costs rising.
Carbon Impact	On ship	High		Fossil fuel so naturally high in Carbon. ICEs near theoretical efficiency limits so limited opportunity to improve. Would require use of energy efficiency measures to reduce further.
	Supply chain	High		Assuming derived from crude oil. Would be possible to support production, refining and transportation with green energy sources.
Energy density		Very Good	**42MJ/Kg** **38.6MJ/L**	Baseline – liquid hydrocarbons have highest energy densities of all considered liquid and gaseous fuels. Figure shown for MGO.
Matching technology		ICE	TRL/SRL 9	Low cost and mature - Supports mechanical, hybrid and electrical propulsion and power system options. Risk that investment in ICE will reduce with time, due to their removal from other industries (e.g. automotive, rail etc.).
Storage impacts		Baseline	TRL/SRL 9	Known; steel (ship-shaped) prismatic tanks; stored a atmospheric pressure; limited temperature control needed; Some fuel cleaning/ filtering needed.
Applicability		All ships		No limits – ICE and fuel grades available to support applications from small pleasure boats to largest ocean going ships.
SWaP (vs. diesel)		N-A		Baseline for comparison.
Wider environmental		Poor		Exhaust treatment already needed to mitigate NOx and SOx Emissions; low SOx fuels now available; particulates and unburned hydrocarbons a known issue; pollution impact of spillages at sea.

Table 4 - Fuel Characteristics - Marine oil-based diesels

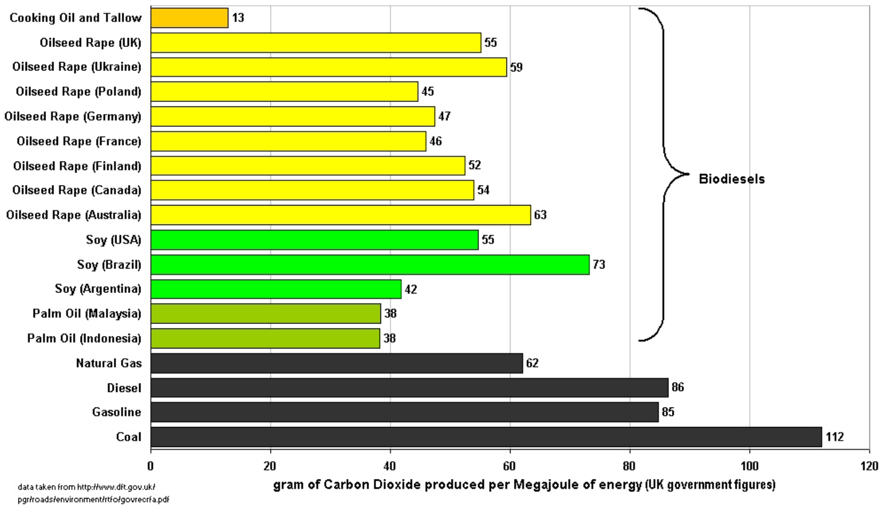
1.4.2 Synthetic & bio-derived Diesels and fuel oils

A range of synthetic and bio-diesels are being considered, developed or are already in use. These are generated from a range of feed stocks, both biological and oil-based, all with the aim of being compatible and equivalent in performance to current oil based marine fuels, and to allow blending with, and easy transfer away from, oil based fuels. For this reason these 'drop-in' fuels are highly attractive to operators and require the least change to ship, fuel storage, and fuel and power systems design.

Oil synthesised fuels (e.g. generated from coal or natural gas) result in almost no net carbon emission benefit as energy is required for the conversion process (such as Fischer-Tropsch), and their use in ICEs will still produce operational carbon emissions, albeit with potential reductions to pollutants such as SOx. The generation of these fuels is therefore only viable when the feed-stock price is low and diesel prices are high, and/or if there is an excess of basis fuel such as Natural Gas [12], circumstances that may become more common in the future.

Future low carbon synthetic diesel production is thought to be viable with improvements to the synthesizing processes, the use of renewable energy sources to power the process combined with sequestering, trading or offsetting CO_2, however currently the costs of this are high, as is the process energy requirement. This also would require significant levels of green electricity production over and above that already supplying national grids. The capability and capacity is also expected to be prioritised to support sectors that are even harder to de-carbonise, such as civil aerospace.

Bio-diesels are generated by methods such as the Trans esterification gasification method. They are fed from feed stocks such as Rapeseed oil and soy. They are attractive from a carbon emissions perspective, as they can significant reduce the carbon-intensity of the supply chain and removes the need to extract and use hydrocarbons. However the actual carbon intensity of different crops and processing can vary significantly and even exceed that of hydrocarbons such as natural gas. Their use in ICEs will still also produce similar operational carbon emissions to that of oil based fuels.



data taken from http://www.dft.gov.uk/pgr/roads/environment/rtfo/govrecrfa.pdf

Figure 5 - Comparisons of the carbon intensity of bio-diesels & fossil fuels [12]

1st generation bio-fuels (e.g. Fatty Acid Methyl Esters – FAME) were widely blended into tradition oil-based fuels and created a range of issues. These included bio-growth and early breakdown of fuels in storage and piping systems, resulting in pipe and filter clogging, the need to clean systems more often, and even issues with ICE fuel injectors. Many of these issues are addressed in 2nd generation bio-fuels, but there are still questions around secondary factors, such as lubricity if the proportion of bio-fuel in a blend rises significantly. For this reason most current ICEs have limits on allowable blends in fuels, and most fuels will have a combination of additives to improve some of these quality issues. Feed stocks are also potentially politically contentious as fuel production can directly compete with land allocated to food production; this is therefore significant effort to identify and use crops that have high yields, are sustainable and can use land unsuitable, or less viable for food production. More novel production processes are being investigated, such as use of algae and seawater, but to date these are small scale and producing low yields.

For future research ship capability there is no need to select power systems or ship design elements to match the full range of synthetic and bio-derived fuels being considered, although operationally they may require additional effort in use, e.g. additional fuel quality testing. It is likely that if future capability retains the need to be able to operate on Diesel (fully or partially), then there will naturally be increasing use of these fuels as they are blended into supplies in greater proportions. It may also become possible to pay a premium to increase the carbon neutrality of a fuel by buying higher blends or even wholly bio-derived fuels. Hence NOC/NERC can benefit from their use with minimal investment, but would only see a reduction in operational carbon-emissions with varying levels of carbon emissions still present in the supply chain.

2/	**Synthetic & bio-derived Diesels**			'drop-in' diesel carbon fuel replacements – either used directly in existing diesel systems or blended with tradition oil based fuels to reduce supply carbon intensity
Availability & cost	Now	Good (as a Blend)		Bio-diesel already available as a blend. Production and availability of higher yield process may boost production with time, but this is likely to just enable an increase in the blended percentage in traditional oil based fuels. Unlikely to be able to produce sufficient quality to wholly replace oil based fuels. Synthetic diesel may become more common as hydrocarbon extraction moves towards gas from oil and coal. Additional processing means costs are currently high, but like to decrease with time. Unlikely to reach parity with diesel unless diesel costs rise.
	2035			
	2050			
Carbon Impact	On ship	High		All synthetic and bio-derived fuels will produce comparable levels of CO_2 when burnet in a combustion engine.
	Supply chain	High to Medium		Bio-derived diesels - Highly variable carbon impact depending on feed-stock, but generally lower then oil-based fuels. Synthetic diesels – as high as or even higher than direct use of oil based fuels due to carbon intensity of production and conversion. Needs Carbon trading, offsetting or sequestration to build carbon intensity down.
Energy density		Very Good	**Variable but close to diesel**	Comparable to oil-based diesel fuels (figure shown for MGO)
Matching technology		ICE	TRL/SRL 9	Able to use same systems, tanks and exhaust treatment systems as oil-based fuels
Storage impacts		As Baseline	TRL/SRL 9	No additional impacts – perhaps extra on-board fuel analysis and testing maybe required.
Applicability		All ships		No limits – available to support applications from small pleasure boats to largest ocean going ships.
SWaP (vs. diesel)		As Baseline		Able to use same systems, tanks and exhaust treatment systems as oil-based fuels
Wider environmental		Better		In particular possible to significantly reduce sulphur content and hence SOx emissions

Table 5 - Fuel Characteristics – Synthetic & bio-derived diesels

1.4.3 Natural Gas

Natural gas (Typically a blend of Methane (CH_4) and Ethane (C_2H_6)) is produced either as a by-product from other fossil-fuel extraction, directly from processes such as fracking or from waste streams such as bio-mass, food production, livestock or landfill off-gassing.

The use of Natural gas at sea in the form of Liquefied Natural Gas (LNG) has been a developing marine fuel trend over the last 10-15 years. This is in part linked to growth in large LNG carriers shipping natural gas to supply national infrastructures. To a much lesser extent, and often for specific and shorter range applications, the use of Compressed Natural Gas (CNG) has also been considered as an on-board fuel.

There is already take up of LNG solutions in the shipping industry due to its advertised potential for reduction in CO_2, NOx and SOx emissions, but also driven by the currently lower and less volatile price of LNG (compared to marine diesel) in certain geographical areas. As a result matching marine ICEs and fuel storage solutions which are now widely available and relatively mature. These solutions have to date often been dual-fuel in nature requiring small amounts of diesel as a pilot fuel. Engine companies are increasingly offering pure gas solutions, removing the need for pilot fuels and further reducing carbon emissions. Most applications are still coastal reflecting and driven by the limited but rapidly growing bunkering infrastructure for the supply of LNG at ports.

While the reduction in NOx and SOx are attractive the combination of relatively modest CO_2 reductions and the arguments around methane slip[6] suggest that LNG may be increasingly looking like a ‘transition’ fuel relative to the emerging low to zero emission fuel options. Recent papers and articles present conflicting reviews on the true emission impacts of the use of LNG presenting both positive and negative assessments when compared to diesel fuels [2, 3], albeit that is based on current dual-fuel ICEs. Several studies have called in doubt the claimed carbon reduction for LNG combustion, in particular when used in medium-speed ICE applications as would be typically used in a research vessel [3]. More widely the debate centres on the impact of Methane Slip, with methane itself a high potent Greenhouse gas at up to 25-36 times that of CO_2 (100 year potential).

LNG and CNG’s low energy density requires cryogenically cooled and/or highly pressurised thermal insulted cylindrical storage systems and a range of other safety features such as twin walled piping. Marine storage solutions are now relatively mature, as are matching regulations and design guides, but do require significant additional space and weight when compared to liquid fuels. While larger ships can use prismatic hull based tanks, similar to those found on LNG carriers, most ships are using standard cylindrical tanks, typically mounted on upper decks. This impacts the general arrangement of the platform, and in particular on ships with large working decks, such as research ships, that need those areas to conduct their primary mission. There is also the corresponding impact of the space inefficiency, and weight distribution (vessel stability) of not being able to use the less operationally useful and irregularly shaped liquid fuel tank spaces along the keel.

Methane slip mitigation measures may be developed with time [4], but for the Methane emissions, upper-deck design and logistical storage reasons LNG may be superseded as the preferred fuel of choice for transition to future low or zero carbon fuels. Even key suppliers such as Wartsila are

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[6] Methane slip – Methane is a highly potent GHG; hence the industry is concerned about the ‘slip’ of methane from engines (unburnt fuel), and fuel supply and storage systems. Small methane slips are seen as potentially negating then benefit from reduced CO_2 emissions from the combustion of methane in an ICE.

describing methane as a transition fuel [4]. As such, LNG appears to be low priority fuel for consideration in future research ship capability in 2035.

3/	**Natural Gas [LNG/ CNG]** {CH_4 & C_2H_6}			Carbon fuel derived from multiple sources – Gaseous hydrocarbon requiring liquefaction and/or pressurisation to be practically stored and transported.
Availability & cost	Now	Growing		Available at many ports – growing and linked to growth in use of LNG in shipping. Typically ports develop supply chains for specific ships and shipping routes – e.g. a ferry route. Costs can be lower than diesel.
	2035	Limited		Hard to assess; range of LNG powered ships will be in service, so unlikely to diminish from current position if not significantly grow. Costs may have started to rise but dependant on source and production. UCL study [11] predicts LNG will reach a maximum share of around 11% in 2030.
	2050	Limited		Several studies suggesting LNG is a transition fuel, so potentially decreasing and costs rising – nations may focus on national domestic supply needs rather than shipping.
Carbon Impact	On ship	High (lower than diesel)		Fossil fuel but burns cleaner than diesels – but widely debated (~20% reduction compared to diesel without methane slip factors). Gas IC engines near theoretical efficiency limits so limited opportunity to improve. Would require use of energy efficiency measures to reduce further. True impact of Methane Slip hard to assess but may in part negate CO_2 benefits in combustion.
	Supply chain	Medium to high (depends on energy/ source used)		Would be possible to support production, refining and transportation with green energy sources. Can also be produced from a variety of bio-derived waste streams.
Energy density (vs. diesel)		Medium	**53.6MJ/Kg** **0.04MJ/L (NG)** **22Mj/L (LNG)** **9 MJ/L (CNG)**	High gravimetric energy density, but low volumetric density even when liquefied (-160°C) or compressed (250bar). LNG volumetric density 2/3rds that of Diesel.
Matching technology		I-C Engines/ fuel cells in future	TRL/SRL 9 (TRL 6-7 for fuel cells)	Limited cost difference to diesel based IC engines; storage and fuel processing costs higher due to need to maintain pressure and temperatures & have dedicated storage tanks. Equally applicable to mechanical, hybrid and electrical propulsion and power systems. Solid-oxide fuels cells offer a potential more efficient method of directly using methane, but limited focus in maritime to date.
Storage impacts (vs. Diesel)		Medium-high	TRL/SRL 9	~1.5 × diesel [5] Known and available solutions, but to date require cylindrical pressurised tanks and matching safety measures significantly impacting fuel storage location and volumetric needs on a ship. Often placed on upper decks to minimise risks potentially impacting upper working deck space availability.
Applicability		All ships		Ocean going ships – ICE and tankage options currently limited to larger vessels such as ferries, offshore support platform and feeder container ships.
SWaP (vs. diesel)		Higher		Fuel systems and storage high per unit energy stored + low volumetric density increases tankage required for similar range and performance. Tank location potentially impacts working deck and superstructure design.
Wider environmental (vs. diesel)		Better		SOx reduced by 90%+ & NOx by a reduction of around 20-30%. [4]

Table 6 - Fuel Characteristics – Natural Gas

1.4.4 Liquefied Petroleum Gas (LPG)

LPG is primarily made up from butane and propane, but also includes a range of other hydrocarbons in smaller concentrations. It has seen relatively widespread use in a range of applications, but predominantly heating, cooking and road vehicles. It is a gas at room temperatures so needs to be stored in pressurised tanks to keep it in liquid form, but at relative low pressures and does not require the cryogenics needed for LNG. It is currently widely available and is estimated to make up about 3% of the energy consumed world-wide annually.

LPG generates very low levels of SOx and particulates when combusted in an ICE, so has gained some interest in the maritime community for its ability to meet IMO SOx requirements without exhaust after-treatment. It is also seen as a potential transition fuel to Ammonia as availability still develops, in that the required basic on-board infrastructure is similar (engines, pressurised storage, energy density etc.). Its widespread availability also results in a price comparable to current marine fuels.

4/	**Liquefied Petroleum Gas [LPG]** {$C3H_8$ & C_4H_{10}}			Carbon fuel derived from multiple sources – Gaseous hydrocarbon requiring liquefaction and/or pressurisation to be practically stored and transported.
Availability & cost	Now	Limited		Widely available, but perhaps not directly at many ports or in sufficient volumes for shipping market – Early adopters at LNG carriers, so supply chains already exist. Costs low.
	2035	Good		Hard to assess, but if adopted more widely in maritime, likely to good availability in range of locations. UCL study [11] predicts LNG will reach a maximum share of around 11% in 2030.
	2050	Limited		Several studies suggesting LPG is a transition fuel, so potentially decreasing and costs rising again as a relatively high carbon-based fuel – will also depend on volumes and practicalities of green production.
Carbon Impact	On ship	High (lower than diesel)		Fossil fuel but burns cleaner than diesels - ~20% reduction compared to diesel and doesn't have GHG slip issues LNG has. ICEs near theoretical efficiency limits so limited opportunity to improve. Would require use of energy efficiency measures to reduce further.
	Supply chain	Medium to high (depends on energy/ source used)		Would be possible to support production, refining and transportation with green energy sources. Could also be produced from a variety of bio-derived or chemical process waste streams.
Energy density (vs. diesel)		Medium	**49.3MJ/Kg** **26.5MJ/L**	High gravimetric energy density, but low volumetric density even when liquefied. LPG volumetric density 62% that of Diesel.
Matching technology		I-C Engines	TRL/SRL 9	Limited cost difference to diesel based ICEs and retrofitting possible; storage and fuel processing costs higher due to need to maintain pressure and temperatures & have dedicated storage tanks. Equally applicable to mechanical, hybrid and electrical propulsion and power systems.
Storage impacts (vs. Diesel)		Medium-high	TRL/SRL 9	~1.5 × diesel [5] Known and available solutions, but to date require cylindrical pressurised tanks and matching safety measures significantly impacting fuel storage location and volumetric needs on a ship. Often placed on upper decks to minimise risks potentially impacting upper working deck space availability.
Applicability		All ships		Applicable across all ship types and scales, albeit impacting design and volume requirements due to storage impacts
SWaP (vs. diesel)		Higher		Fuel systems and storage high per unit energy stored + low volumetric density increases tankage required for similar range and performance. Tank location potentially impacts working deck and superstructure design.
Wider environmental (vs. diesel)		Good		SOx reduced by 97%; particulates reduced by 90%; NOx reduced by around 20%. [16]

Figure 6 - Fuel Characteristics – LPG

LPG is currently almost wholly derived from fossil-fuel sources being generated during crude oil refinement or direct extraction from petrol or natural gas. Its carbon emissions generally sit between natural gas and oil based fuels, with a 20% reduction when compared to HFO [16]. Green LPG options are being pushed in certain areas, based on bio derived products or chemical process waste materials such as Glycerine. These appear small scale currently and don't impact carbon emissions generated when combusted. It is also a common by-product of many of the synthetic diesel syntheses processes.

LPG can be combusted in a range of ICEs, both 2 and 4 stroke, and as suggested by recent contracts can be achieved through conversion of current engines [16] or used with other fuels in dual, or multi-fuelled engines. Early marine adopters, unsurprisingly, have included LPG carriers themselves, removing the need to modify or add significant additional pressurised tankage. For a new build, as is the case for all liquefied fuels, net volumetric density is significantly lower than marine diesels resulting in greater volumes being needed to maintaining comparable ranges. Also tank locations have the potential to add upper deck and working-deck space demands and could result in poor utilisation of existing tanks spaces along the keel.

LPG has several safety risks. When in gaseous form it is heavier than air (unlike natural gas) so can pool on the floor of confined spaces generating combustion and asphyxiation risks for humans. It also needs careful pressure regulation and fire protection, which typically limits storage to about 85% of the container volume to allow for rapid expansion.

LPG may offer an interesting transition route to lower or zero carbon fuels on future research ships and developments in this space should be monitored.

1.4.5 Methanol & Dimethyl Ether (DME)

The use of Methanol (CH_3OH) is another method to more practically handle, store and transport hydrogen – i.e. acts as a Hydrogen carrier. It can also be considered an electro-fuel. It is a liquid and can be stored in standard tanks without pressurisation or thermal management making it attractive to shipping. It does however have a range of material incompatibility, fire and toxicity risks.

It is possible to generate a range of hydro-carbons, gasoline, and olefins from methanol via gas to liquid processes, hence it is also seen as a highly flexible energy transportation fuel. It has low emissions of NOx and SOx making it attractive to meet IMO requirements, but it still emits Carbon (CO_2 and water) if directly combusted in an ICE, seeing maybe only a 5% reduction compared to diesel (HFO) [5]. Several shipping companies including Stena Line, have investigated and tested the use of methanol due its potential ability to meet IMO requirements (NOx & SOx) without the cost impact of adapting ships to use Ultra-low sulphur diesels or to add exhaust scrubbers [10].

Methanol production was traditionally via the distillation of wood pulp, but is now more commonly via syngas methods using methane/ natural gas. Hence almost all production options have a notable CO_2 footprint, with methanol in-effect being part combusted Methane. Greener alternatives based on use of waste wood & crops (bio-mass) have been proposed but currently have limited production levels. Geothermal sources in Iceland are also being used to generate ‘green’ methanol used as an additive in EU petrol supplies.

Dimethyl Ester (DME) (C_2H_6O) can be derived from Methanol, but also directly from biomass or natural gas. It is discussed specifically here, as it is often compared to methanol as a potential fuel for marine applications. DME is highly comparable to diesel, supporting direct use in compression engines without pilot fuels. It also offers low particulate, SOx and NOx emissions and hence needs no exhaust treatment systems, and also has less compatibility and toxicity issues. Again it will produce similar levels of CO_2 as fossil fuels when use in ICE. It has slightly higher energy density than Methanol, but boils at -24°C so requires larger, slightly pressurised or cooled tank systems to maintain it in a liquid state, resulting in greater storage volumes required.

Methanol can be easily be used directly in ICEs, requiring minimal conversion of current designs although some reports suggest a drop in engine performance and efficiency when compared to diesel. Primary considerations are is that it is both corrosive to some common metals such as aluminium, and hence potential materials used in ICEs, fuel systems and storage. It also has lower lubricity and pilot fuels may also be required in a compression engines. It can also be de-hydrogenated and then used directly in fuel cells or Hydrogen adapted ICEs; a demonstration of this approach is currently underway on the ferry MS Marielle using PEM fuel cells, but is limited to 90KW. While the technology used for this demonstration is unclear, a sub-class of PEM fuel cells designed for direct use of Methanol (Direct-Methanol Fuel Cells (DMFC)) has widely explored for mobile electronics, however their size and power-ranges are currently limited in size. While methanol is comparative easy to store within a ship's traditional tanks, it has a relatively low density compared to diesel, so would require over twice the tank volume to achieve the same range as a diesel ship.

5/	**Methanol** {CH_3OH} **DME** {C2H6O}			Carbon based fuels derived from multiple sources; can be considered as a hydrogen carrier or an electro-fuel. Methanol can be stored as a liquid; DME requires pressurisation or cooling to be maintained as a liquid
Availability & cost	Now	Limited		Moderate levels produced globally for a variety of uses – but not a major contributor to marine fuels – i.e. not at volumes required for more global use. Costs higher than diesel fuels and dependant on supply chain.
	2035	Limited		May find markets as an electro-fuel where its production can be achieved with green techniques
	2050	Limited		Hard to assess at this point.
Carbon Impact	On ship	High		If used directly in ICEs - Still produces ~95% of the CO_2 levels of diesel. If converted into hydrogen still needs to release excess Carbon monoxide/ Carbon Dioxide
	Supply chain	Medium to High (depends on energy/ source used)		Mostly produced from conversion of Natural gas/ methane (a fossil fuel). Possible to use green energy and/or use Bio-mass or geothermal sources for greener forms of production. DME can be directed generated from Methanol.
Energy density (methanol)		Moderate	**19MJ/Kg** **15MJ/L**	Less than half the volumetric and gravimetric energy density of diesel.
Energy density (DME)		Moderate	**28.4MJ/kg** **19.03MJ/L**	~3/4s of the density of diesel, but high storage volumetric requirements will reduce the benefit. [Lower heating values (LHV shown]
Matching technology		ICE & fuel cells	TRL/SRL 9 (ICE) TRL/SRL 7 (H_2 Fuel cells)	ICE's easily adapted and already available across a range of ship scale powers. Dual fuel options (i.e. Diesel or methanol) possible to provide fuel flexibility. Fuel cell (hydrogen fuelled) technologies have lower TRLs; DMFCs are currently unviable at ship scales. Can support both mechanical and electrical systems.
Storage impacts		Moderate	TRL/SRL 9	Methanol Can be stored in prismatic tanks as a liquid without pressurisation or thermal management. So storage only impacted by additional volumes need to overcome reduced energy density. Material compatibility and health risks to humans need management. DME requires low level pressurisation of cooling to maintain as a liquid – similar to standard propane tanks. This will negate much of the energy density benefit over methanol.
Applicability		All ships		If used in ICEs then widely applicable across all ships sizes and powers.
SWaP (vs. diesel)		Higher		Primarily driven by need for larger tanks for the same range/ endurance to overcome low energy density.
Wider environmental		Good		Low NOx ~(30-50% reduction), SOx (~90% reduction) and Particulate emissions (90% reduction) compared to diesel (both fuels). Toxicity issues with methanol.

Table 7 - Fuel Characteristics – Methanol & DME

Methanol also has health risks associated with it, so it is likely additional safety measures would be needed. Methanol and DME were widely debated as potential marine fuels of interest when the higher tiers of IMO emissions were coming into effect (mid 2010's), however, they have limited benefit on operational carbon emissions and have a low energy density so are considered to be less attractive for future research ship capabilities.

1.4.6 Hydrogen

Hydrogen (H_2) is the most gravimetrically energy dense fuel available, with the exception of Nuclear fuel sources, and offers low to zero emissions at use. Its carbon intensity is therefore highly dependent on its production and source. ‘Brown’ Hydrogen was produced from Coal and hence is highly unattractive from a carbon perspective. Most hydrogen today is ‘Grey’ being produced from Natural gas and hence still offers relatively high Carbon emissions, although ‘Blue’ hydrogen production aims to mitigate this via the use of carbon sequestration and offsetting at production. Finally ‘Green’ Hydrogen is produce via the electrolysis of Water using green energy such as wind, and hence offers the lowest carbon impact. As such it can be described as an Electro-fuel – i.e. a method of turning waste/spare electricity into a useful transportation fuel.

Hydrogen is highly attractive fuel from an emissions perspective and has been pushed as a future solution for many years across a range of different industries. While direct combustion of Hydrogen in ICEs is theoretically possible and being investigated, hydrogen is more practically combusted in ICEs when mixed with other gaseous fuels such as methane. Hydrogen is more ideally partnered with fuel cells where its use results in a process that produces mostly water as a by-product. Several maturing fuel cell technologies are matched to direct use of pure hydrogen, e.g. Proton Exchange Membrane (PEM) fuel cells.

There are currently several barriers to the direct use of hydrogen in larger ocean going ships. Firstly the maturity and size of fuel cell systems are still limited, although there are a number of marine focused hydrogen projects and partnerships developing over the last few years. One example of this is the partnership between Ballard and ABB, and more recently Hydrogen-de-France developing modular PEM based fuel cells at the MW scale. Recent marketing shows proposed packages in the 3MW range [14, 15]. While solutions exist and are now being tested at sea, their current power rating would drive the need for very large arrays of fuel cells to meet the propulsion power requirements of an ocean-going ship. Fuel cells have also yet to see large market demand and hence while prices have dropped, they are currently relatively high-cost compared to mass-produced ICEs. This situation is likely to improve with time, though perhaps unlikely to see parity with diesel based ICEs by 2035.

Secondly, while hydrogen has a very high gravimetric energy density, it has a low volumetric energy density requiring highly pressurised (typically around 350 bar) and/or cryogenically cooled storage (liquefaction) systems to achieve practical on-board storage solutions. While these solutions are relatively mature, they result in significant increases in required space and weight when compared to liquid fuels, or an acceptance of significantly lower operational ranges. Storage tanks are typically mounted on upper decks for safety reasons; this impacts the general arrangement of the platform, but is likely to have greatest impact on working deck areas which are core areas of operations of platforms such as research ships. Again, there is also the corresponding impact on the space inefficiency, and weight distribution (vessel stability) of not being able to use the less operational useful and irregularly shaped liquid fuel tank spaces along the keel.

Finally while there are many programmes and government efforts world-wide focused on developing Hydrogen infrastructure and production, these are still immature and generally low-scale. These are likely to develop with time, but as yet how mature and available pure hydrogen will be in the 2035 timeframe is hard to assess. The initial focus is likely to be on coastal and river applications, generally combined with battery systems to overcome the performance limitations of larger fuel cells (speed of response, start times etc.) [8]. Larger marine suppliers such as Siemens have recently announced partnerships for fuel cell development, but also in creating systems for hydrogen production [9].

In conclusion while hydrogen is highly attractive from a carbon emission perspective, there are significant barriers to its use for long range ocean going research ships in the 2035 timeframe. If fuel cell systems or adapted ICEs become available, then the use of ‘hydrogen-carrying’ fuels such as Ammonia, are likely to offer a more practical solution for future ocean going ships.

6/	**Hydrogen** {H_2}			Gaseous pure hydrogen – requiring liquefaction and/or pressurisation to be practically stored and transported.
Availability & cost	Now	Low		Limited availability in ports, in terms of production, transportation and storage. Costs high.
	2035	Limited		Likely to grow to meet governmental and industrial hydrogen economy aims. Market demand still unclear; may be restricted to ports supporting short-sea shipping (e.g. ferries). Opportunities for direct generation via offshore wind.
	2050	Widely		Likely to continue grow to meet governmental and industrial hydrogen economy aims. Market demand still unclear; may still be restricted to ports supporting short-sea shipping.
Carbon Impact	On ship	Near Zero		No direct carbon emissions on-board.
	Supply chain	Low to High (depends on source)		Would be possible if supplied with ‘Green’ hydrogen but majority of Hydrogen produces is currently ‘Grey’. Blue hydrogen supply options may also develop. Likely to be a wide variation in carbon intensity of hydrogen production around the world and at different supply points.
Energy density (vs. diesel)		Low	**120MJ/Kg** **0.01MJ/L (gas)** **8.5MJ/L (Liquid)** **4.5MJ/L (690 bar)**	Very high gravimetric density (~3 x that of diesel); low natural volumetric density; requires liquefaction or pressurisation to achieve acceptable densities.
Matching technology		Fuel Cells & electric systems	TRL/SRL 7	Marine Systems exist and are being tested at sea - at lower powers than needed for large ocean-going platforms. Recent announcements [9,14,15] suggest modular system may make low MW fuel cells available by 2035. ICE solutions theoretically possible and have been demonstrated – but limited commercial availability currently.
Storage impacts (vs. Diesel)		High	TRL/SRL 9	Significant weight and volume requirements for fuel storage and its associated packaging for cooling, safety, isolation and fire management.
Applicability		Limited		Limited to short range applications in smaller coastal or river vessels. Applicability will grow with time but unlikely to reach research ship scales and world-wide operation by 2035.
SWaP (vs. diesel)		Very high		Dominated by energy density issues of fuel storage – residual electrical system mature and SWaP manageable in most applications.
Wider environmental (vs. diesel)		Good		No secondary emissions of other pollutants if used in a fuel-cell. If used in an ICE, then low levels of SOx, particulates etc., but NOx still produced. Risks in carbon footprint of managing materials required for fuel cells – some will have environmental risks around disposal and recycling.

Table 8 - Fuel Characteristics – Hydrogen

1.4.7 Ammonia

Ammonia (NH_3) offers a volumetrically denser, more practical way to transport and store Hydrogen – a so-called Hydrogen carrier. Its recent more widespread use as feedstock for Selective Catalytic Reduction (SCR) exhaust treatment systems (to reduce ICE NOx emissions), and its transportation on-board ships has also allowed the marine industry to understand and de-risk its use and storage.

Ammonia production is categorised in the same way as hydrogen, reflecting that its production is fed from the combination of hydrogen and nitrogen extracted from the air; i.e. it can be grey, blue or green. The additional stage in processing hydrogen into ammonia requires additional energy, so net carbon emissions can be higher than for pure hydrogen. Currently most ammonia produced would be categorised as Grey.

Ammonia can be used either directly in ICEs or re-converted back into hydrogen and used directly in fuel cells or Hydrogen adapted ICEs. MAN, for example, is developing an ICE designed for use with

Methanol to direct burn Ammonia, removing the SWaP requirements of a system to re-generate hydrogen from ammonia [5]. While the technology appears currently restricted to large slower-speed 2-stroke propulsion engines, there are recently announced efforts by Wartsila to look at smaller 4-stroke engines, and solutions across the power range are likely to be available by the 2030's. In general ammonia engines need a pilot fuel to initiate combustion and require significant exhaust gas treatment to overcome higher NOx emissions. Fuel cell solutions for use of hydrogen are the same as those described in the hydrogen section, but there is some discussion of the ability to direct use ammonia within high-temperature Solid-Oxide Fuel cells (SOFC) which can internally split the hydrogen from ammonia due to their high operating temperatures.

7/	**Ammonia** {NH_3}			Gaseous Ammonia generated from Grey, blue or Green Hydrogen – requiring liquefaction and/or pressurisation to be practically stored and transported. More volumetrically energy dense hydrogen-carrier.
Availability & cost	Now	Low		Limited availability in ports, in terms of production, transportation and storage. Costs high but lower than pure hydrogen.
	2035	Limited		Likely to grow to meet governmental and industrial hydrogen economy aims (as a transportation fuel for hydrogen). Market demand still unclear; but has interest of larger commercial ship supply chain and system suppliers. Opportunities for direct generation via offshore wind.
	2050	Widely		Likely to continue grow to meet governmental and industrial hydrogen economy aims. Market demand still unclear; may still be restricted to ports supporting shipping sectors adopting the fuel.
Carbon Impact	On ship	Near Zero		No direct carbon emissions on-board if converted into hydrogen and used in a fuel-cell; 95% reduction in CO_2 emissions if used in ICE
	Supply chain	Low to high (depends on source)		Would be possible if synthesised with 'Green' hydrogen but majority of Hydrogen and hence ammonia produced is currently 'Grey'. Blue (i.e. with carbon-capture) supply options may develop
Energy density (vs. diesel)		Moderate	**18.6MJ/Kg** **12.6MJ/L** **(Liquid - 37°C)**	Less than half the gravimetric and volumetric density of diesel; requires liquefaction or pressurisation to achieve these densities.
Matching technology		Fuel Cells & electric systems	TRL/SRL 7 (ICE & H_2 Fuel cells) Lower for SOFC	Recent announcements [5] suggest direct combustion of ammonia in 2-stroke large ICEs possible – but limited experience to date. Fuel cells maturing but power limited. Much less evidence of experience in direct use of ammonia in SOFCs.
Storage impacts (vs. Diesel)		Moderate	TRL/SRL 9	Moderate weight and volume requirements for fuel storage and its associated systems for thermal management, safety, isolation and fire.
Applicability		Limited		Limited currently; if supply infrastructure develops, fuel storage and availability of ICEs and/or fuel cells in appropriate size ranges likely to be limiting factors. Applicability will grow with time, potentially supporting use in a research ship – Still likely to be high risk at time of design for 2035 in-service date.
SWaP (vs. diesel)		Higher		Dominated by energy density issues of fuel storage – residual electrical system mature and SWaP manageable in most applications.
Wider environmental (vs. diesel)		Better to Good		No secondary emissions of other pollutants if used in a fuel-cell. If used in an ICE, then low levels of SOx, particulates etc., but NOx production potential very high without exhaust after treatment. Risks in carbon footprint of managing materials required for fuel cells – some will have environmental risks around disposal and recycling.

Table 9 - Fuel Characteristics – Ammonia

Ammonia liquefies at -34°C or at higher temperatures if pressurised, making storage more practical and denser then hydrogen, but still relatively poor compared to Diesel, even before the consideration of additional tank insulation, pipe systems and other handling safety measures need to manage the toxicity of ammonia to humans. Availability currently varies significantly around the world, and production often matches local demands, such as in support of fertiliser production.

Ammonia is currently seeing real interest and push within the commercial marine industry, but is very much at early development. As such it is perhaps likely that supply and matching technology options would start to mature during the design of a future research platform, making its selection attractive, but a higher risk as a single fuel option in a 2035 timeframe.

1.4.8 Stored electricity

It is likely that the majority of future ship power systems will incorporate some degree of electrical energy storage in a hybrid configuration with power generators such as ICEs and fuel cells. This has the potential to provide energy efficiency and performance benefits and even pure electric operation for short durations. This section, however, considers the potential option to wholly use electrical energy storage as a ship's primary energy source, only recharging when alongside. This would represent a zero emissions system at use, and potentially across the supply chain if supplied by green electricity.

There are already examples of battery technology use in commercial service, primarily for short duration ferries. As yet there are no examples with ranges and endurances comparable to deep ocean research ship needs. As an example of the current state of art, the largest battery fitted to date [6] is a 20MWh system on *Stena Julandica* Ferry with gives it a range of around 10nm on a 184m, 1,500 passenger, and 550 car capacity Danish ferry. There are plans to increase the capacity to 50MWh which is claimed will allow the ship to travel one way fully electric (~3.5 hours at sea).

The main barrier for full battery propulsion and power systems for traditional research ship operation is the low energy density of the batteries and matching systems. While the energy capacity of battery based systems has risen significantly in recent years (driven by automotive and consumer electronics industries) and has the potential to continue to do so going forward, batteries are and will continue to be significant less energy dense than liquid fuels. The best of current performing batteries (such as used in a Tesla model 3 [5]) are ~50× less gravimetrically energy dense and 14 × less volumetrically dense than Marine diesel fuels.

Marine batteries are made up of long strings of small cells combined in parallel and series to meet the required voltages, while offering some level of resilience to single cell failures. The energy density of battery systems is highly dependent on packaging requirements, which are driven by the need to monitor, protect, cool and isolate individual cells and strings of cells to support both system resilience and to mitigate the known safety issues with some battery chemistries.

Battery life and hence overall cost through life is also another potential concern for future ship based designs. While cell life is growing, almost all chemistries have lives that are dependent on depth, rate, and number of cycles of charge and discharge, but also on ambient environmental conditions. Battery life issues further reduce net energy densities through the need to incorporate margins to overcome a drop in performance with time. For long-life vessels such as a research ship it would be highly likely that batteries would need to be changed during its life, incurring potentially significant costs, albeit these may be mitigated by reduced operating costs.

An alternative to closed cell batteries are flow redox batteries. These are cells in which the energy is stored in liquid electrolyte pumped from a tank into a cell. The use of liquid electrolyte offers a potential benefit in the ability to re-charge the electrolyte ashore and simply re-fuel a vessel in a traditional manner. Recent studies including the Shore Power for Shipping (SPIDS) project [7] show that the latest technologies have seen improvements in energy density and suggest they could compete with traditional cells on costs and density, and even with ICEs on example short-sea, coastal applications.

Full battery propulsion systems are unlikely to be viable for larger deep ocean shipping requirements, including research capabilities, based on the known emerging technologies likely to be available by 2035. The rate of development of battery technology (along with cost reductions), will, however, make battery power highly attractive for use in hybrid propulsion and power systems for future large research ship designs. There may also be potential options for the introduction of smaller coastal/regional vessels as part of a reorganised, restructured research fleet, which if coupled with, for example, with UK and EU coastal infrastructure development proposals [21][23] could provide further opportunity for use of batteries.

8/	**Stored Electricity**		Stored Electrical sourced from shore based electric generation infrastructure & networks	
Availability & cost	Now	Limited	Shore connectivity available at many ports – but not everywhere and electrical capacity can currently be limited in certain locations. Electricity costs low; system costs high.	
	2035	Widely	Likely to grow to meet demand for both all electric applications (e.g. ferries) and to support wider use of shore power to reduce in-port emissions.	
	2050	Widely	Likely to continue to grow to meet demand for both all electric applications (e.g. ferries) and to support wider use of shore power to reduce in-port emissions.	
Carbon Impact	On ship	Zero	No direct emissions on-board.	
	Supply chain	Low	Would be possible to supply with green energy sources.	
Energy density (vs. diesel)		Low	**< 1MJ/Kg** **< 6MJ/L**	Maximum current energy densities (closed cells) stated across a wide range of current battery technologies; rising with development and new technologies, but significantly lower than liquid and gaseous fuels
Matching technology		Batteries & electrical Systems	TRL/SRL 9 (Wide Range dependant on chemistry)	Existing and developing electrical systems and batteries – state of art solutions can be selected at ship design. Ship solutions likely to be an older generation because of cost and need for robustness.
Storage impacts (vs. Diesel)		High	TRL/SRL 9 (closed cell) TRL/SRL 6-7 (Flow)	Significant weight and volume requirements for battery systems, and their associated packaging for cooling, safety, isolation, performance margins and fire management. Experience and class society rules perhaps currently relatively immature but developing. Flow batteries are seeing a resurgent interest, but have had less focus and investment to date.
Applicability		Limited	Limited to short range applications. Applicability will grow with time but unlikely to support ocean-gong longer endurance ships needs by 2035 or even 2050.	
SWaP (vs. diesel)		Very high	Dominated by energy density issues of batteries – residual system manageable. Batteries will need to be serviceable and removable through-life. Flow battery applications – less evidence found for net impacts.	
Wider environmental (vs. diesel)		Good	No secondary emissions of other pollutants. Risks in carbon footprint of materials required for batteries, electrolytes and electrical machines – can include rare-earth elements; some have environmental risks around disposal and recycling.	

Table 10 - Fuel Characteristics – Stored Electricity

1.4.9 Nuclear energy

Nuclear power (either thermal battery or fission reactor based) technologies have been considered in the past for commercial ship applications such as high-speed cargo ships and ice-breakers. Operationally Nuclear power offers zero-carbon emissions, but depending on the technology considered there is often significant carbon emissions from the mining, processing, and disposing of nuclear fuels and systems.

To date these technologies have proved unviable commercially due to cost, with initial, support and decommissioning costs far outweighing through-life cost benefits. Currently most ship-board nuclear systems are designed for naval use and hence are subject to availability, security and safety limits and are also generally overpowered for most commercial vessel applications.

Nuclear also brings considerable and often unpredictable risks with respect to varying world-wide political and social opinions of nuclear energy, as well as the need to manage the impacts of security, risks of accidents and a need for significant shore based shore infrastructure to support it. Operationally this drives risks around access to certain operating areas and ports.

The consideration of nuclear power for ships has seen a slight resurgence recently due to industry efforts looking at alternative, potentially lower risk, and lower cost nuclear technologies. Also the concept of compact, modular, factory-built reactors (often described as Small/micro Modular Reactors (SMRs/MNRs) based on low-enriched fuel are also being considered to reduce set-up costs. These technologies are currently focused on shore based applications but could offer maritime opportunities in the longer term.

Based on current and expected technology risks and costs, nuclear options are unlikely to be viable or cost effective for future research ship applications in the 2035 timeframe, despite its low operational Carbon emissions.

9/	**Nuclear energy**		Use of nuclear isotopes either to generate heat and hence power from decay, or via fission in a reactor	
Availability & cost	Now	Limited/ High Cost	Wide range of nuclear fuels and technologies available but at high costs from limited sources and suppliers	
	2035	Limited/ High Cost	Unlikely to see significant change from now	
	2050	Some/ High Cost	Potentially depending on the development of SMRs – cost may be significantly reduced, but likely to still be high relative to fuel based systems	
Carbon Impact	On ship	Zero	No direct carbon emissions on-board	
	Supply chain	High	Fuel and materials extraction, processing, build, storage and disposal generate significant carbon emissions	
Energy density		Highest available	**3.9Million MJ/Kg**	Very high energy density within a range of isotopes (U235 listed here)
Matching technology		Steam & electric plant	TRL/SRL 9	Mature matching plant, but current limited suppliers and high costs, both in nuclear system design but also to support matching steam-to-electricity systems. Likely to need fall-back power systems for safety.
Storage impacts		High	TRL/SRL 9	Containment and shielding would impact SWaP and overall ship design, access etc. Would attempt to design to be fuelled-for-life as refuelling general complex and costly.
Applicability		Larger ships	Would only be viable in larger ships due to impacts of protection and shielding the nuclear plant. Also almost all current nuclear plants are relatively large and high-powered – much higher than need by a research ship.	
SWaP (vs. diesel)		Higher	No tanks required, by significant space needed for nuclear plant, it's supporting systems, protection, shielding, redundant systems and steam plant.	
Wider environmental		Poor	Dominated by the need to treat, store and dispose of spent nuclear fuel, and by the complexity of decommissioning the ship at its end of life.	

Table 11 - Fuel Characteristics – Nuclear energy

1.4.10 Secondary sources – Wind & Solar

While wind and solar cannot be considered as fuels, they are discussed here as they can form a primary or secondary energy source to support ship propulsion and/or power generation. They are inherently low carbon in nature, in effect harvesting additional energy at point of use, reducing or negating the need for primary fuels and their associated supply chain carbon emissions. They are described here as secondary sources to reflect that in general they reduce the power demand on the ships primary fuel powered engines and generators, or they can provide Wind Assisted Propulsion (often described as WASP). While theoretically wind may provide a primary propulsion system for some future commercial shipping, those platforms will have to still retain some level of fuel powered systems for safety, redundancy and to maintain schedules.

There is resurgent interest in wind systems, with the design and materials options for sail, wing, foil and rotor based propulsion system having seen significant improvements in operation, efficiency and hence power outputs. This has been driven in part by yacht racing teams and superyacht designs. Several organisations are investigating the feasibility of sail based commercial vessels, where sail forms the primary propulsion method. The International Windship Association describes seven categories of wind systems; Soft sails, Hard sails, Flettner Rotors; Kites, Suction wings, Turbines, and Hull-shaping Wind Systems. It's also interesting that most of the classification societies have updated their rules with respect to wind propulsion in the last 2-3 years.

Rotor systems are seeing a resurgence from original trials in the last century; they have been added to cargo ship decks to reduce power demand on the main engines. The key challenge for all of these system is the need for free upper deck space to mount and manoeuvre the sail or rotor based systems, hence it is most attractive for ships such as bulkers where the main weather deck only becomes a working area when alongside to load or unload cargo. They are also best used in locations and routes with reasonably predictable winds.

Kites have also recently been tested at sea. These have the advantage of operating off board, only demanding winch and recovery areas on the ship. Kites are size limited (by line weight and strength) so can only ever be a propulsion assistance system. Experience has shown that they need to be fully automated for crews to routinely use these systems, and that the costs savings from reduced fuel use need to be considered against the cost of replacing any kite losses.

Wind can also be used as an electrical generation source via on-board turbines. Outputs are likely to be low and mounting locations restricted on many vessels due to other upper deck needs (e.g. communications), hence these systems can be considered more as an energy efficiency measure.

Solar cells have seen significant decreases in cost and also notable increases in power outputs per unit area. This is likely to improve further by 2035 and may include technologies that can be integrated or applied as a coating into structures or other materials (e.g. glass). Many ship types have large unused upper deck surface areas that easily host solar cells, however outputs are low per unit area and hence are only ever likely to reduce net power generation needs on large commercial ships. It is also harder to maximise outputs due to the impacts of salt spray (and hence the need to clean) and the fact cells cannot easily be orientated to track the sun on a free moving platform.

Various wave based systems have been proposed at ship scales. Again these are better considered as an energy efficiency measure, as they generally harvest the wave energy to reduce the required propulsive power through the use of underwater foils. Their effectiveness is limited and varies with ship speed and wave conditions. They are also likely to be size limited by stress and strain considerations as well to avoid their own parasitic drag at low speeds and the need to safely navigate and dock the ship.

While these techniques have already shown value in smaller low-speed science focused marine platforms, their application to large multi-role research vessels is more challenging. These ships have limited usable upper deck space to host large systems, whether wind or solar based, with these decks needing to be accessible for the handling and storage of off-board systems or to conduct on-board science directly, or potentially helicopters. Equally these platforms operate across a wide speed range, including periods operating near stationary. This drives a need for high-powered mechanical based propulsion systems for speed and manoeuvring flexibility and accuracy, leaving only transit periods for effective use of WASP systems.

Solar system are likely to be deployable and have improved in energy density by 2035 and could provide useful efficiency boost to power generation based on other fuels. Rotors, suction and hard sails and kites are also possible options to provide propulsion assistant in transit, but would need a balance of investment to be undertaken during the design process.

10/	**Secondary sources (wind, wave & solar)**			Use of natural energy sources (Wind and sun) to generate secondary electrical energy – likely to be a supporting energy source, or need an additional energy source for hotel and/or additional propulsion needs.
Availability & cost	Now	N/A		Sun and wind are in effect infinite, if highly variable natural energy sources – harvested at point of use. Costs limited to procurement only – typically low payback periods.
	2035			
	2050			
Carbon Impact	On ship	Zero		No direct emission from either wind or solar. Some slight Carbon emissions if actuators, winches etc. are powered by a Carbon intensive primary fuel/ energy source.
	Supply chain	Low		Only emissions associated with build and disposal of the systems themselves. No energy deliver supply chain.
Energy density		Poor	**N-A**	Wind and solar system relatively inefficient, but acceptable as energy source is in effect free. Energy density will depend on route, average weather conditions, and size of usable upper deck areas and spaces.
Matching technology		Energy storage & ICE	TRL/SRL 9	Wind systems largely independent of primary power generation systems (however fuelled) – general act as an assist to a primary propulsion, but could provide the majority of propulsion on some low speed vessels in the future. Solar can be connected to any electrical system, but ideally requires electrical energy storage (e.g. batteries) to mitigate variation in generation and use.
Storage impacts		N/A		As above – benefit of adding electrical energy storage if using solar cells.
Applicability		Depend on upper deck design		Wind systems – require varying levels of upper deck space for rotors, sails or kites. Solar systems – relative low power outputs of solar cells requires significant upper deck and superstructure areas to be fitted with cells to provide useful powers. Future flexible coasting, films and integrated window solar cells may have ship applications. All options will have varying impacts on the design of working decks, cargo decks, and superstructure, and could impact access, cranes, masts, flight decks and pilot house visibility.
SWaP (vs. diesel)		Variable		Often a secondary system in effect reducing demand on primary power systems. Large scale use of Sails may allow wind to be a dominant propulsion system in the future, but still likely to need secondary electrical generation system. I.e. Likely to significant impact overall SWaP of power systems on a ship due to their size and area needs, and because they are an additional system.
Wider environmental		Good		No significant other environmental impacts, other than associated with final disposal of the system or from potentials loss of sails, panels, or kites at sea.

Table 12 - Fuel Characteristics – Secondary energy sources

1.5 Alternative marine fuels – summary

Key conclusions with respect to fuels market and availability of options in the 2030's:

- *Alternative Fuel options are maturing* – there is an expected trend towards gaseous fuels in the interim (LNG & LPG), potentially operating in dual or multi-fuel enabled systems that support continued use of diesel where supplies or costs are unpredictable during a ship's life. In the longer term there is an expectation that Ammonia will be the solution for larger deep ocean international ship operations and the use of stored electricity or hydrogen will support shorter range coastal ships

- *Fuel choices will diversify in the medium term* – i.e. the market place will have multiple fuels available to varying degrees around the world, all with different carbon intensities depending on local power generation and fuel feed stocks. Operators may use different fuels for their ships depending on operational location, supply chains on main routes, and whether it is coastal or deep-sea in operation

- *Significant uncertainty around supply, costs and matching infrastructure* – supply chain and infrastructure are immature, hence uncertainty to predict clear fuel and machinery solutions.

- *Renewable electricity availability a significant risk factor in market* – Many fuels, to be green, will require a significant increase in renewable energy production. EU studies, for example, show that green energy demand would have to increase by over 60% current levels just to meet its civil aerospace synthetic fuel demands.

- *Overall Carbon intensity of a fuel is complex* – need to aware of the carbon intensity of WTT production as much as operation use (TTP). Estimating and understanding energy source-to-use carbon impacts of fuels is complex and influenced by the selected process, feed-stock, electricity source and hence is geographical and plant specific.

- *Bunkering locations & local supplies of fuels will change* – reflecting the fact that fuel synthesis will be produced near areas of significant renewable energy production and/or are close to relevant chemical and biomass feed stocks.

Conclusions around specific fuel options for future RV capability:

- *Stored electricity & Hydrogen attractive in smaller, low range coastal applications* – energy density of batteries, and storage density of Hydrogen unlikely to support ocean going ships even in the long term, but both offer true zero-carbon operational emissions

- *Ammonia most attractive long term option for larger, longer range ships* – Potential to be a true net-zero fuel, but production volumes and availability immature. Other gaseous fuels may offer a transition to ammonia (e.g. LPG) as market develops. Will impact ship design, costs and ranges as still has a relative low energy density.

- *Current focus on LNG is waning* – risks around methane slip and only limited CO_2 emissions reductions suggest it is not a long term solution to zero GHG emissions.

- *Synthetic or E-diesel diesel* – are attractive as drop-in fuel replacements, but there is limited development to date, volumes are low, production energy intensive and costs high. Would still create operational emissions.

- *Bio-fuels likely to remain limited to blending* – Waste streams are finite and crop based bio-fuel sources will have to compete with food production making it highly unlikely that production volumes can meet shipping needs in volumes suitable for anything other than a blend. Wide mix of carbon intensities based on production method – some higher than fossil fuel based diesels.
- *Methanol and derivatives expected to see limited uptake* – expected to be suited to niche applications, potentially linked to local availability of supplies.

Conclusions around matching technologies to enable the adoption of alternative fuels:

- *Technology development unlikely to be a barrier* – while fuel cells may still be immature and not cost competitive in the short term, there is good evidence that there will be single, dual or multi-fuel ICE options able to manage the expected range of fuel options by the end of the 2020's. This may even include those capable of using blends of hydrogen.

- *Transition pathways & fuel flexibility will be needed* – i.e. it is possible that an intermediate fuel solution will be needed for ships built in the 2030's to bridge availability gaps and inconstancies of a longer term zero-carbon fuel options. This might be delivered by the initial use of a fuel with similar characteristics, or through the continued ability to use marine diesel through the use of dual or multi-fuel ICEs. This may also include design flexibility to allow mid-life upgrades to new technologies such as fuel cells.

- *Electrification and hybridisation are enablers* – Electrification of power and propulsion systems provides the flexibility to integrate many enabling technologies for alternative fuels. This will include fuel cells and energy storage, as well as a range of EMMs (see next sections). With appropriate design it also allows easier technology changes and upgrades through life.

Recommendations with respect to alternative fuels

1 Maintain a market watch up to the commencement of initial design for future ships – i.e. be ready to adapt and modifying specifications and requirements for the next ship(s) based on best data and information. Also supports touch points with key suppliers and ship designers to optimise options based on maturity and market take up which can be proposed in response.

2 *Develop design concepts to understand risks and opportunities to science capability of low to zero-carbon fuels* – designing high-level multi-fuel or gaseous fuel based RV design concepts would provide better data to assess potential impacts to ship and science capabilities.

3 *Explore potential to conduct early de-risking of alternative fuels on current platforms*. If feasible this would open up life extension of current ships, and hence move future ship design and build windows into a time where more certainty around options and market direction is available

4 *Develop partnerships with similar operators to explore options and risks* – smaller operators will need to develop partnerships with operators of similar ships to mitigate costs and risks of developing and adopting alternative fuels.

1.6 Influencing energy demand & use

Operational carbon emissions will, in part, flow from managing the energy consumption demand of a future vessel – i.e. through both managing energy demand in design and though operational Energy Efficiency Measures (EEMs).

The consideration of EEMs is important at design, in part to influence the resultant ship's IMO Energy Efficiency Design Index (EEDI). It will also be important to continuously assess and improve through-life to support current Ship Energy Efficiency Management Plans (SEEMP). It is likely that the current development of the IMO Energy Efficiency Existing Ship Index (EEXI) (in force in 2022) will also drive operators to demonstrate continuous improvements through life, which will heavily rely on EEMs, if operators are unable to utilise zero or low carbon fuels.

EEMs can mitigate the emissions from the use of higher carbon fuels, but they could also mitigate the energy density impacts of low or zero carbon fuels following their adoption. Critically any efficiency measure will mitigate costs irrespective of the fuel used.

Energy consumption will, at the highest level, be as a result of the following highly interlinked design choices:

i. **Required science capabilities to be hosted, deployed or recovered on-board** – these will influence factors such as the overall platform size, the required range and endurance, and design issues such as ice capability. This needs to be considered in the round; i.e. not just in deployed systems and capabilities but also in their resulting impact of the corresponding crew and science staff requirements. All of these factors will result in a baseline energy requirement for the vessel both to meet the matching propulsion need and the hotel/services loads.

ii. **Operational regime** – i.e. how the platform is used and operated, both individually but also within a wider NOC fleet and potentially a wider UK collaborative fleet context. This will again influence the individual platform's size, speed, range and endurance, but also areas such as systems design. A platform's power and propulsion systems would, for example, be very different for a highly predictable operation regime (constant speeds; limited station-keeping) than for one that is optimised for high degrees of flexibility in operation (mix of speeds; station-keeping; highly varying service/hotel loads). Net energy requirements will flow from correctly matching hull, propulsion and power system design to the expected operational regime. This is a key area for a future fleet restructure as part of a 'UK wide fleet renewal strategy'.

iii. **Crew & scientist numbers** – While there is a link between crew levels and energy consumption, this is not a linear relationship. Reducing the number of crew or scientists could have a benefit on overall ship size and the associated systems needed to support habitability. However increased levels of automation and a reliance on, for example, flying specialist engineering crew to lean or un-crewed platform would in turn reduce the overall net benefit

iv. **Hull, power & propulsion & auxiliary systems selection** – while designing for i & ii allows a degree of optimisation to the specific future requirements, there are also a range of technologies and design approaches that could additionally be applied to reduce energy demand. These include, but are not restricted to; hydrodynamic optimisation; use of alternative materials (light-weighting); energy recovery & re-use; and novel approaches to thermal management.

v. **Digitisation, automation and AI** – i.e. the ability to automate a range of ship management and science functions, either enhancing capability or to reduce on-board requirements for crew and scientists. While this may reduce energy consumption through reduced platform size, better energy management and a reduction in crew and scientists, it is also likely to increase energy demand to power additional actuators and sensors, and to support higher levels of computing and communications.

vi. **Use of secondary energy sources** – effective use of solar, wind or thermal energy sources to provide energy at point of use. Pragmatically the viability of these systems at sea will improve up to 2035, but are unlikely to remove the need for stored energy in the form of fuel or electricity, so are most likely to be considered as an energy efficiency measures.

The UK government, NERC and NOC will have significant influence over design and operational choices described in i & ii above.

They will have less influence over those listed in iii, iv and v, as their selection and use will be highly dependent on the net availability, maturity and the relative affordability of systems and design features in the late 2020’s (at a notional design selection point for 2035 in-service vessel). There will be a balance between procurement costs and the resultant carbon-emissions.

Energy efficiency through good design, appropriate systems selection, and optimisation of the operation of a future platform has the potential to significant reduce net energy reduction, but cannot achieve carbon neutrality alone.

It is also important not to consider a vessel’s potential energy efficiency improvement as a sum of a selection of energy reduction measures. Most measures are interconnected and many offer optimal benefit across a limited speed or power range, and can even reduce efficiency outside of these ranges. The selection of two similar measures, say in the hydrodynamic area, are likely to reduce the net benefit to significantly less than the sum of two if used independently, and have the potential to interfere with each other without whole systems level analysis and design. Adding features that offer improvements in narrow speed ranges that the vessels seldom operates within either initially or due to a mid-life change in operational regime could also present a poor return on investment.

Over-optimisation of a ship design and its systems to minimise energy use or carbon emissions also creates a risk that changes in operational tempo, profile or science mission through-life could result in a significant drop in efficiency. Hence designing for operational flexibility, while potentially resulting in an uplift to emissions compare to an optimised design could offer a greater net benefit through-life. An example of this would the use of all-electric integrated power and propulsion system which would allow the optimal use of all generation engines for all energy needs across the vessel irrespective of operating profiles.

To date the focus in the commercial marine sector has been on energy technologies that offer the best paybacks – e.g. technologies whose resultant fuel cost reduction can payback the non-recurring costs. This approach is less relevant if a primary aim is to achieve net-zero carbon emissions unless those organisations have a value assigned to them. This approach also requires enterprises to be able to invest saved future operational costs against initial procurement costs which is often challenging, especially for government agencies.

1.6.1 Energy Efficiency Measures (EEMs) – Behavioural

Raising awareness regarding the level of priority and targets for energy and carbon emissions reduction throughout the design, build, operational and disposal stages of a ship's life can help to drive carbon emissions reduction through efficiency. For behavioural change to occur and be sustained across an organisation a range of measures, incentives, training and data products will be needed. A widely used approach to considering how behavioural change can be achieved is described in the COM-B model. This suggests for an individual or organisation to successfully change behaviours towards energy use you need to address three interlinked components:

- **Capability** – The individual or organisation needs to have the knowledge, skills, experience, understanding and tools for them to make positive changes with respect to energy. For future research capability it will be essential, therefore to be able to measure baseline energy performance of a ship at design through life to provide an understanding of performance, progress against targets and the impacts of interventions. This information needs to be at a fidelity that supports both operators and corporate reporting, and that supports assessment, and separation of the impacts of both small and large interventions. To achieve this a new ship would need appropriate levels of sensing, data reporting and energy dashboards tailored to different users. Typically data capture today is limited and would need augmenting to help to understand the impact of operating in a highly varying environment (i.e. Waves, weather, temperature etc.). This also suggest a need for continuous energy focused training tailored to different skills, roles and responsibilities.
- **Opportunity** – The individual or organisation has the ability to make a change. This references the need of providing the organisational structures, processes and opportunities for ideas and changes to be made – i.e. empowering people to make positive changes.
- **Motivation** – The individual or organisation is motivated (and not demotivated) to consider energy and make positive changes. This includes both positive and negative behavioural aspects. It is supported by general societal opinions towards energy and the environment (e.g. younger individuals are generally more aware and engaged), but also by interventions. These could include regular reporting, appropriate messaging, through the use of incentives and penalties. A balance is needed to avoid negative impacts, for example, when a target or incentive biases different groups, or if factors outside of an individual's control routinely prevent success. Another common challenge is trying to avoid adding workload to an individual without then seeing a clear benefit.

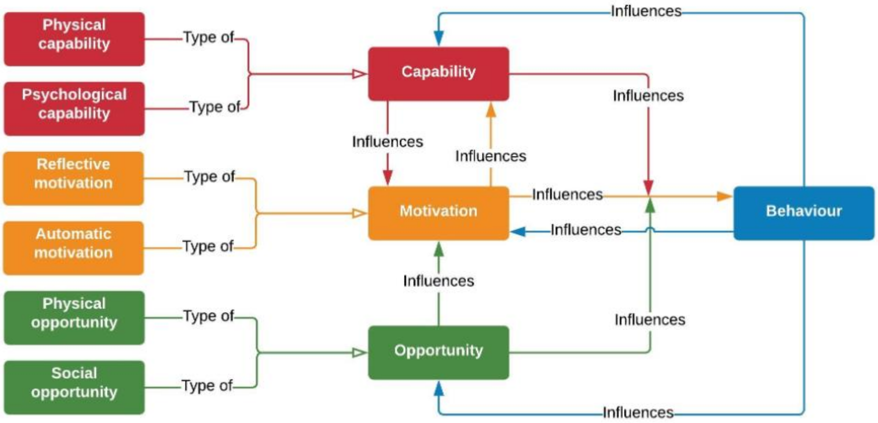

Figure 7 - COM-B model of Behaviours [17]

Practically significant energy reduction can be achieved through changes in behaviours. This needs to be done through a combination of suitable and targeted training, dissemination of meaningful and actionable energy/emissions information and targets, the provision of tools and processes that can assess the impact of changes made and through engagement throughout an organisation's workforce.

1.6.2 EEMs – complement reduction (crew & scientists)

Other sections in this study consider the various technology approaches that could result in the reduction of crew and/or scientists needed on-board a future research vessel. This sub-section therefore focuses on the energy demand implications of a reduction in personnel on-board.

Reducing complement will reduce the space allocated to the systems that provide hotel services, accommodation, storage, and communal spaces such as messes and gyms. This could reduce the energy demands from those spaces and systems, but also from the macro effects of the ship reducing in size. However the reduction in space and energy demands does not alter linearly with complement numbers; reasons for this non-linearity include:

- Even a single crew member, or perhaps an infrequently deployed small engineering team will need a range of hotel services when on-board. This will include heating, ventilation, air-conditioning (HVAC), fresh and hot water, waste management, lighting, food preparation and sleeping areas. It will also critically include safety systems such as fire suppression systems and life-saving equipment.
- Supporting systems are generally supplied in steps of capability or capacity – e.g. a Hot water system may be identical for a complement ranging between 30 and 50 people. Smaller capacity sub-systems are also proportionally larger than high capacity systems, so a system that is sized for half the demand will not use half the energy or need half the volume.
- A research vessel's size is not simply a reflection of the volume demanded. For a ship with large working spaces, such as a research ship, its size is often defined by a range of length drivers. These will include the required length for a working/handling deck, possibly a helicopter landing spot, off board systems' launch and recovery systems, and for basic ship functions such as boat davits and a bridge. I.e. a reduction in crew, may result in, perhaps, a smaller superstructure, rather than a significant reduction in a ship's principal dimensions, unless the personal reduction is also coupled with a drop in overall science capability. Ship size will also be influenced by deep ocean stability and sea-keeping requirements for both safety and to support science operations.
- Significant space on a ship is allocated to access, e.g. corridors, stairwells, access spaces around machinery and auxiliary systems. Even on an un-crewed platform, while these spaces may be optimised, they will still be needed to allow for maintenance and safety for even occasionally deployed crew or shore based maintenance party.
- Most auxiliary systems, electronic systems and information systems need a degree of environmental support, often comparable to what is also acceptable to humans and hence the potential to reduce HVAC requirements significantly is reduced.
- Added automaton to mitigate the loss of humans in itself will create additional energy demand, waste heat and space.

- A ship's systems will be designed to a maximum surge capacity, hence if crew or scientist reductions are only made for a sub-set of experiments or missions, there is less opportunity to reduce energy consumptions in a ship's design.

In summary energy reduction can be achieved through a reduction in personnel on-board, however there are practical limits and wider design considerations that will limited overall energy reduction.

1.6.3 EEMs – ship design

Technology measures for energy and/or emissions reduction can be split between those that are a fundamental integrated aspects of a ship design and hence must be implemented during the design process and those which could be considered as a standalone additional systems that theoretically, could be retrofitted during a ship's life. This section considers those measures that are integral to a ship's design.

There is already effort within the marine industry to reduce the energy consumption of a range of ship types at design. This is in part driven by IMO MARPOL requirements for steady improvement in the EEDI with time, aiming to ensure that newer vessels are intrinsically more efficient than the previous generation of design. EEDI however is currently limited to larger, more common ship types such as container vessels and bulk carriers. It does not work with complex ships such as a research vessel, in particular unable to reflect the use of integrated electric propulsion systems. It is therefore harder to fully assess and compare design options during procurement. Clearly this may change by the 2030's.

The following are key design EEMs that can be addressed during design development to reduce energy demand, use or improve efficiency. They are split between measures that integral to the ship's hull and structural design and those that implemented within the ships systems (power, cooling, HVAC etc).

EEMs – Ship design (Hull focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
Alternative hull Design &/ or optimising hull form	Hull-form shaping is constantly evolving through a combination of Finite Element Analysis tools and tank testing. For certain applications alternative hull-forms offer efficiency benefits – e.g. X-Bow, multi-hulls; Small Waterline area Twin Hulls (SWATHs) etc. Specific modifications to, for example, bow design can improve sea-keeping and provide energy benefits in heavier seas.	The need to manage both high volumes and masses in a RV are likely to drive the retention of a mono-hull with relatively high block coefficients. Likely possible to make some gains if optimum hull design based on operating profile is used as basis for design. Equally if the hull is designed around expected propulsors their respective efficiency can also be improved. Balancing the needs of transit and station keeping will lead to a compromise however. A balance between sea-keeping, ship motions and efficiency will need to be considered at design, i.e. improvements should not compromise ability to deploy off-board systems in higher sea states. Implemented at design.
Optimising for lower speeds	Reducing ships speed can significantly reduce the energy needed for propulsion.	Current research vessels already have relatively low maximum speeds; likely to be limited opportunity for savings.

EEMs – Ship design (Hull focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
	If this decision is made at design the hull-form and propulsion system can be optimised for the lower speed enhancing efficiency further.	At lower speeds different propulsor options are viable potentially offering other capability benefits in terms of manoeuvrability and station keeping. Implemented at design.
Optimising Appendages	Ships have a range of under-water appendages – stabilising fins; keels; blisters, bulbous bows etc. Modelling and optimising flow and hence design and size of these appendages can offer efficiency benefit.	Current research vessels already have relatively low maximum speeds; likely to be limited opportunity for significant savings. Should ensure appendage design is part of basic hull-form design optimisation. Implemented at design; some potential to retrofit
Optimising Steering systems &/or podded propulsion	Ships rudder impact significant appendage drag. Their size, shape and angle of attack can be optimised to match hull-form shape and speed. Alternative approaches to minimising rudder use can also reduce drag – e.g. through the use of small trailing edge flaps or independent interceptors at higher speeds. Combining steering & propulsion into podded propulsors can lead to higher manoeuvrability and reduced drag.	Current RVs already have relatively low maximum speeds; likely to be limited savings through steering system optimisation alone. Should ensure appendage design is part of basic hull-form design optimisation. Podded propulsors are a realistic option at likely speed ranges of a research vessel – these provide manoeuvring benefit, but if matched to operating speed and integrated into the after-body shaping of the hull can also offer significant efficiency benefits. Podded propulsion also needs to be optimised for research ships stern and side deployment and recovery activities which requires special attention for equipment deployment management. Implemented at design; some potential to retrofit
Superstructure air flow optimisation	While overcoming water drag dominates power requirements for a ship, wind drag also has an impact. Superstructure shaping can reduce this drag and offer operational benefits.	Research ships have a largely defined upper deck arrangement leaving limited opportunity to 'streamline', however good design practices could be integrated at design to minimise windage. Implemented at design; minor modifications possible as retrofit
Hull Lifting bodies	Several concepts for lifting foils and bodies to reduced drag by lifting hull-form slightly out of the water have been tested. Generally only works at higher speeds where lifting effect produces a net benefit over and above the drag of the foil itself.	Unlikely to be applicable for a relatively slow but high displacement ship like a large RV. Implemented at design.
Hull Air lubrication	Uses compressed air fed under the hull to reduce drag at the water-hull interface. Requires a hull form to be shaped to prevent significant loss of bubbles along the hull length.	Most research has focused on large cargo ships and Oil tankers, but high-block coefficient of a research vessel may make it a possible option. Costs to benefit likely to be less than for cargo vessel due to limited benefit when station keeping and less time spent at transit than for a cargo vessel System likely to add a maintenance burden and may be subject to bio-fouling due to long periods at slow speeds or being stationary. Implemented at design.

EEMs – Ship design (Hull focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
Alternative materials	The use of alternative materials to reduce overall structural weight. This may include novel steels, aluminium or composites or hybrids of them.	Currently alternative materials are constrained to smaller vessels due to costs, build capability and availability of skills. For a future research ship there may be opportunities to use composites for key pieces of sub-structures to support weight reduction e.g. bridge wings, masts etc. but likely to make limited impact for relatively higher costs. Significate debate over carbon impact and wider environmental disposal or recycling of non-steel based hulls. Implemented at design.
Wind systems (Sails, Rotors & kites)	A range of wind based propulsion systems are available and are already in use.	Sails and Rotors could offer savings in operational energy, in particular during transits. They do, however have a significant impact on an overall ship design, impacting upper deck arrangements and the operating of working systems such as cranes. A Research Vessel design is not well suited to these technologies due to the combination of a large superstructure, a large handling deck and the potential use of helicopters. These systems realistically can only be considered as Wind Assisted propulsion (WASP) addition of these systems would also not reduce the need for traditional power systems, as they will still be needed to support science operations (e.g. dynamic positioning) Kites required less space, but will produce less benefit (~10%). A research vessels highly variable operation would likely restrict the use of kites to transit periods only, hence the benefit could be limited. Implemented at design; Kites and some small hard sail or rotor systems have some potential as a retrofits.

Table 13 - EEMs – Ship design (Hull focus)

EEMs – Ship design (Systems focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
Integrated all-electric power systems	Power system that feeds both hotel and propulsion loads with electrical generators via a common electrical distribution system.	Already routinely implemented on Research Vessels as it supports efficient and flexible power for dynamic station-keeping with multiple propulsors. Should be retained and optimised as further system level efficiency gains are identified across the market. Also supports easier mid-life changes to generators and systems, and hence supports fuel flexibility and possible mid-life changes to new generators such as fuel cells. Implemented at design.
Direct Current (DC) power systems	Ships power systems have been based on Alternating Current (AC), but there is a trend towards DC distribution with	Likely to be a viable option for a research ship in 2035 based on current trends.

EEMs – Ship design (Systems focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
	available voltages and powers rising. Enables a reduction in SWaP of distribution system components, the use of Variable speed power generators and easier integration of energy storage.	Potential to save weight in electrical system and to improve ICE generator efficiency by operating at variable frequency. Potentially more flexible to change mid-life than AC systems – e.g. Fuels cells and energy storage have DC outputs. Implemented at design.
Integrating Energy Storage - hybridisation	Adding batteries or other energy storage options into the electrical system to manage transient loads, ride-through of faults and potentially powering short periods of operation emission free. This could also include the use of thermal energy stores to reduce energy consumption of cooling / heating systems.	The majority of new ships that require some degree of dynamic positioning are now including energy storage. This provides efficiency benefits through management of load peaks and a reduction in the need for spinning reserve[7]. Inclusion in future research ships is likely to have a significant benefit on emissions and potentially engine maintenance. If energy capacity is increased it may be possible to operate with very low noise and zero emissions allowing low emission harbour entry or to support noise sensitive experiments. Implemented at design; some potential to retrofit depending on space and weight availability
Gas, Dual or multi-fuel ICEs	Marine market has, or is beginning to see ICEs adapted for use with alternative or multiple fuels. This includes gaseous fuels (LNG, LPG etc.) either with diesel as a pilot fuel or as pure gas, and expected developments in the 20's to provide ICEs able to operate on Ammonia and blends of Hydrogen.	Key benefit to future research ships is that the retention of an ICE could enable easier adaptability to varying fuel supplies, either by operating on multiple fuels (retaining the ability to use marine diesel) or to allow easy modification to accept a new fuel during the ship's lifetime. As previous sections have highlighted ICEs may not be the preferred option for some alternative fuels as they still produce other emissions (e.g. higher NOx). Implemented at design; some potential to retrofit depending on design flexibility and engine scale
Alternative power generators	Linking to the alternate fuel options sections – the potential use of alternative technologies, such as fuel cells that are inherently more efficient that today's ICEs.	These systems are likely to be still immature for a 2035 in-service ship. However the potential to add suitable access, weight and volume provisions into a design that would allow later modifications may be highly desirable. This should include adequate access (e.g. soft patches) to reduce retrofit complexity and cost. Ideally Implemented at design; Future-proofing by adding design flexibility could enable retrofit
Sub-system optimisation & procurement based on energy efficiency	Historically much of efficiency focus was on primary power and propulsion systems. Possible to apply systems engineering principals, good requirements setting and processes during design that could optimise the selection and purchase of more energy efficient or smaller auxiliary systems.	Managing energy use, removal and re-use within a ship's sub-systems (cooling, water production etc.) could lead to significant reductions in energy demand. This can be done at design using energy modelling techniques, with an aim of reducing total energy demand, or to utilise waste energy for other purposes (e.g. using ICE jacket water to heat domestic water supplies.) Also a focus within the procurement of the ship's system on energy

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[7] Spinning reserve – reserve power available when an engine is running although not strictly needed from a power perspective, can provide redundancy if the system sees a generator trip, or there is an unexpected load demand.

EEMs – Ship design (Systems focus):		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
		efficiency can ensure that modern, industry leading sub-systems are specified. Implemented during design
Waste Heat Recovery (WHR) systems	Many on-board systems including ICEs produce large quantities of waste heat. WHR systems can capture waste heat from either, or both, exhaust gas or fluid systems to be reused in other ship's applications. These could be to heat domestic water supplies or to generate additional electricity.	Significant developments in WHR systems on-shore, where plant size is less constrained. Some marine systems operational afloat, but again to date mostly on larger commercial ships. Most WHR systems are better matched to steady state operation, so applicability to a Research Vessels highly varying operation may be limited, in both generation and potential uses for the recovered energy. While potentially WHR systems could be considered as an add-on system, the size and scale of most WHR systems would require integration at build. Implemented at design; some potential to retrofit depending on space and weight availability

Table 14 - EEMs – Ship design (Systems focus)

1.6.4 EEMs – technology insertion

A wide range of technology measures have been developed or proposed for marine use. Those systems that can be considered as independent of the core design of a ship and its systems, and hence have potential to be included both at design or as a retrofit are highlighted in this section.

While these measures can be retrofitted, integration at design and build would allow some of them to be optimised and integrated, and hence offer higher levels of efficiency benefit.

These systems could also be retrofitted to existing ships to reduce overall fleet energy use and/or to demonstrated benefit ahead of specification within a new build – i.e. using current fleet as a demonstrator.

Energy Efficiency measures – technology insertion:		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
Electro-Turbo Chargers (ETC) WHR	An alternative WHR system based on extracting energy from exhaust turbo-chargers on ICEs and using it to generate additional electricity.	A compact method of extracting waste energy from ICE systems, however studies have shown it is better integrated and supplied as part of an ICE design. Some indication that engines may include this technology inherently within their design, so this may become more widely available by 2030's Implemented at design; Potentially retrofit
Pre & post Swirl devices	A range of add-on systems to propellers and other hull appendages to improve either the flow into the propulsor or the flow leaving the propulsor, resulting in a net efficiency gain. These include a range of vanes, ducts and fins.	Ideally these systems should be considered when the hull is being designed to maximise their benefit. In many cases retrofitting is still likely to reduce propulsive power and depending on the technology, also benefit areas such as slow speed thrust. Research Vessels operate across a wide range of speeds, so the benefit of these systems may be restricted to a sub-set of speeds.

Energy Efficiency measures – technology insertion:		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
		Implemented at design; Retrofit
Hull Coatings	Coatings continue to evolve and provide energy benefits by reducing surface friction and/or by reducing bio-fouling build up.	The key is to procure best performance level coatings at build and at each maintenance period. Selected coatings should be optimised for research ship speeds and significant periods operating at slow or zero-speeds. Implemented at design; Retrofit at docking periods
Hull cleaning & bio-fouling prevention	Over and above the use of appropriate coatings, implementing a regime of routine hull cleaning will minimise bio-fouling and hence additional hull drag. A range of robotic systems are under development that could be deployed at sea. Also systems that claim to manage bio-fouling through the use of Ultra-Sonics may also provide benefit.	Maintaining a clean hull has a significant benefit on hull drag and hence the energy needed for propulsion. While coatings reduce the burden there is still a need for hull cleaning. Legislation is likely to make hull-cleaning a more complex activity to achieve in water in the future, i.e. there will be a need to collect the majority of waste material to prevent bio-contamination. Robotic systems are maturing and likely to be available by 2035, making at sea cleaning a potential possibility. Independent of the ship Several systems are being marketed that can reduce bio-fouling through the use of ultrasonics – no evidence found that these have been applied to larger ships (such as a research vessel) and there use would need to be considered against any impacts to the science needs of the ship. Implemented at design; Potentially retrofit
Energy management control	The integration of sophisticated ship's systems control that allows a system to automatically configure ship's systems to the most energy efficiency line-up for the given operation.	Most manufactures of Platform management systems (PMS) already offer an 'energy efficiency mode'. This can be restricted to the prime generation system, but if sufficient levels of control are provided on sub-systems it could also manage areas such as HVAC, or water production in the most efficient way. Highly attractive for a Research Vessel with a highly variable operational profile and likely to be offered as standard feature in PMS by 2035. Implemented at design; Potentially retrofit if sufficient sensing and control implemented.
Energy Dashboards	Adding to previous line – a useable, understandable and actionable against, dashboard that allows operators to understand energy use on-board and what they can do to influence it.	Various PMS manufactures have demonstrated dashboards They need optimising and configuring for individual ship types and to reflect crew's training, understanding and motivations to manage energy. Needs human-factors inputs to be successful and to be visible in key operating spaces. Needs to be matched to a level of sensing and control that allows operators to make informed and positive operational impacts to energy use. Implemented at design; Potentially retrofit if sufficient sensing and control implemented.
LED lighting	Slow move to use of low energy LED lighting on ships. Some niche areas still	Low energy lighting likely to be standard design practice by 2030's. Potentially useful to consider lighting needs at design to ensure appropriate, but minimal levels

Energy Efficiency measures – technology insertion:		
Measure	Description	Potential Impact to a 2035 Multi-role research ship's design, efficiency & carbon emissions
	not fully converted – e.g. navigation lights	installed and to manage issues such as colour and impacts to human factors. Ideally Implemented at design; Potentially retrofit.
Variable controls	Replacing fixed speed or flow control systems with stepped or continuously variable controls and actuators will allow systems to operate at or nearer the required power, flow or intensity, minimising energy use.	Implementing variable control of HVAC and fluid systems on a ship can make a notable energy impact and often improves environmental conditions, systems availability and maintenance needs. Likely to be a natural proposal from suppliers if energy efficiency requirements included in specifications. Ideally Implemented at design; Potentially retrofit
Photovoltaic cells (PV)	Integrating PV onto the structure, or in the future potentially within coatings and flexible panels to generate additional electricity.	Limited available superstructure space on a research ship for traditional solar panels. Advances in solar panel manufacture may make it possible to integrate solar capabilities into superstructures and windows or as additive layers of flexible panels and coatings. Need to maintain a watching brief. Also some work to capture multiple radiation frequencies – i.e. ability to generate power from warm water emissions at night. Ideally Implemented at design; Potentially retrofit
Motion based energy recovery	There is significant energy generated from ships motions in sea-states. There has been work to look at technologies to capture that motion and harvest electricity from it.	Immature and currently low yields, but may be a developing technology by 2035. Ideally Implemented at design; Potentially retrofit
Thermal Energy Generation (TEG)	A range of energy recovery technologies that convert heat flow directly into electricity, potentially inserted into ICE exhaust stacks, or cooling systems heat exchangers.	Current TEG systems have very low efficiencies, so perhaps most usefully implemented for local energy use (e.g. on-engine power for sensors). TEG efficiencies may develop by 2035 but area likely to be integrated into individual systems supply, so are unlikely to be specified directly. Ideally Implemented at design; Potentially retrofit

Table 15 - EEMs – technology insertion

1.6.5 Influencing energy demand & use - Conclusions

Key conclusions with respect to general use of EEMs on a ship delivered in the 2030's

- *EEMs cannot meet net zero carbon operation emissions alone*
- *EEMs can reduce emissions on current and future ships* – and help to mitigate the energy density impacts of lower or zero carbon fuels.
- *EEMs need matching to a specific ship type* – Research Vessels have relatively unique hull-forms, propulsion systems and operational profiles making some EEMs more attractive than others. They are mostly closely matching to the offshore support platforms used for offshore energy.
- *EEMs are better designed in, but can be retrofitted* – benefits likely to be higher if part of the design process and optimised with other design features.
- *EEMs need whole-life cost assessments at a systems level* – i.e. they should be consider at design, based on carbon benefit, whole-life costs and compatibility with, or impact on other EEMs. It may be better to improve system design, than add an addition EEM to mitigate inefficiencies.

The most attractive EEMs for future Research Vessel capability include:

- *Electrification and hybridisation* – while already common on Research Vessels electrification brings both efficiency and flexibility benefits, potentially enabling the introduction of alternative fuels & technologies such as fuel cells.
- *Energy storage* – while bringing efficiency benefits, integrating energy storage will also mitigate the performance impacts of some fuel options and their matching power systems. At the right size they can also provide limited zero-emission operational capability in a hybrid configuration
- *Optimised hull and propulsor design* – it is important to base any new Research Vessel design on the optimum hull design based on operating profile. It is also now possible and beneficial to integrate the design of the propulsors into the hull design to optimise flow and hence efficiency.
- *Optimised energy management, harvesting and re-use* – the effective use and re-use of waste energy generated within the ship will ensure efficiency is maximised. This can be achieved through integrated system design, enhanced control, use of waste heat recovery systems and automation
- *Bio-fouling management* – this will be driven by a combination of hull and systems costings, hull cleaning systems and potentially active management systems such as ultrasonics.
- *Behavioural change* – While automation can remove some of the behavioural impacts on energy efficiency, enabling operators and manager to understand, influence and enact changes that improve efficiency is important. This will be achieved through data, dashboards and training, and integration of human-factors in their development

Recommendations

1. *Development is only needed in Research Vessels specific aspects* – i.e. development of the most efficiency hull-form and propulsor combination. Most other EEMs will be procured as mature off-the-shelf solutions
2. *Integrate energy efficiency requirements into future design* requirements – this is to ensure consideration of EEMs during design. This should also include setting requirements and targets against science systems to ensure any growth in energy demand is managed
3. *Maintain a tech watch on the offshore support vessel market* – this include developing/ maintaining relationships and partnerships to ensure technologies and lessons learnt are shared between the communities with respect to ship and systems design and specification and the use of EEMs.
4. *Include EEMs in any future Research Vessels concept development* – i.e. integrate selected EEMs within any alternative fuelled RV ship design development to understand risks, costs and benefits, plus optimal mixes of EEMs.
5. *A study of research ship operating profiles* -completed as a key next step to matching fuel, machinery and efficiency measures to both existing ships and future designs. The UCL energy institute is well placed to carry out this study as a key area of information development.

1.7 Technology options - conclusions

- Reducing or removing operational carbon and wider GHG emissions from future Research Vessels will require the adoption of alternative fuels or energy sources, supported with the potential use of a range Energy Efficiency Measures (EEMs).
- While the range of fuels likely to be offered to marine operators in both the mid and longer term is becoming clear, the availability, adoption rate and cost of alternative fuels, and the pace of development of the matching infrastructure is highly uncertain. This uncertainty is made more complex with some of these fuel options also attractive across a range of 'hard-to-decarbonise' segments such as civil aerospace, resulting in potential future competition for supplies.
- There is likely to be significant carbon intensity differences between alternative marine fuel options. This reflects the fuel type, blend, and production and supply issue. Supply chain carbon emissions will vary with fuel production methods, feed-stocks, and the availability of Carbon-capture and will be based on how green the matching electricity supply is. As such many low or zero carbon fuels (at use) can still have high carbon emissions when considered on a full lifecycle, well-to-propeller basis. Realistic carbon intensities for many fuel options are currently hard to assess as the market and infrastructure is still low volume and immature. As a result any current assessments and recommendations for suitable fuels for research ship capability in the 2030s must be treated with a high degree of uncertainty when considering the total supply chain process.
- All alternative fuel options have lower energy densities than diesel fuels potentially impacting both future ship design and hosted science capabilities. These impacts are amplified by the additional Size, Weight and Power (SWaP) needs of the systems needed by some fuel options to manage fuel storage and safety; for example when changing from a liquid to a gaseous fuel. These impacts could be partially mitigated through ship design optimisation (i.e. matched to the new fuel or fuels), and through the introduction of EEMs to improve efficiency. Without these changes a future research ship design will need to grow in size to maintain current volume and weight provisions for science capabilities.
- It is likely that operators will see a fuel market in the 2030's and 2040's that has diversified (i.e. multiple fuels being available and used) and are highly variable in terms of the regional availability and costs. Bunkering locations are also likely to change in the mid to long term, as are the fuel options they offer.
- It is currently expected that a combination of Hydrogen and stored electricity (for smaller, lower range ships) and Ammonia (for larger longer range ships) will form the dominant low carbon marine energy sources in the longer term.

  Alternative carbon based fuel options have limited operational carbon emission benefits, although may still offer useful net carbon benefits if produced by 'green' methods. These may form transition fuels, allowing ships to be more easily adapted to zero-carbon fuels as their availability matures and to operate in the interim on more widely available, or cost acceptable fuels. An example of this would be to design a ship to operate on gaseous fuels, initially using LPG and then moving to Ammonia in the longer term.
- Nuclear and non-fuel based alternative energy options are attractive from a carbon emissions perspective and are seeing a resurgence in interest, research and developments. Nuclear power, while seeing interesting developments in areas such Small Modular Reactors

(SMRs) are still faced with a range of regulatory, public perception and political challenges, and is currently still high cost. Wind and solar, in the context of a typical research ship design, are limited to being considered as useful EEMs or in the case of wind options a potentially useful propulsion assistance device. They can't meet all of the propulsive and energy requirements of a research ship, its complex operating profile and dynamic positioning requirements.

- The impact of a diversified but immature alternative fuels market will, for most ships built in the 2030's, result in the need to build in fuel flexibility. This may be in the form of operating with multiple fuel capability (including the use of dual or multi-fuel ICEs) or through flexibility in design to allow upgrades and additions to support alternative fuels later in life. This may result in designs, for example, that can operate on a range of gaseous fuels, or on a mix of diesel and a gaseous fuel to ensure world-wide operation is possible, irrespective of local alternative fuel supply constraints.
- It is expected that there will be no significant technology barriers to using the alternative fuel options being considered for marine use. The major manufacturers of ICEs have, or are in the process of developing solutions that can burn a range of fuels, either in a single, dual or multi-fuel system. Many of these systems are already available, with those still in development expected before the end of the 2020's. There is less certainty around the development rate and costs of fuel cells, which would enhance efficiency and reduce carbon emissions (and of other non-GHGs such as NOx and SOx) for a sub-set of alternative fuels.
- Future research ship design are likely to include, and benefit from, enhanced control and automation, the continuing use of advanced electric propulsion systems and the introduction of electrical energy storage into their power systems. Combining these features should ensure improved efficiency and carbon emissions reduction, while enabling future upgrades and modifications to lower or zero carbon fuels and their associated technologies; i.e. provides enhanced flexibility. There are also significant potential benefits of promoting behavioural changes (both at design and operational) with respect to energy use. This requires investment in the technology to support energy management and assessment against targets and incentives.
- There is limited assessment to date on the optimal mix of EEMs for both current and new research ships, when compared to other ship types. Assessment of EEMs needs high quality data and assessment tools, driving a need to capture improved operational data from current ships and to develop or employ models based on high-level research ship design concepts. In part this can also be achieved by maintaining a technology watch on offshore support vessel (OSV) market, whose designs are operationally and physically the closest to research ship designs. As a small community, operating relatively few, and often niche ship designs, it would be useful to collaborate with other research ship operators to support data collection, and the assessment and potentially trials of EEMs and other alternative fuel enabling technologies.
- EEMs are best included in an integrated design with today's retrofit EEMs becoming tomorrow's standard design feature. Most EEMs cane be adopted as mature technologies and adapted for research ship designs, however development of high-efficiency research ship hull and propulsor combination is likely to provide the most significant benefit to efficiency at design and may require dedicated investment.

- Crew and scientist complement reduction will result in energy demand benefits and a reduction in space and system's need, but unless a ship is fully un-crewed, energy use will not reduce linearly with complement number, with research ship designs driven by other factors such as specific science needs, deck space and sea-keeping.

1.8 Technology options - Recommendations

1 *Maintain a market watch with particular focus on offshore support vessel market* – accepting the high levels of uncertainty up to at least the end of the 2020's, there will be a need to adapt and modify emerging specifications and requirements for the next ship(s) based on the best and most current information. It will also be beneficial to develop and maintain touch points with key suppliers, ship designers and other research ship operators to ensure sharing of lessons learnt, and information and experience of design and technology developments.

2 *Capture high quality operational energy data to inform assessment of candidate technologies and designs* – overcome current gaps in data needed to assess fuel, supporting power and propulsion systems, and EEM options. This will also enable designers to develop future research ship design concepts. These resulting designs and assessments can then inform investment decisions, requirements development, optimal mixes of EEMs and future efficient hull and propulsor design. They will also help more generally to understand the risks and opportunities of a range of fuel options on both ship design and on hosted science capabilities.

3 *Explore potential opportunities to de-risk future technologies on current platforms* – this would reduce carbon emissions earlier, open up life extension opportunities for current ships, and reduce procurement and operational risks of key technologies to be integrated in future ships. This could also support delaying future ship procurement to a time where more certainty around future fuel options is available.

4 *Explore and develop partnerships with wider research ship operator community to explore options and risks* – some industries operating small numbers of niche platforms have formed partnerships to spread risk and costs of adapting to future technologies. This approach seems appropriate to the research ship operator community, potentially allowing sharing of operational data, assessment tools and experience or trials data on EEM or enabling technologies.

5 *Develop design requirements, targets and assessment criteria to ensure future ships are efficient and low carbon* – Time and investment will be needed to ensure the most effective requirements and metrics are used in future procurement to ensure a ship is sustainable and low carbon. This is non-trivial, with risks around setting, for example, realistic and measurable targets, and finding a way to balance between costs and resulting emissions. These requirements must apply to both the ship and the science systems hosted upon it, capturing and assessing better data will help to inform these.

2 Capability demand & utilisation - current to 2035 replacement timeline

2.1 Background

This chapter provides a review of the past development of the Natural Environment Research Council (NERC) fleet and the drivers of ship designs to understand the context of why NERC currently operates multi role research ships, and why the fleet structure is as it is today. This section reviews the past development of the fleet, the operational and science community drivers that influenced past ship designs, and assesses the mode of operation of the vessels in response to the requirements of the programming criteria of the NERC Marine Facilities programme (MFP).

There is no doubt that the need for more effective data gathering capabilities will persist with continued focus on marine Earth sciences from the academic, economic and societal perspectives. This could lead to the conclusion that the solution is a next generation research ship simply needs to be 'bigger and better', but it is valuable to review the approach to the fleet renewal programme, alongside some of the emerging disruptive technologies that may provide opportunities to change the way the NERC and the UK wide fleet is structured. This chapter considers how future delivery capability and infrastructure can continue to innovate to not only equal that of our current capabilities, but continue to evolve and expand on these capabilities in response to the changing needs of the science community in a more sustainable and innovative way.

2.2 Context and rationale for multi-discipline global class research ships

Review of the past development of the Natural Environment Research Council (NERC) fleet and the approaches to fleet renewal projects will help to understand the context of why NERC currently operates global class multi role research ships.

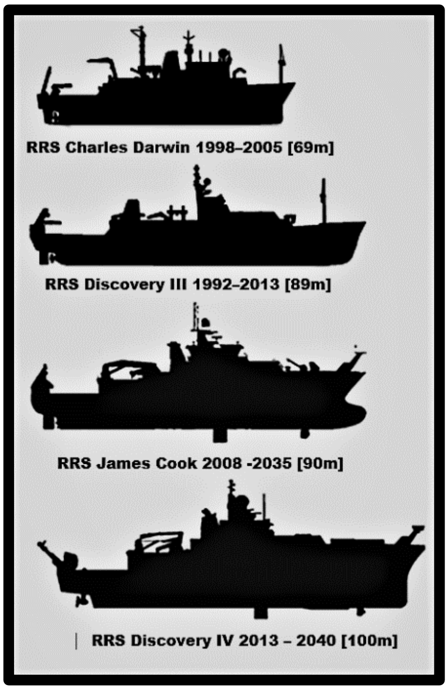

Figure 8: RVS/NOC operated NERC ships since 1992

The general research ship classifications used in this study; Global, Ocean, Regional and Coastal ships, in general refer to the operating regions the ships are designed to be capable of operating in. The classification also gives indication of science compliment, ability to support multiple types of equipment, and operational duration.

Global class ships are designed to operate globally (ice class permitting) and are not constrained to one ocean, they generally have greater science berth capability, can support larger more complex equipment, more flexible multi system capability and longer operational durations. Ocean class ships generally operate within a single ocean, but are mostly also capable of supporting multiple equipment systems with much of their design similar to global class ships, but with limitations due to their smaller size. Regional class ships operate from coast to shelf edge with specialist design for these operations in shallow water to shelf edge, again also capable of multi system operation relative to their size. Coastal ships are generally smaller, highly flexible platforms, support near coast operations and can operate multiple days at sea with smaller science berth capability.

Between 1985 and 1999 the main vessels in operation for the delivery of the Natural Environment Research Council (NERC) Marine Facilities Programme (MFP) were the RRS Discovery II, RRS Charles Darwin and the RRS Challenger; these were classed as Global class, Ocean class, and Regional class vessels respectively (although the RRS Charles Darwin has carried out multi-ocean programmes during its lifetime). The RRS Challenger remained in service until 1999 when it was retired, and the fleet reduced to two ships.

In 1990 the RRS Discovery II began a major two year rebuild transforming the ship into a modern Global class multi role research ship (https://www.youtube.com/watch?v=VOsWgZIfA_Y). This redesign demonstrated a major step change in the capability and technology of the NERC research ships to support the changing requirements of marine science delivery. The redesign which produced the RRS Discovery III, provided a ship capable of supporting the full range of deep-sea multi discipline science research, and the associated equipment necessary for a modern Global class multi role research vessel of her day. This step change in design was driven by the evolving science requirement for multi discipline science projects, and the increasing amount of science sampling and survey technology required to be embarked in support of multi-discipline science projects.

Between 1992 and 2005 NERC operated the RRS Charles Darwin and the RRS Discovery III until the end of RRS Charles Darwin's service in late 2005 when the ship was sold. During this period an increasing quantity and variation of equipment was being installed for expeditions, with increasing numbers and diversity of scientific teams and technicians embarked to support the integrated multi discipline science projects. Both the Darwin and the Discovery III were multi-role ships, designed with configurable decks, over side handling systems to deploy a range of over board sampling equipment, and laboratories supporting the installation of a broad range of portable laboratory equipment integrated into the ships support infrastructure.

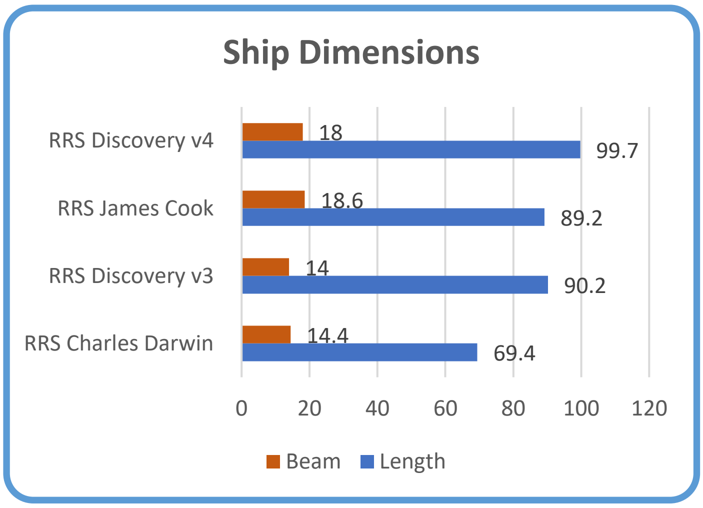

Figure 9: ship dimensions (Curtesy G West)

In 2006 the multi role, multi discipline concept of ship design was further progressed with the replacement of the RRS Charles Darwin with the RSS James Cook. The James Cook's increased size and power, comprehensive laboratory space, increased number of science berths' and equipment support systems, were a further step change in the multi role capability of the research fleet. This trend in increased ships capability was again driven by the multi discipline requirements of the UK science community, together with the rapid advance of specialist scientific survey and sampling equipment.

This approach continued into the replacement of the RRS Discovery III in 2013 which again resulted in a larger, more powerful, and more multi role capable vessel than its predecessor. The progressive development of research ship capability between 1985 and 2013 was in response to the scientific requirements to continue to enhance multi discipline science operations. Parallel developments in equipment technology were able to be integrated into the increasingly complex and technologically advanced research ship design. In turn, these increased capabilities required greater numbers of embarked scientists and technicians to support the increased quantity and complexity of science support equipment.

The advances in multi role capabilities of research ship design over the past 3 decades is a result of a number of factors; the increasing collaboration across science disciplines, the adoption of new technology to support science at sea, and the requirement (and ability of the ship) to operate more remotely, in increasingly challenging weather conditions. The development of scientific requirements was matched by rapid technology developments providing new generations of sampling, survey, sensing and data management tools, much of which required large multi role research vessels to enable their operation at sea, further enabling the multi discipline science aspirations of the science community.

This feedback loop of enhanced science requirements, developing technology, larger more capable ships, and greater numbers of embarked scientists and technicians is also reflected on an international scale across the marine science communities. The fleet renewal programmes of the EU Global Class vessels show a similar trend of larger more capable ships able to support larger specialist equipment, long duration expeditions and greater numbers of embarked scientists and technicians.

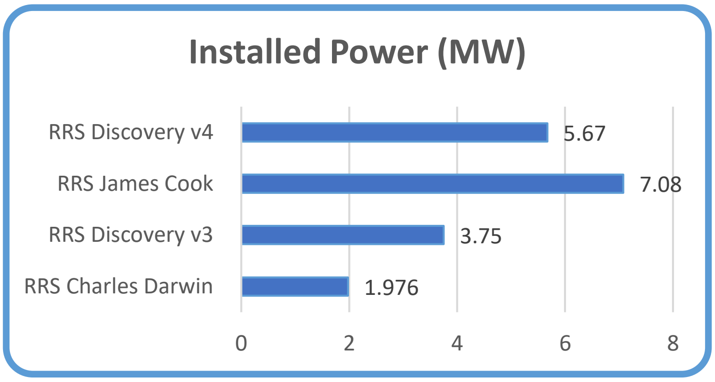

Figure 10 ship installed power (Curtesy G West)

In 2019 the European Marine Board commissioned an expert working group to produce a position paper titled *Next Generation European Research Vessels [29]*, which carried out a comprehensive review of the European research fleet along with the key equipment used to support research at sea. Based on the extensive reviews of the EU research fleet the report outlines the essential role of Global class multi discipline research vessels in supporting large portable equipment such as deep water ROVs, Rock Drills, large seismic systems and long coring systems. The Global class vessels also cover the essential requirements of deep water capable winch and cable systems, large numbers of personnel, portable laboratory containers, and the laboratory equipment needed to support multi discipline deep water research. The most capable Global class vessels in operation across the EU are owned by only four countries; the UK, France, Germany and Norway. A small sub set of these (which includes the RRS James Cook and the RRS Discovery), fulfilling the majority of large multi role vessel criteria.

Reflecting on the past three decades, the marine and science technology sectors ability to respond to the innovative requirements of the science community by developing the ship designs, and new sampling, survey and sensing capabilities, is a hugely positive success story for those involved with marine science and technology which has dramatically increased the ability to carry out marine research across the world.

2.3 Rationale for operation of multi-role global class ships: 2035 replacement of the RRS James Cook

The National Oceanography Centre (NOC) operates two large Global Class research ships on behalf of NERC which carry out a broad range of multi-discipline science operations in any one typical programme year, using multiple ports within the UK, EU mainland, and internationally. Each annual programme will comprise a mixture of coastal, regional and international expeditions, with each expedition of varying durations.

For this report it was important to review the operational profiles of the NOC ships to understand three key areas of operations projecting to a replacement of the RRS James Cook;

- The viability, and impact of the various alternative fuel options for a future research ship design based on an assessment of the ships operational profile. (Previous chapter).
- The potential technology development in the areas of ship design and autonomous capabilities, and how these will influence changes to the fleet structure and operational practices to deliver the NERC marine science remit.
- The scale of use of ship fitted and portable science equipment and how this equipment may change in the coming decades, and how emerging technology may change and influence human interactions at sea for the science community.

2.3.1 Operational durations and geographical profiles of expeditions:

Figure shows the combined number of days at sea (direct science activities) for the RRS James Cook and the RRS Discovery over a 4 year period based on geographical region of the start and end port calls. The review of the NOC ship operational profiles is based on programmed activities, geographical areas of operation, and typical operational duration over a period of four programme years; 2016/17, 2017/18, 2018/19, and 2019/20.

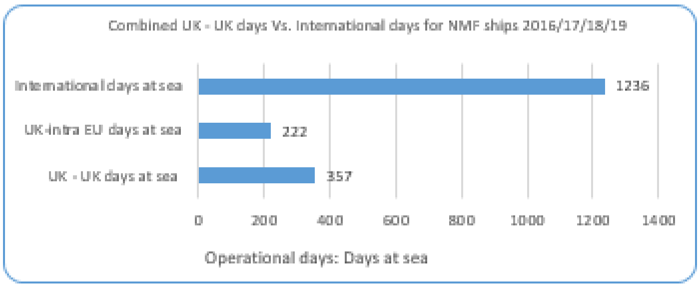

Figure 11 - Combined UK-UK vs. International Days (2016-19)

For the UK to UK expeditions over the 4 year period the total number of expeditions was 16, the average duration of expeditions was 21 days.

The breakdown of days shows that the majority of expeditions (13 out of 17) were ≤25 days at sea. 2 of the expeditions were greater than 30 days duration

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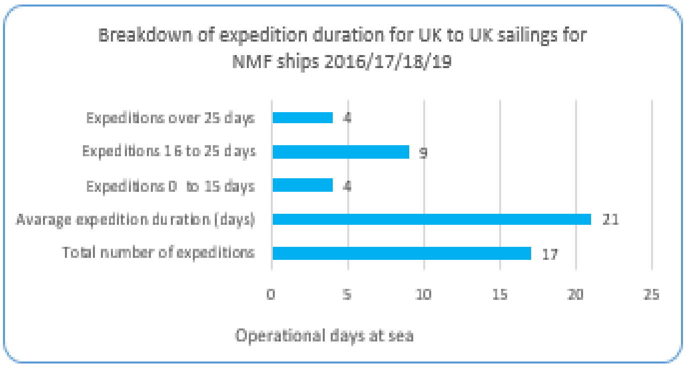


Figure 12 - Expedition duration for UK-UK sailings 2016-19

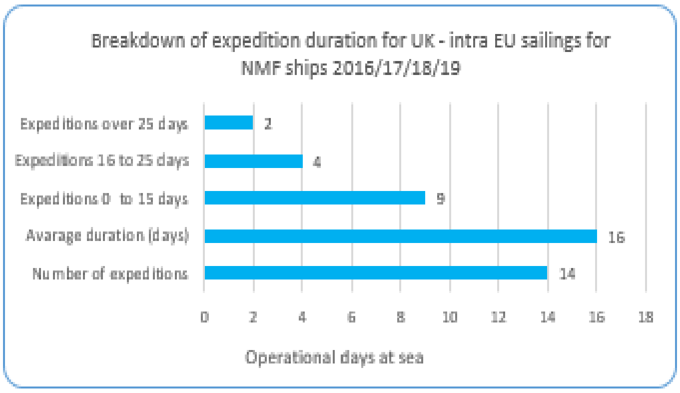


Figure 13 - Expedition duration for UK-EU sailings 2016-19

For the UK to intra EU expeditions over the 4 year period the total number of expeditions was 15, and the average duration of expeditions was 16 days. Figure shows the breakdown of the number of days at sea for these 15 UK to intra EU expeditions.

The breakdown of days shows that the majority of expeditions (13 out of 15) were ≤25 days at sea.

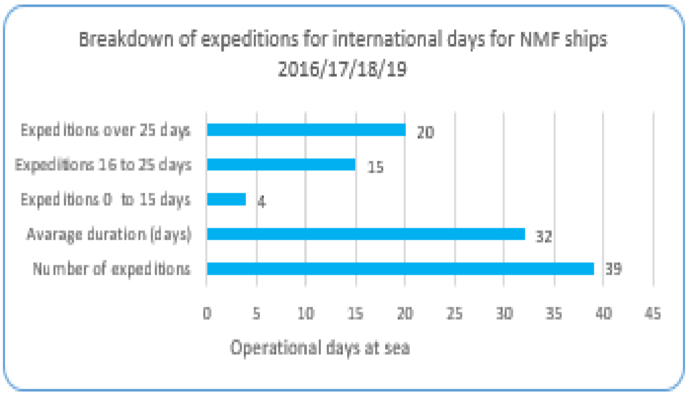


Figure 84 - Breakdown of expeditions for international days 2016-19

(International data includes international outbound from UK / international inbound to UK & deep water UK to UK)

For international expeditions over the 4 year period 2016/17/18/19 the total number of expeditions reviewed was 39, and the average duration of expeditions was 32 days.

Note: All data in above figures is from the NERC Marine Facilities planning system.

A further breakdown of days shows that the majority of expeditions (35 out of 39) were over 25 days at sea. For international operations 20 of the expeditions exceeded 30 day durations with 17 expeditions operating towards the upper duration limits at 37 days.

Notes:

- Total expeditions for 2016/2017/2018/1019 was 71, 39 of which classed as international, 15 classed as UK – intra EU, and 17 classed as UK - UK
- Expeditions include science related relocation passage legs as well as science expeditions
- 17 of the 39 (43%) of **international** expeditions required the ship to operate to the upper limits of maximum at sea duration.
- 1 of the 15 (7%) of UK - **intra EU** expeditions required the ship to operate to the upper limits of its maximum at sea duration.
- 1 of the 17 (6%) of **UK - UK** expeditions required the ship to operate to the upper limits of its maximum at sea duration.
- 19 of the 71 (27%) **total number** of expeditions required the ship to operate up to the upper limits of maximum at sea duration.

(Although the RRS James Cook and RRS Discovery maximum operational duration is 45 and 40 days respectively, the 'upper limits' of vessel duration has been assessed as 37 days at sea for general operations with any greater days at sea requiring special attention; maximum duration is a factor of expedition activity (speed/passage/tow loading/DP), and the loading characteristics of the ship based on embarked science equipment which require a trade-off of fuel weight, embarked equipment loads, duration of operations and ship stability, so the maximum limit is often not achievable for specific expeditions when the full operational profile is taken into account.)

Looking at the operational profile of the RRS James Cook and the RRS Discovery above it is clear that the greater part of programmed activity can be categorised as 'international operations' as opposed to 'regional' or 'coastal'. This is no surprise as the design criteria for both vessels were as Global Class deep sea multi role research vessels. It's also notable that just under half of the deep sea international expeditions pushed the duration of the vessels to their limits, with the average duration at 32 days. It is also notable that there is a reasonable proportion of expeditions operating from *UK to UK ports,* and *UK to Intra EU ports* with both categories operating with durations up to 15 and 25 days respectively, therefore significantly below the upper duration limits.

Operational duration is only one indicator of vessel utilisation with science activity providing a further indicator, the next section looks at the programmed activity based on multi discipline science, multi role equipment support and embarked science and technical teams.

Details of the RRS James Cook and RRS Discovery regional operations areas from 2016 to 2020:

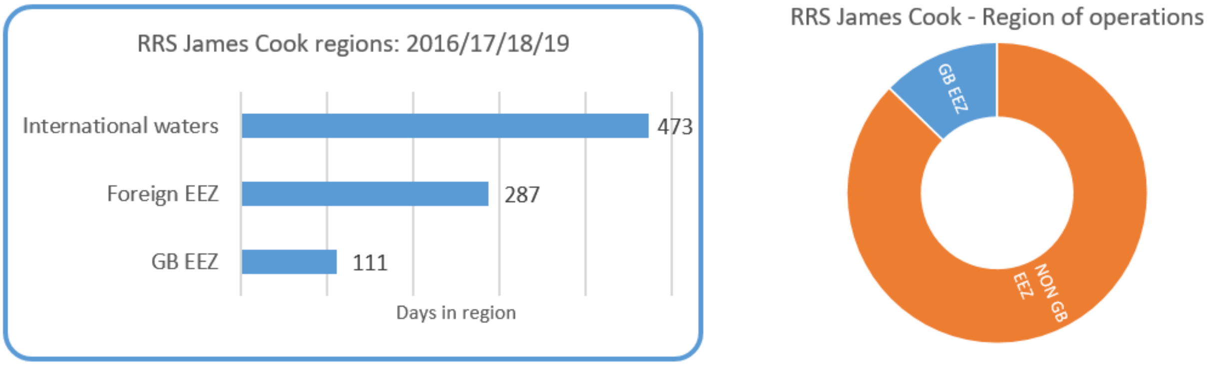


Figure 15 - RRS James Cook – operating regions

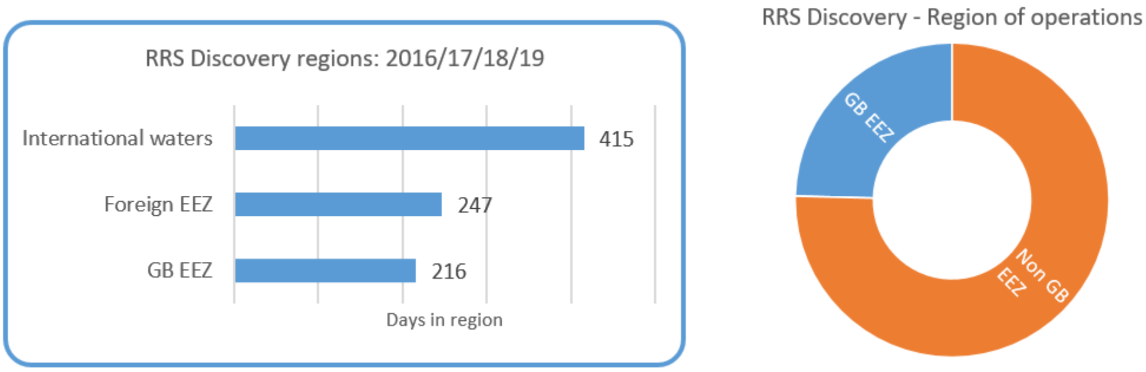


Figure 16 - RRS James Cook – operating regions

Note: All Data from NERC Marine Facilities Planning system

2.4 Multi discipline science & heavy equipment expeditions

As well as geographic location and duration, a second key area for consideration when reviewing ship operational profiles is the data and sampling requirements of the expeditions the ship needs to support. This is important as research ships are required to embark a diverse range of portable sampling, survey and handling equipment for installation on open deck, with access to over boarding systems for equipment deployment, as well as large quantities of specialist laboratory equipment for integration into ships laboratory spaces. These open deck spaces, multiple over boarding systems, large laboratories, significant science storage space, and the complex ships infrastructure and services needed to integrate this equipment into the ships systems, must be considered when evaluating utilisation of a vessel.

A typical set of operational base lines have been assessed by reviewing the profiles of expeditions from previous annual NERC programmes looking at the multi discipline science requirements of the annual programmes, along with the multi role equipment support capability required for the various sampling and data gathering equipment needed for each project. Work Package 1 of the NZOC project looked at the multi discipline nature of expeditions, and from analysis of expeditions since 2017 the Work Package leaders identified a significant proportion of science expeditions carried out multi discipline science activities throughout the programme years. Review of the past data from 2017 showed that for the RRS James Cook and the RRS Discovery, of 37 expeditions, 25 (68%) were classified as relating to two or more science disciplines, and 16 (43%) were classified as relating to three or more disciplines". This trend for multidiscipline science activity was echoed by the workshop participants as a continued requirement for science operations looking forward to the replacement timeframe of the RRS James Cook.

The tables below spanning *2016/17/18/19* show the take up of science and technical berths over a four tear period demonstrating the high science berth requirements for multi role research ships delivering multi discipline science operations averaging at 24 person berth occupancy per expedition. Typically the greater the multidiscipline nature of the expedition the greater the requirements to operate multiple items of sampling and survey equipment, both ship fitted and portable equipment. This impacts the science and technical berth numbers and overall demand on the ships capabilities.

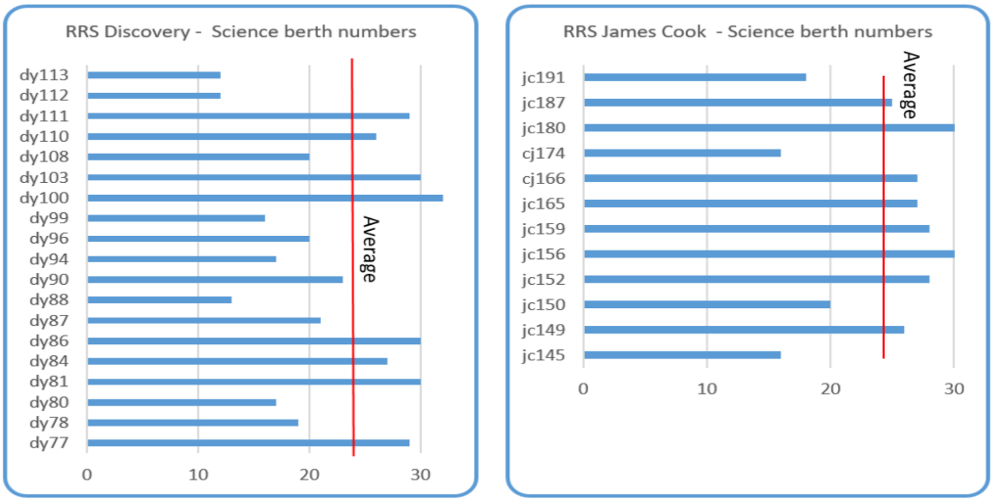


Figure 17 - Science berth numbers – RSS Discovery & RSS James Cook

The multi discipline nature of expeditions does not in itself determine the scale of on board science support and embarked equipment needed for an expedition; a range of complex portable equipment may be required to support both multidiscipline or single discipline expeditions, both potentially having a high demand for embarked equipment and scientific and technical support to deliver the science requirements. Specific examples of large complex equipment are; seismics operations, sea bed sediment sampling (coring systems), rock drills, deep sea ROV systems and sea bed mooring operations. These categories of equipment require the use of some of the most complex equipment and machinery across the programme. These areas of equipment operation can be single discipline or multi discipline expeditions requiring complex machinery to be installed, high levels of embarked science and technical support, and generally long duration operations.

These factors; multi discipline science, multiple items of science support equipment, and large complex and heavy equipment, have shown consistent trends in the composition of the NERC marine programme over the past years and are benchmark indicators for the profile of marine science programmes in the future years. The feedback from the other work packages within this project, and feedback from the engagement workshops for this work package clearly indicate that multidiscipline science projects and high levels of ship fitted and portable science equipment including heavy infrastructure equipment expeditions are projected to be key areas of the NERC marine science programmes for a RRS James Cook replacement.

The trend for multi discipline science has developed over the past two decades alongside an expansion in the scope of marine science sampling and data gathering capabilities that have become available. The prevalence of large complex equipment, deep water mooring arrays, autonomous vehicles, autonomous data gathering floats and profilers, integrated fixed bed observatories, satellite data and data gathering systems on commercial ships has greatly expanded. This has provided huge benefits in data acquisition but also huge challenges for managing this diverse range of ‘data gathering platforms’. These challenges include complex project management and logistics, ship programming for interventions with deployed equipment, and technical skills training and development.

This *network* of data gathering platforms has resulted in a marine science data and sampling ecosystem which is increasingly diversified, but increasingly integrated. The broad spread of data and sampling capabilities referred to above are already an integral part of the marine science data and sampling capability and looking to 2035 is clear that this trend will continue as the technology develops. In parallel to the development and increased prevalence of the diversified data gathering environment, the rapid increase in ship borne marine science sampling, data acquisition and management systems, and new generations of portable scientific equipment has also dramatically increased. This has added to the complexity of the ship design needed to support these capabilities, which are collectively gathering ever increasing quantities of data.

As part of work package 3 we held a workshop with invited participants from the UK and international science community, research ship operators, ship designers and equipment suppliers to gain feedback in the areas of multi discipline science operations, and the uptake of MAS into marine science programmes. One of the key areas of feedback being how MAS can develop and influence the more difficult areas to automate such as heavy sampling and survey systems traditionally operated from large research ships. Work package 1 also held a workshop looking at future science requirements and trends and the feedback was complementary to work shop 3 in these key areas.

There was also complimentary views from the 2019 European Marine board Position paper 25 on current and future trends for research ship capability across the EU which is also referenced in this report. The 2019 EU Marine Board position paper 'Next generation-European Research Vessels identified the limited deep sea capability of the European research fleet, and identified the RRS James Cook as one of the most capable ships within the European/UK fleet with regard to power, modular multidiscipline science design, heavy infrastructure deep sea science capability, high numbers of science berths, and sea keeping capability.

Evaluation of the UK marine science community feedback for this project suggests there is a clear requirement for multi role research ships supporting multi discipline science looking forward to 2035 and beyond. The continued development, adoption and integration of MAS is also seen as a key area of development and a step change in how the science communities will approach scientific operations in the future. They expect to be working both with MAS operating as part of ship based projects launched and recovered from ships, and with MAS operating independently of ships in their own right. Although it is anticipated there will be significant advances and increased take-up of MAS during the next decade, the feedback outlined that in the next one and two decades it is difficult to see how the development of MAS could advance sufficiently to enable these technologies to replace research ships and provide an equivalent or greater capability to support the NERC Marine Facilities programme.

UK and international science communities feedback from Workshop 1 related to Work Package1 *(Future science Need)* noted that human presence at sea is still seen as a critical area for onsite collaboration, real time decision making, and training of the next generation of researchers. The ability to go a research area and saturate the area with the broad science sampling and data gathering capabilities of a multi role research ship, with a multi discipline science team on board, is an important capability to support the integrated nature of marine research. The ability to then revisit the sites separately (even continuously) with MAS systems, using smaller, autonomous sensing platforms augmenting the primary sampling/sensing expedition provides the ideal merger of the integrated science capabilities that technology is providing modern marine science.

The 3rd workshop *(Work Package 3: Future Ship technologies)* provided feedback on multi role research ship operation also noting there is a continuing trend across international partners for multi role research ship operation, based on their ability to support the breadth of equipment required for modern multi discipline science projects, and their flexibility to adapt to integrate and support emerging technologies such as MAS. This enables these emerging systems to be embedded into existing multi discipline science projects providing the integration and transition environment for the adoption of new equipment and processes into the marine research landscape. The adaption of multi role research ships as 'Mother ships' for increased use of MAS alongside the use of traditional multi discipline equipment, providing MAS as an additive as opposed to a replacement for many science data gathering process was also noted as a key area for future traditional ship and MAS use.

Alongside the 2019 EU Marine Board position paper referenced in this report, the feedback from the NZOC workshops identified that large multi role research ships are critical capabilities for multi discipline marine science and are projected to remain necessary to support aspects of deep sea sampling and data gathering requiring large heavy equipment and integrated multi discipline science projects up to and beyond 2035.

2.5 Technology trends affecting ship design and programme delivery

Looking forward to 2035 there are a range of technology and operational developments that are likely to significantly change research ship design and the way operations are managed, some of the key areas are;

- Technology that can influence embarked science and mariner numbers;
    - Automation, remote management and monitoring of ship fitted science systems
    - Telepresence and high speed data transfer
    - Integrated/semi-autonomous handling systems for MAS, ROV and other deployed tethered science platforms.
    - Advances in remote monitoring and management of bridge and engine room operations

- Integration of Marine Autonomous Systems (MAS) / Marine Autonomous Surface Ships (MASS) into programme delivery
    - Adoption of MASS/USVs as force multipliers alongside crewed multi role research ships, and operating independently within their own survey and sampling programmes.

It is highly probable a 2035 RRS James Cook replacement would have the potential for full remote operation and management of underway acoustic surveys by shore based teams. This will enable ships to carry out acoustic survey and sensing operations during programmed passage/transit periods, or science expeditions, requiring minimal (or no) scientists and technicians on-board to manage the equipment and processes, increasing the overall effectiveness of the ships programme. For operations during science expeditions, this capability would enable science and technical staff to work remotely ashore working in real time with on board science and technical teams, extending the science teams to an integrated, real time ship and shore science project. For transit/passage legs, underway acoustic, atmospheric and sea surface underway sampling systems could be operated and managed remotely with either skeleton (or no) support on board, with data monitoring and processing carried out by science teams ashore increasing the efficiency of ship use during passage and transit periods. Integrating ROV handling systems and matched vehicle design(s) into the ship at the design stage and adopting semi-automation of deployment and recovery systems, can provide flexibility in how ROV operations are managed. This could enable minimal science and technical teams to be embarked to manage on board systems, to direct the science, and process samples, working with shore teams via data and video link. This integrated ‘matched handling system/vehicle’ concept could be extended to AUVs enabling the ship to extend its sensing and survey footprint via integrated on board AUVs operating alongside shore based science and technical teams. This can reduce embarked science and technician numbers for science activities, or release berths for alternative capabilities and science staff to be included in the project.

Using technology to provide options to vary embarked technical and science support numbers to fit individual project requirements will become increasingly viable for science and technical support. This approach can provide options to manage science and technician numbers for expeditions depending on the requirement to reduce overall embarked numbers, or to increase the capability of embarked operations by using remote support teams ashore in partnership with embarked teams, freeing up berths for the inclusion of additional science capability. These initiatives could be planned and managed on an expedition by expedition basis. Although this project by project based approach can work for science and technical teams to flex team numbers according to project requirements, it is more complex to adjust mariner numbers on an expedition by expedition basis. The approach for mariner numbers would be to apply technology to support a 'lean mariner compliment' at the ship design stage, by adopting bridge and engine room technology and efficient hotel services design to support reduced embarked mariners numbers as standard. This can increase efficiency of operations, and reduce the 'minimal mariner levels' required on board so reducing operating costs. The ability to manage the numbers of embarked mariners, science and technical teams also has a positive incremental environmental impact reducing travel carbon footprint which is a key area when considering international operations.

New technology and techniques (particularly MAS and MASS technology), will replace some of the traditional equipment and activities currently carried out on traditional research ships, but new large ship borne systems are also likely to be developed driving further requirement for ship use. These new systems will then replace some of the systems and processes that are superseded by MAS or become obsolete. Additionally, as new MAS/MASS technology is developed to replace some of the current large sampling and data gathering systems that are currently outside current autonomous systems capability (as they already have, such as towed side scan sonar systems), it is likely these emerging systems will have to be operated alongside existing traditional sampling and data gathering methods to prove the new processes and to integrate them into the science community working landscape. For certain areas of marine science requiring large complex sampling systems such as multi-channel seismics, rock drilling and sediment sampling systems there are still no viable options on the technology horizon, with the time scale thought to be well beyond 2035 before significant inroads are made to make a transition away from large multi role research ship support for these categories of equipment.

Autonomous sensor platforms are developing as highly capable systems in a number of areas of marine science, *but still in clear need of improvement in the areas of reliability*. There is high potential to make further inroads into their use across marine science delivery, but as noted above there are areas of sampling and process related studies where MAS systems are not capable of replacing traditional equipment. This is a key area for further development of MAS technology and marine science methodology. The development of sonar systems for biological detection and analysis, and emerging sensors for physical and chemical oceanography are key areas of progress in bridging the gaps in MAS use for marine science. The rapid development of MASS, and the ability of MAS to survey and monitor large areas of the ocean efficiently and cost effectively with projects such as MASMO has shown that fleets of autonomous platforms can operate independently without a ship, and can effectively support subsets of the marine monitoring component of the Marine

Facilities Programme (MFP) in a different way to ships due to flexibility and continued persistence. It is clear that MAS systems are already at a level where they can support survey and monitoring programmes independently of ships, in addition to operating as force multipliers for traditional research ships as embarked systems. As their sensor capability improves *and their level of reliability is brought up to acceptable levels* there will be significant further adoption of MAS by the science community.

The ability to carry out multi discipline science with a research ship, combining both ship based MAS operations managed from the ship, alongside the primary ship based activities, and to then have the potential to revisit the sites separately and continuously using smaller, MAS platforms augmenting the primary sampling/sensing expedition, is a significant additive function and step change in the way marine science can be planned and programmed in the future.

To support a continued transition and adoption of MAS, (and the emerging opportunities for MASS), there is a requirement for a major area of research to develop the marine sampling technology and science processes that are currently outside their operational capabilities. This area of work would bring scientists and engineers together to identify and develop novel scientific methods and processes, and the tools and technology to support these requirements with a new generation of MAS/MASS equipment. This would advance the design and development of the autonomous systems used for marine science (AUVs, ASVs, and ROVs), to the next level, focussing on the areas that are currently outside the capabilities of autonomous technology. In turn autonomous system development can act as a next generation influencer for ship design, for both traditional crewed research ships in the short to medium term, and autonomous un-crewed research ships.

Technologists and scientists within the autonomy community also need to embark on a review of the current scope and capability of autonomous systems to identify the main areas *of current capabilities* that need to be developed and improved to promote the take up within the science community in areas such as *reliability* and *operational duration*.

Alongside MAS, there are significant advances in Marine Autonomous Surface Ships (MASS or Uncrewed Surface Vessels (USVs)), with in-service examples already operating commercially which show the rapid adoption of commercial USVs carrying out commercial and academic related survey and inspection missions successfully.

These existing activities are bringing together the key technologies necessary to provide viable USV platforms capable of supporting sea bed mapping, survey, inspection, and ROV and AUV operations from coast to deep water. This area will develop at a fast pace during the current decade and is a critical area in which the next generation of integrated NERC fleet developments can benefit.

2020 USV survey: 22 day expedition, 1200nm, 1000km^2 mapped, 391hrs data collection

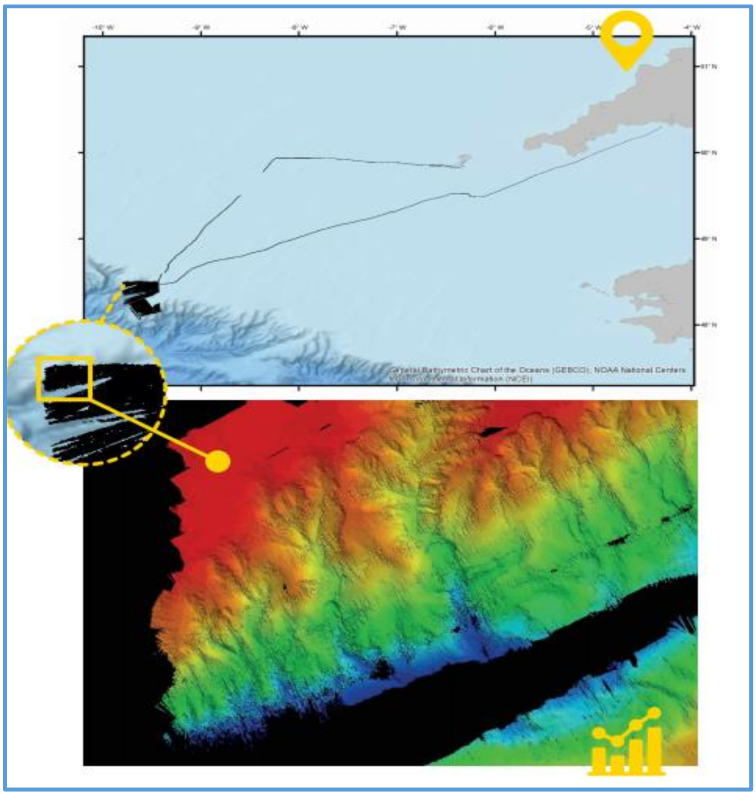


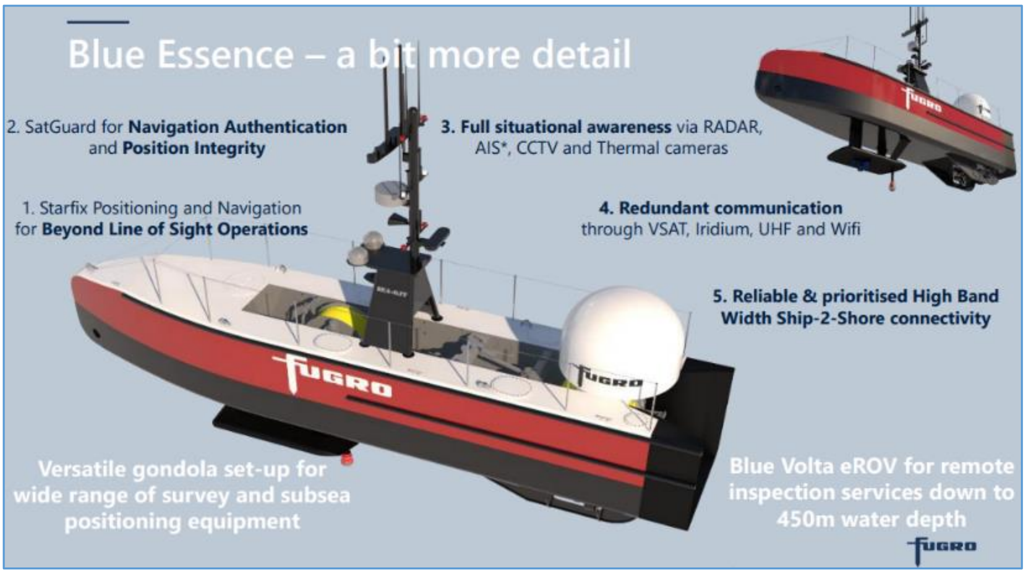
Figure 98 - Kongsberg MBES USV survey contributing to Seabed2030 (curtesy SEA-KIT)

In 2020 the UK Company SEA-KIT carried out a 22 day sea bed mapping ‘proof of concept’ mission with their USV, operating between the UK and the shelf edge. The USV mapped over 1000km^2 of the sea bed with the USV monitored and controlled from a control centre in the UK. The USV design has an endurance of 28 day and operating range of 2000nm. SEA-KIT are one of a number of companies developing these capabilities which are increasingly being taken up by the commercial offshore survey and oil industry.

The rate of development in the area of USVs is expected to be significant during the current and next decade with opportunities for research ship owners/operators and the marine science community to re-think how these systems can be integrated into science projects, and more broadly how they can be integrated into the UK research, survey and monitoring capability.

The Dutch geotechnical and survey company Fugro are working in collaboration with SEA-KIT to develop the Fugro fleet with a range of USVs which can deploy remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs) for marine survey, inspection and intervention, together with on board positioning and sea bed mapping sensors for survey operations.

Fugro operate two 12m USV’s which are monitored and operated from their remote operation centres. One USV is already in commercial operation, and is about to start its first commercial project after an extensive test phase. The second unit is in testing phase in UK, planned to be operational summer 2021 equipped for deep water survey operations. Currently these USVs are remotely controlled from shore control centres, and are not fully autonomous, operating at Autonomy level 3, moving towards autonomy level 4. Fugro also operate 2 other autonomous level 4 USVs carrying out commercial hydrographic mapping operations.



Blue Essence – a bit more detail

2. SatGuard for **Navigation Authentication** and **Position Integrity**

3. **Full situational awareness** via RADAR, AIS*, CCTV and Thermal cameras

1. Starfix Positioning and Navigation for **Beyond Line of Sight Operations**

4. **Redundant communication** through VSAT, Iridium, UHF and Wifi

5. **Reliable & prioritised High Band Width Ship-2-Shore connectivity**

Versatile gondola set-up for wide range of survey and subsea positioning equipment

Blue Volta eROV for remote inspection services down to 450m water depth

Figure 109 - Blue Essence project overview (Curtesy of Fugro)

The rate of development of USV technology and its adoption into the commercial market is increasingly demonstrating the capability and benefits for survey, inspection, mapping and intervention in the marine environment. In the current decade this area of operations is likely to significantly mature, with greater capability integrated into the vehicles, such as long duration heavier payload variants of the SEA-KIT USVs discussed here, support range and endurance up to 12000nm and over 100 days at sea, with 8kt operational speeds. The vessels support DP, ROV, AUV, and MBES operations with flexible, configurable payloads.

USVs operating with highly efficient hybrid propulsion systems will also benefit from the ongoing development of alternative fuels for reduced emissions operations and advances in propulsion machinery. This will further add to the benefit of adopting these increasingly advanced, and more capable un-crewed autonomous vehicles into an integrated, diversified fleet structure in support of the NERC marine Facilities Programme, both as force multipliers alongside crewed multi role research ships as part of programmed expeditions, and operating independently within their own survey and sampling programmes.

Figure 20 - SEA-KIT USV configured with AUV (Fugro)

2.6 Changing landscape

Assuming a typical 5 years period from inception of a ship build project to completion, a James Cook replacement in service for 2035 would typically require a concept design process to be in place by 2030. For previous ship replacement projects, projecting 5 years into the future, developing a concept design has been a difficult task in itself, evaluating the potential operational and technological changes that may need to be incorporated within this timescale. When considering the James Cook replacement the position is more challenging due to the fast changing technological and operational environment in the areas of emerging fuels, remote operation and autonomy. Current evaluation of market development (for global operations in particular) shows the 2030 – 2035 timescale looks to be at a critical point in the commercial shipping sector's development of infrastructure and take up of emission reducing fuels, propulsion machinery and the emerging technologies for autonomous shipping. It should be noted that focussing on the commercial sector is relevant, as it is the commercial shipping sector that will drive the technology changes and infrastructure development that will then be adopted for the next generation of research ship designs, and integration of autonomous ships within a developing and changing fleet structure.

Review of the past three decades of NERCs research fleet evolution and the development of the sampling and data gathering ecosystem discussed earlier in this report demonstrates significant advances and adoption of technology, with these advances providing major benefits in science delivery. The progress of change and development has been incremental, with capabilities (ships, equipment, science process) evolving within feedback loops of advancing technology and science process requirements. When looking at the changing technology landscape over the next one and two decades the operational and technology drivers for change may well present opportunities to make major step changes, or radical shifts in direction in both surface fleet design and operation, and in the diversified ecosystem of sampling and data gathering systems available to deliver NERCs (and the broader UK) marine facilities programme.

The RRS James Cook and the RRS Discovery replacements should be approached as part of a strategic integrated fleet renewal programme; cognisant of the fact that 2035 through to 2040 will be very different operating environments for the emerging technologies of new fuel sources, autonomous shipping and the broader marine science sampling and data gathering environment. The 2035 timescale presents some unique challenges and opportunities for the fleet renewal programme.

Based on the traditional operating landscape as we see it today, operational analysis of ship use over the period of 2016 to 2020 shows the need to operate 2 multi role ships to deliver equivalent marine science programmes to those previously programmed by NERC. The requirement for continued access to multi discipline deep sea research ships up to and beyond 2035 is supported by the feedback from the UK science community, and the comments and feedback from the NZOC project consultation workshops. The design and capability of the RRS James Cook replacement (and the RRS Discovery replacement) will likely have an operational delivery span to 2070. Fleet development needs to be reviewed as part of the increasingly dynamic, integrated sampling and data gathering ecosystem. This design assessment needs to consider the deep sea multi discipline component of the programme, alongside the potential for UK wide coastal and regional collaborations, operating within the increasingly capable autonomous technology landscape, including MAS, fixed sea bed systems, autonomous drifters and floats, satellite systems, and importantly, an awareness of the fast developing opportunities in the development of autonomous, un-crewed ships driven by the commercial shipping sectors which will increasingly be an operational reality in this current decade.

2.7 UK 'Zero-Carbon Coastal Highway' & EU 'Motorways of the Seas'

A consortium fronted by Maritime Research and Innovation UK (MarRI-UK) comprising a group of UK Universities and the UK industry sector proposes to develop the framework for a 'zero-carbon Coastal Highway' to transform the UK commercial transport system[21][23].

The proposal is to develop the concept to increasingly move commercial road transport to a 'marine coastal highway' supported by zero-carbon vessels, increasingly autonomous, targeting 2030 nominally as an operating timescale. This ambitious initiative would require the substantial investment necessary in vessel design, shore and maritime infrastructure, policy and regulation to support the development of low/zero-emission, autonomous shipping.

The EU is also pursuing a comparative strategy for an integrated zero Carbon transport network, also targeting the EU coastal regions and major sea basins as zero Carbon 'Motorways of the Seas' (MoS) [21][23].

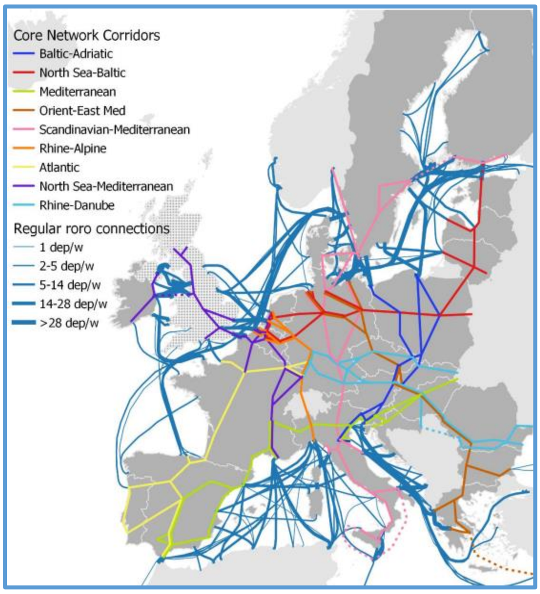


Figure 21 - European short-sea shipping core network Corridors (MOS study consortium)

These commercial focussed initiatives would in turn provide the infrastructure to support the integration of marine autonomous surface ships (MASS) into the marine science environment as part of a diversified marine science fleet concept. Assuming these UK and EU initiatives mature within their proposed timescales, in combination, they would cover a substantial area of UK and EU territorial waters; at minimum covering the UK coastal and regional operations carried out by the current UK organisations, as well as more broadly across the extended areas from UK and EU ports for shelf sea and some deeper water operations.

The initiatives to develop the coastal infrastructure across the UK and EU regions as 'zero Carbon marine highways', and 'Motorways of the Seas' with the associated development of the enabling technologies, infrastructure and regulatory frameworks will present NERC (and the broader UK research ship and survey ship operators) the opportunity to rethink the structure of the broader UK research, science and monitoring fleet(s), and the way the science, monitoring and coastal management obligations can be programmed and delivered. These initiatives will present opportunities to adapt commercial developments into the marine science environment which can have an accelerated impact on the development and uptake of autonomous ships for marine science operations.

The (UK zero Carbon coastal highway and the EU Motorways of the Seas) are proposed to have targeted timelines commensurate with the RRS James Cook and RRS Discovery replacement timelines.

Based on previous UK research vessel replacement project timelines, there is less than a decade to the start of the 2030 – 2035 concept design for the RRS James Cook.

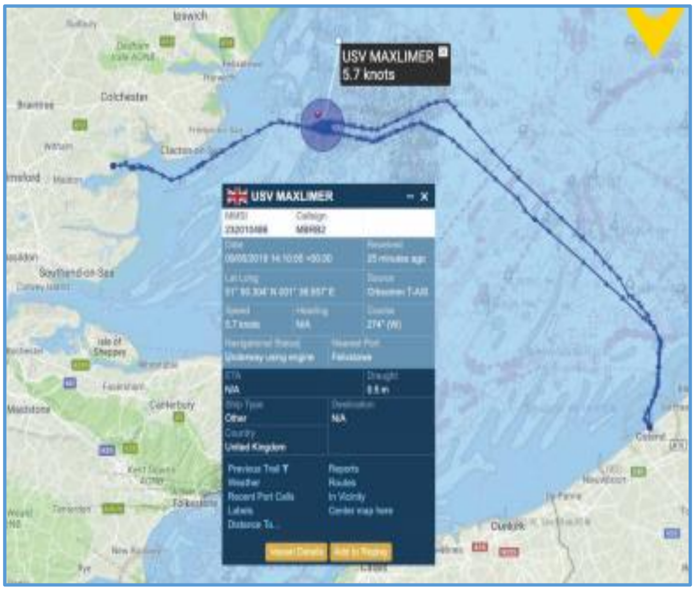


Figure 22: Cargo voyage proof of concept 2019 (SEA-KIT)

The design process is traditionally incremental in nature, assessing technology and science process requirements that will influence the ship design. For a 2035 build these may be focussing on a multi role research ship adopting the advanced technologies of the day in the areas of; alternative fuels and machinery, data handling, remote operation of science systems, increased adoption of MAS, and operational integration with the broader data gathering ecosystem. But the rapid development and adoption of autonomous, zero emission vessels by the commercial sector potentially presents an opportunity to step outside an incremental fleet design strategy and consider a more radical approach.

The disruptive influence of the fast paced development and adoption of new technologies to decarbonise transport (and in this case the marine sector), alongside the rapid advances in marine autonomous vehicles (MAS) and marine autonomous surface ships (MASS) presents an opportunity to step outside the incremental constraints of concept design for the RRS James Cook. There are options to focus more broadly on the potential structure of an integrated fleet of data gathering capabilities that the transformational advances in technology and maritime policy frameworks are likely to present. This wider perspective can inform and influence the concept design process for the RRS James Cook (and the RRS Discovery), as part of a broader assessment of fleet structure, taking into consideration the opportunities for collaboration and economies of scale across UK partner organisations which is explored in more detail in the next section.

Figure 23 - SEA-KIT USV – configured as a container carrier (SEA-KIT)

The commercial developments in the shipping sector supporting the UK ‘Zero-Carbon Coastal Highway’ & EU ‘Motorways of the Seas’ initiatives can be co-opted for research ship design as part of the next step in an advanced research fleet concept, with the potential to operate state of art crewed multi discipline, deep sea research ships *alongside* autonomous research ships; this approach would encompass autonomous ships carrying out independent science programmes for coastal and regional science, and/or as part of integrated fleet research projects, depending on the science and programming imperative. These disruptive technologies will influence debate (and drive) organisational change across the UK marine science support infrastructure in areas such as research ship operations, cross organisation collaboration and industry engagement.

Although there is increasing confidence in the *technology* for zero-carbon fuel production, the associated propulsion machinery, and the required infrastructure necessary to deliver the change from fossil to zero-carbon fuels, there is significant uncertainty around the timeline for global availability of these fuels, in particular implementation of the supporting infrastructure and supply chains. This is likely to be a limiting factor when looking at a 2035 in service new build timescale for a ‘zero-carbon fuel ship’ designed to operate with a single fuel type. A 2035 in service build for the RRS James Cook looks to be at a pivotal timeframe in the adoption and availability of low/zero emission fuels particularly for international operations. This presents a more complex operating environment to plan within than previous ship replacement projects due to the uncertainty of timing of the markets to effectively implement these changes, particularly the variable regional availability of zero-carbon fuels at different international ports worldwide.

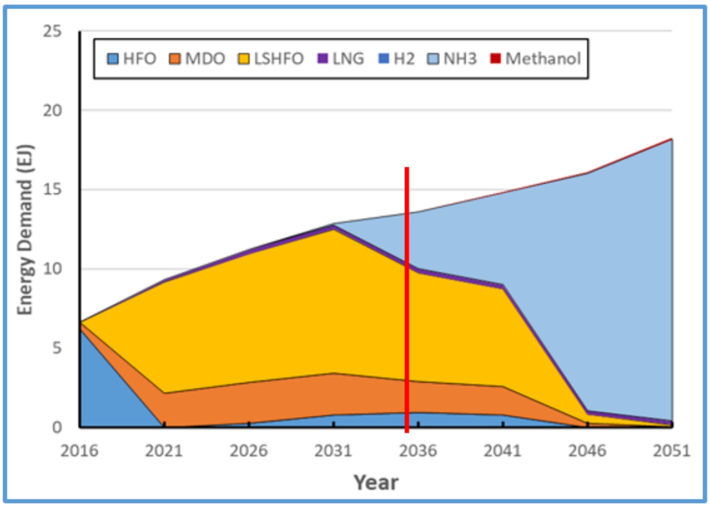


Figure 24 - Projected fuel mix based on full decarbonisation by 2050 (UMAS 2021)

The accelerated timeframes proposed by UK and EU governments to decarbonise the maritime operation, principally for short sea shipping (coastal and regional), with the greater number of zero carbon fuel projects being within the UK/EU regions, suggest if these time scales are maintained, the UK/EU will likely achieve greater maturity at an earlier point in the global realignment to zero-carbon fuel adoption than some other regions of the world.

With the near proximity to UK and EU ports available for UK coastal and regional ship operations, there is likely to be a relatively faster rate of development of zero-carbon fuel, and autonomous shipping uptake than for international operations due to the greater early adoption options for ships operating shorter duration activities. The short distance for port to port operations compared to international deep sea operations, enables different fuel and machinery mixes to be adopted such as full electric battery or hydrogen/electric battery mix using fuel cell or modified ICUs, where these fuel and machinery options would not be viable for long duration large vessel operations.

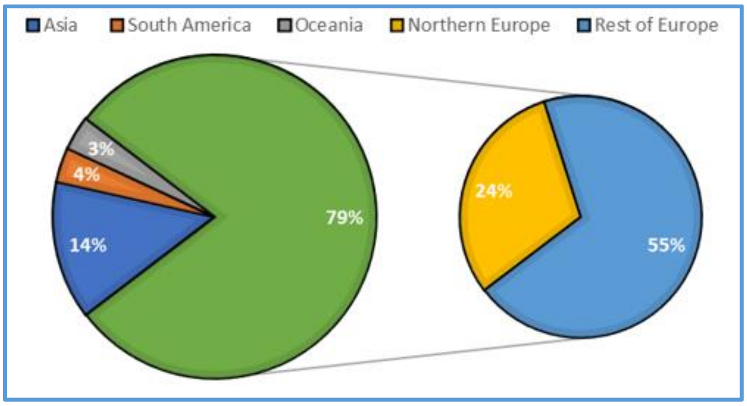


Figure 25 - Projects and developments for zero-carbon fuels -Hydrogen/Ammonia (UMAS 2021)

A broader fleet wide approach to a ship replacement strategy would enable the fleet design process to review the options around the 2035 timeframe with a view to optimising the RRS James Cook replacement strategy. A broader fleet wide approach also supports the evaluation of options to determine if a different fleet structure is better suited to future UK marine science and monitoring delivery based on the development of an integrated, mixed fleet model of global, regional and coastal class crewed ships, together with coastal/regional autonomous un-crewed ships operating as an integrated fleet. When this concept is looked at from a broader UK perspective the potential options and benefits are further magnified, and this area is explored in more detail in the next section of this report.

This approach also allows for a review of the organisational architecture needed for a different science support infrastructure, namely crewed and un-crewed autonomous research ships, MAS, remote fixed sea bed and floating and drifting data gathering systems, operating across a broader integrated UK landscape. The current structure of a traditional ship operator and marine autonomous system group is likely to not be the optimum structure for a more complex integrated fleet approach, and an objective review of fleet structure will likely identify alternative fleet management options as well as options for cross UK organisational asset programming.

Review of past NERC programmes show a proportion of global class ship operations are carried out in coastal/regional areas to a greater or lesser extent depending on the component projects within each annual programme (~22% on average), but still the main proportion of each annual programme being long duration, deep sea, multi discipline, science expeditions requiring large multi-purpose research ships. Review of operations carried out by Cefas, Marine Scotland Science and AFBI vessels, (also referencing Environment Agency, English Heritage, JNCC, Natural England and the Countryside Council for Wales), show a network of activities covering their operations for acoustic surveys, monitoring and sampling, almost exclusively around the UK and regional waters.

As noted earlier it is highly likely that in the time scale to 2035, deep sea operations will have different zero-carbon fuel and machinery options for large vessel long duration expeditions, to those fuel and machinery options which may be viable for smaller vessel shorter duration expeditions. UK and international government initiatives are likely to accelerate the technology and infrastructure within the commercial short sea shipping sector, to develop the low/zero emission fuel production and supporting infrastructure at a faster rate. It is likely that progress to zero emission and autonomous shipping in the commercial sector (which is where the funding and investment will be needed to make zero emissions and/or autonomous shipping a reality), will likely be driven initially by small coastal and regional vessel operations, as the technology and infrastructure is developed and integrated into the market, progressively developing the technology and operating landscape towards international shipping.

The zero carbon coastal highway and motorways of the sea concept could compliment and expand the NERC MAS and MASS aspiration by enabling research organisations to capitalise on the development of small to medium sized, zero emission autonomous commercial vessel technology, adopting and adapting the technology, designs and supporting infrastructure into the development of coastal and regional research vessels, as part of a diversified but integrated coastal/regional/global marine research and survey programme delivery structure.

The UK Clean Maritime Plan makes direct reference to government *specialised vessels* with regard to public procurement policy to progress emissions reduction, this could be explored to leverage funds to support the research fleet engagement with UK industry research in to autonomous shipping to mutual benefit of NERC science and UK industry.

The reduced build costs of USVs along with their very low running costs means that a different financial model could be considered potentially allowing for the development of a mixed surface fleet model providing a step change in capability and flexibility for survey, and research programme planning. Options could be explored to develop combined 'marine science delivery platforms' and 'industry research platforms' in partnership with UK industry. This could support development of alternative fuel and autonomous systems technology, using the 'coastal highways infrastructure' to deliver the NERC 'coastal/regional' science remit, and using the autonomous research ship platform to take a direct research role in the industry sector research and development. The vision would be working in collaboration with academic and industry partners, with the NOC ship(s) as joint marine science/commercial development data gathering platform(s) working as part of an integrated academic and industry collaboration.

The current approach to delivery of the NERC marine science programme uses two large global class ships to support the science, whether UK based or international, operating in coastal, regional or deep water locations. The future developments in commercial coastal and regional autonomous shipping could present opportunities to rethink how the UK fleet and marine research and survey delivery is organised.

The disruptive technologies and changing operating environment that the RRS James Cook and the RRS Discovery renewal programmes timescale will coincide with, will benefit from adopting a holistic overview of the potential changes to the emerging sampling and data gathering capabilities. A piecemeal approach will likely miss the synergies and cross over between these different emerging and maturing capabilities. A staged approach to fleet renewal is still necessary as not all the main areas of technology and infrastructure development that will support the new operating environment will develop and mature at the same time. A UK wide approach to the broader coastal, regional and deep sea activities will provide opportunities to realise benefits of scale for fleet renewal and opportunities for development into these new areas of technology.

Looking to 2035 and beyond it is clear that an optimum sampling and data gathering fleet of the future is a mix of advanced traditional crewed ships, autonomous un-crewed surface ships, integrated with marine autonomous vehicles.

The acceptance of new technology into the science user community data gathering landscape is a critical factor to manage during the substantial change over the next one or two decades if these major initiatives are to be implemented. In order to inform, engage and bring the science community along with NMF on the development and integration of this new technology, it’s important that this process is seen as open, objective, and inclusive.

To support any major changes over the next one or two decades, which potentially includes the adoption of new ship technology for emerging fuels, novel technologies for advanced research ship design, adoption of un-crewed vessels, continued development of marine autonomous systems, sensors and instruments, NMF needs to focus heavily on equipment reliability, and effectiveness of the various delivery systems and operational management. This may require the inclusion of a more formal process for reliability management working cross organisation, independently from any engineering or operations group. The reliability management process would focus on technology and equipment adoption and integration (both new and existing), organisational structure, as well as the operational capabilities across NMF for equipment, process and operations management. There will be a need to review best practice, and areas needing development, and/or failing areas that need change or restructure.

With the pending capital costs of fleet renewal and technology realignment in the hundreds of millions across the UK science monitoring and sampling landscape in the coming decades, along with the intent to develop new and high risk emerging technologies, investment in reliability management will be a very small investment in consideration of the overall financial landscape.

2.8 Conclusions: Capability, demand, utilisation, current to 2035 replacement timeline

- The progressive development of increasingly complex and technologically advanced research ship capability between 1985 and 2013 was in response to scientific requirements to develop a multi discipline approach to science expeditions, and parallel developments in equipment technology. These requirements and increased technical capabilities also required greater numbers of embarked scientists and technicians to support the science processes and complexity of equipment.
- Multidiscipline science and the complexity of equipment are consistent trends in the composition of the NERC marine programme over the past years and are benchmark indicators for marine science programme profiles in future years. Feedback during this study indicate multidiscipline science projects and high levels of ship fitted and portable science equipment are projected to be key areas of the NERC marine science programmes projecting to 2035.
- The ability to visit a research area and saturate the area with the broad science sampling and data gathering capabilities of a multi role research ship, supported by a multi discipline science team, is an important capability to deliver the integrated nature of marine research. Human presence at sea is identified as a critical area for onsite collaboration, real time decision making, and training of the next generation of researchers. To then revisit the sites separately (even continuously) with MAS systems, augmenting the primary sampling/sensing

expedition provides the ideal merger of the integrated science capabilities that technology is providing modern marine science.

- Large multi role research ships are critical capabilities projected to remain necessary to support aspects of deep sea sampling and data gathering requiring large heavy equipment and integrated multi discipline science projects up to and beyond 2035. Emerging technology such as telepresence and remote operation provides opportunities to change the way the science community access the ships. The continued development, adoption and integration of MAS is also seen as a key area of development and a step change in the science communities approach to scientific operations in the future.
- Based on the traditional operating landscape as we see it today, operational analysis of ship use shows the need to operate two multi role ships to deliver equivalent marine science programmes to those previously programmed by NERC.
- The design and capability of the RRS James Cook replacement (and the RRS Discovery replacement) will have an operational delivery span to 2070. Fleet development needs to be reviewed as part of an increasingly integrated sampling and data gathering ecosystem. A fleet design assessment needs to consider the deep sea multi discipline component of the programme, alongside the potential for UK wide coastal and regional collaborations, operating within the increasingly capable autonomous technology landscape. This landscape will comprise MAS, fixed sea bed systems, autonomous drifters and floats, satellite systems, and an awareness of the fast developing opportunities in the development of autonomous, un-crewed ships driven by the commercial shipping sectors increasingly available in this current decade.
- Significant advances and increased take-up of MAS is anticipated during the next decade, but in the next one and two decades it is difficult to see development of MAS advancing sufficiently to enable these technologies to fully replace research ships and provide an equivalent or greater capability to support the NERC Marine Facilities programme. For areas of marine science requiring large complex sampling systems such as multi-channel seismics, rock drilling and sediment sampling systems there are still no viable MAS options on the technology horizon, with the time scale thought to be well beyond 2035 before significant inroads are made to make a transition away from large multi role research ship support for these categories of equipment.
- There are significant advances in Marine Autonomous Surface Ships (MASS or Uncrewed Surface Vessels (USVs)), with un-crewed ships already operating commercially demonstrating the application of USVs delivering commercial and academic related survey and inspection missions successfully. The rate of development of USV technology and its adoption into the commercial market demonstrates the capability and benefits for survey, inspection, mapping and increasingly intervention in the marine environment. In the current decade this area of operations is likely to significantly develop, with greater range, operational duration, and integrated capability. Looking to 2035 and beyond it is clear that an optimum sampling and data gathering fleet of the future is a mix of advanced traditional crewed ships, autonomous un-crewed surface ships, integrated with marine autonomous vehicles.

- Developments in the autonomous shipping sector can be co-opted for a UK wide fleet renewal strategy as part of an advanced research fleet concept, comprising state of art crewed multi discipline, deep sea research ships alongside autonomous research ships. These disruptive technologies will influence organisational change across the UK marine science support infrastructure in areas such as research ship operations, cross organisation collaboration and industry engagement. The advances in marine autonomous ships and vehicles present an opportunity to step outside the traditional incremental constraints for ship design and look at future ship replacements in a broader context of developing an advanced, integrated mixed fleet structure. A piecemeal approach to ship renewal plans will likely miss the synergies and cross over between the different emerging and maturing capabilities.

2.9 Recommendations: Capability, demand, utilisation current to 2035 replacement timeline

1. The replacement RRS James Cook research ship build should integrate key technology advances which will change the way ship operators, science and technical teams access ships, and enable the reduction of embarked science and mariner numbers. These include; remote management and monitoring of ship fitted science systems, telepresence and high speed data transfer, integrated/semi-autonomous handling systems, and advances in remote monitoring and management of bridge and engine room operations.
2. It is critical that designers of future research ships understand the integrated nature of the marine research, survey and monitoring ecosystem, and apply this broader system concept into individual ship designs seeing them as part of a broader networked delivery system.
3. During the 2020s there is a need to monitor policy, funding and shore side infrastructure development both UK/EU and internationally to identify the rate of progress towards emerging fuel infrastructure development, and autonomous shipping take up to inform on fleet development options.
4. There is a requirement to rethink the structure of the science and monitoring fleet(s), and the way UK wide science, monitoring and coastal management obligations are programmed and delivered. Initiatives to develop the coastal infrastructure across the UK and EU regions as ‘zero Carbon marine highways’, and ‘Motorways of the Seas’ with the associated development of the enabling technologies, infrastructure and regulatory frameworks can be enablers to develop a UK un crewed autonomous marine science fleet as part of an integrated deep water to coast fleet concept.
5. To mitigate the limitations of the adoption and transition into MAS, significant levels of research should be undertaken to develop marine sampling technology and science processes that are currently outside the operational capabilities of the MAS available to the science community. This should bring scientists and engineers together to develop novel scientific methods and processes, and the tools and technology to support requirements for a new generation of MAS.

6. The current scope and capability of autonomous systems should be reviewed to identify the main areas of reliability, operational endurance and sensor capability that need to be developed and improved to promote take up within the science community. The acceptance of new technology by the user community is a critical factor during the substantial change likely during the next one or two decades. If these major initiatives are to be successfully implemented it is important that this process is seen as open, objective, and independent. NMF needs to focus on equipment reliability, and effectiveness of the various delivery systems. This may require a more formal process for reliability management working cross organisation, independently from engineering or operations groups with focus on technology, equipment adoption and integration (both new and existing), as well as the operational management. Change of this scale will require constant review of best practice and areas needing development, and/or failing areas that need change or restructure.
7. Develop a broader fleet wide approach to a ship replacement strategy to enable a review of fleet design to see if alternative fleet structures are better suited to future marine science delivery. This is based on the projection of an integrated, mixed fleet model of crewed ships and autonomous un-crewed ships operating as an integrated fleet. This approach in turn allows for a review of the organisational architecture which may be needed to support a broader collaborative UK science support infrastructure, operating across an integrated UK landscape. The current structure of a traditional ship operator(s) and marine autonomous system group is likely to not be the optimum structure for a more complex integrated fleet approach. An objective review of fleet structure will likely identify alternative fleet management options as well as options for inter-organisational asset management and programming. When this concept is looked at from the broader UK perspective the potential options and benefits are further magnified, and this area is explored in more detail in the collaboration section of this report.
8. The substantial reduced build costs of USVs along with their very low running costs means that a different financial landscape needs to be considered enabling the development of a mixed surface fleet model providing a step change in capability and flexibility for survey, and research programme planning on a broad UK perspective. There are opportunities for greater collaboration with academic and industry partners, with the USVs operating as joint marine science/commercial development data gathering platform(s) working as part of academic and industry collaborations.

3 Options for collaboration and consolidation

3.1 Introduction

The UK government operates a range of research, survey and monitoring vessels to support the UK obligations for the deep sea marine science research programme, environmental monitoring, survey, fisheries stock assessment and coastal navigation aids. The fleet is diverse in its capability, operational management, and remit; operating from coast to shelf edge and globally for deep water research.

Part of the remit of the NZOC project allocated to Work Package 3 is to assess the potential options for collaboration with other partners both UK and internationally with a view to enhance capability and develop areas for operational efficiency across the operating landscape which includes vessels, shore support equipment, infrastructure and operating structures.

The replacement of the RRS James Cook notionally targeted at 2035 presents an opportunity to look more holistically at the NERC research fleet in light of the major technological, policy and regulation changes in the marine sector, in particular; emerging fuel options for low/zero emission operations, the rapid development of marine autonomous surface ships (MASS), and the technology advances in marine autonomous systems (MAS). The potential advances in technology and support infrastructure in this time scale further present opportunities to assess if a changing NERC fleet structure and operating concept may in turn present options to more broadly collaborate and coordinate on some of the more diverse monitoring, survey and science activities currently carried out across the UK by the various organisations and their associated assets.

Over the past decade there have been at least three reviews and reports which either fully, or in part looked at the area of multiple vessel operators, fleet utilisation, collaboration and cost/programming efficiency. Three of these are briefly identified below and all three show some clear correlation in their observations and recommendations.

In 2013 the Marine Science Coordination Committee (MSCC) produced a report titled *‘UK Marine Research Vessels - An assessment and proposals for improved co-ordination’.* The report centred on large research vessels greater than 50m, with the vessels reviewed carrying out coastal, regional and deep water operations. A very brief synopsis of the main findings and recommendations are itemised below:

- Requirement to carry out an assessment of required fleet size (and structure)
- The need to optimise arrangements for integrated operations and programming (common scheduling and programming tools)
- Adopt mechanisms to evaluate fleet utilisation to ensure optimised use of assets
- Assess options for integrated fleet management and operations
- Develop cross organisation sharing of assets.
- Assess options for future joint procurement and/or joint ownership of new vessel builds
- Use of emerging technologies to support the various delivery requirements

A further report carried out by the European marine Board in 2019 titled *'Next Generation European Research Vessels – Position paper 25'* used the EurOcean research ship database as the basis of an EU wide assessment (including the UK fleet) which covered a broader range of UK ships assessed on capability as well a size. The difference in the lists of ships between the EurOcean database and the MSCC report were the inclusion of the Alba Na Mara (Marine Scotland), Prince Madog (P&O Maritime), and the Sir John Murray (SEPA), all classed as coastal vessels. These were included in the Marine Board report due to their effective capability.

Although the Marine Board report had a much wider remit to review and assess European research vessel fleets across all of their operational aspects, section 7 of the report is directly relevant to this chapter as it provided a good insight to the broad management processes, partnerships and collaborations necessary for efficient inter-fleet operations within Europe and also for the respective national operators. The main findings of the report relative to this section were;

- Due to the large European fleet there is significant potential for more cost- effective collaboration in the use of research vessels and exchangeable equipment
- Collaboration on ship and equipment sharing could also have significant benefit at the national level
- There are effective exchange mechanisms for Global and Ocean class vessels the (Ocean Facilities Exchange Group (OFEG)), but limited activity for regional class vessels
- Use of common programme planning systems across ship operators will make collaboration more effective by enabling information sharing in a consistent way also enabling evaluation of utilisation and capacity availability
- Existing European initiatives such as EUROFLEETS are a valuable mechanism to engage community users and foster exchange at the European level

In 2021 Cefas produced a report as a supporting contribution to the NZOC project titled *'The future of the UK National Monitoring fleet capability'*. The report centred on the same UK research fleet as the MCSS report, and again common themes were identified in its recommendations. The main findings and recommendations relating to fleet operations are itemised below:

- Assess options for greater integration and collaboration for UK fleet operations
- Joint evaluation of new UK vessel build specification and design with a view to greater interoperability of equipment
- Consider joint strategic roadmaps for fleet renewal programmes for UK operators
- Review the application of vessels and the respective remits to broaden/overlap operations to improve fleet efficiency
- Apply autonomy options to support UK monitoring, survey, research remit with specialised platforms
- Collaboration on Energy Efficiency Measures (EEM) for UK fleet development

As can be seen from the key findings above, there are clear similarities in the main recommendations across the three reports. The MSCC report was commissioned following the House of Commons

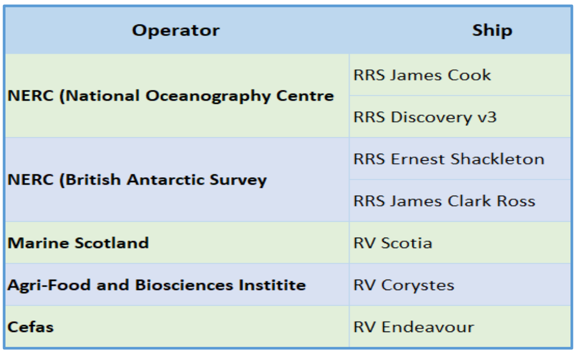
Select Committee 2007 report 'Investigating the Oceans' which recommended increased co-ordination of UK research vessels. The MSCC report was tasked with asking similar questions in 2013 as are being asked now within the NZOC report. Much has changed since 2013 with changes to fleet structures due to vessel retirements and replacements, and significant development in technology for both ship design and autonomy, but the main change is the requirements to apply emission reduction measures across the marine science, survey and monitoring enterprise. Despite the very different operational landscape from 2013 to now, the MSCC report still remains as essential background reading for this section, with the main vessel operators and the core of their fleets being the same from the 2013 MSCC report as of today. As the MSCC report is aligned to this NZOC chapter in some areas, the intent is to be cognisant of the previous MCSS work and to consider the report's recommendations in light of the 2021 operational landscape, and the projection to the 2035 RRS James Cook replacement timescale.

The main differences today, are the drive to adopt emission reduction fuels, and the emerging technological and shipping sector developments looking to the next one and two decades. The emerging technologies within the marine research and commercial shipping sector are likely to provide greater opportunities for inter-organisation collaboration and rationalisation than were available at the time of the MSCC report publication.

Previous reports have approached the question of collaboration and coordination initially from the perspective of financial savings, then impact on operational effectiveness. This report primarily focusses on the operational aspects of collaboration and consolidation and the opportunities this presents for 'equal or greater delivery capability'. Key consideration has also been given to the new emerging technologies that will change the way we all deliver science at sea. This focus on adoption of emerging technologies, operational effectiveness, and the opportunities this brings for collaboration can then be evaluated from the cost benefit perspective.

3.2 Scope of vessels covered in the various reports:

The MCSS and Cefas reports centred on the larger UK ships as shown in tables below. There is a further fleet of vessels within the UK research monitoring, survey and support environment operated by Trinity House and Northern Lights which collectively carry out a range of hydrographic survey, wreck survey, navigation buoy survey, positioning, service and support intervention; these ships are shown in a further table below. Trinity House and Northern Lighthouse ships were directly referenced in the 2019 Department of Transport maritime 2050 report 'Clean maritime Plan', therefore already part of the UK fleet assessment with regard to future options on emissions, so we likely need to include them in a broad UK marine research, survey, monitoring, support fleet assessment. Some of these vessels are highly capable vessels able to support multi role operations and able to contribute to the broader integrated UK science, survey and monitoring delivery portfolio. They may or may not be considered as part of the broader UK research, survey, and monitoring capability for collaboration purposes, and this is a broader political question, but either way, they are relevant in this report as part of the emission reduction aspiration for the broader UK marine enterprise.



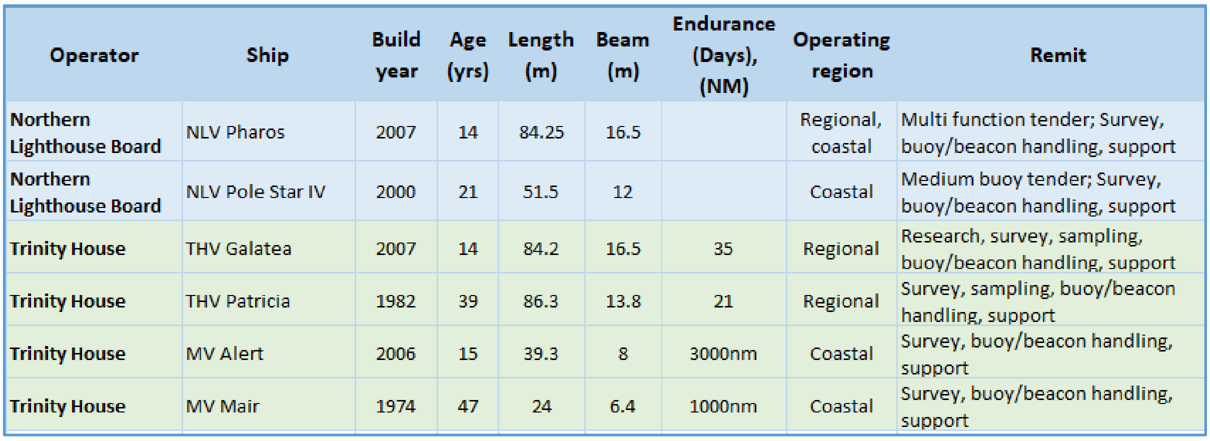
Operator	Ship
NERC (National Oceanography Centre	RRS James Cook
	RRS Discovery v3
NERC (British Antarctic Survey	RRS Ernest Shackleton
	RRS James Clark Ross
Marine Scotland	RV Scotia
Agri-Food and Biosciences Institite	RV Corystes
Cefas	RV Endeavour

Note: The RRS Ernest Shackleton and RRS James Cook are now both retired and have been replaced by the RRS Sir David Attenborough

Table 16 - UK ships included in the MSCC report

Operator	Ship	Build year	Age at 2021 (yrs)	Length (m)	Beam (m)	Endurance (Days), (NM)	Operating region	Remit
AFBI	RV Corystes	1988	33	52.25	12.8	20	Regional	Regional research, monitoring, survey, sampling
BAS	RRS Sir David Attenborough	2020	1	129	24	60	Global ice class	Deep sea multi role research, survey, sampling, logistics
Cefas	RV Endeavour	2003	18	73.9	15.8	30	Regional, Ocean	Multi role research, monitoring, sampling, survey
Marine Scotland	RV Scotia	1998	23	68.6	15	28	Regional, Ocean	Monitoring, sampling, survey
Marine Scotland	RV Alba Na Mara	2008	13	27	8.8	14+	Regional, Coastal	Monitoring, sampling, survey
NOC	RRS James Cook	2008	13	89.2	18.6	45	Global	Deep sea multi role research, survey, sampling
NOC	RRS Discovery v4	2013	8	99.7	18	40	Global	Deep sea multi role research, survey, sampling
P&O Maritime	RV Prince Madog	2001	20	34.9	8.5	10	Coastal	Coastal multi role research, survey, sampling
SEPA	RV Sir John Murray	2004	17	23.9	9		Coastal	Monitoring, sampling, survey

Table 17 - UK ships included in the Marine Board report



Operator	Ship	Build year	Age (yrs)	Length (m)	Beam (m)	Endurance (Days), (NM)	Operating region	Remit
Northern Lighthouse Board	NLV Pharos	2007	14	84.25	16.5		Regional, coastal	Multi function tender; Survey, buoy/beacon handling, support
Northern Lighthouse Board	NLV Pole Star IV	2000	21	51.5	12		Coastal	Medium buoy tender; Survey, buoy/beacon handling, support
Trinity House	THV Galatea	2007	14	84.2	16.5	35	Regional	Research, survey, sampling, buoy/beacon handling, support
Trinity House	THV Patricia	1982	39	86.3	13.8	21	Regional	Survey, sampling, buoy/beacon handling, support
Trinity House	MV Alert	2006	15	39.3	8	3000nm	Coastal	Survey, buoy/beacon handling, support
Trinity House	MV Mair	1974	47	24	6.4	1000nm	Coastal	Survey, buoy/beacon handling, support

Table 18 - UK ships operated by Trinity House/Northern Lights not included in MSCC or marine Board reports

The broad and diverse range of ships referenced in the three tables above mostly operate around the UK coastal and continental shelf areas but collectively have a complete coastal, continental shelf and deep sea global remit. The fleets cover the very broad UK marine obligations for marine science research, environmental monitoring, survey, fisheries stock assessment, and marine navigation management. Table 19 below shows the integrated fleet to gain a broader UK fleet perspective.

Operator	Ship	Build year	Age at 2021 (yrs)	Length (m)	Beam (m)	Endurance (Days), (NM)	Operating region	Remit
AFBI	RV Corystes	1988	33	52.25	12.8	20	Regional	Regional research, monitoring, survey, sampling
BAS	RRS Sir David Attenborough	2020	1	129	24	60	Global ice class	Deep sea multi role research, survey, sampling, logistics
Cefas	RV Endeavour	2003	18	73.9	15.8	30	Regional, Ocean	Multi role research, monitoring, sampling, survey
Marine Scotland	RV Scotia	1998	23	68.6	15	28	Regional, Ocean	Monitoring, sampling, survey
Marine Scotland	RV Alba Na Mara	2008	13	27	8.8	14+	Regional, Coastal	Monitoring, sampling, survey
NOC	RRS James Cook	2008	13	89.2	18.6	45	Global	Deep sea multi role research, survey, sampling
NOC	RRS Discovery v4	2013	8	99.7	18	40	Global	Deep sea multi role research, survey, sampling
Northern Lighthouse Board	NLV Pole Star IV	2000	21	51.5	12		Coastal	Medium buoy tender; Survey, buoy/beacon handling, support
Northern Lighthouse Board	NLV Pharos	2007	14	84.25	16.5		Regional, coastal	Multi function tender; Survey, buoy/beacon handling, support
P&O Maritime	RV Prince Madog	2001	20	34.9	8.5	10	Coastal	Coastal multi role research, survey, sampling
SEPA	RV Sir John Murray	2004	17	23.9	9		Coastal	Monitoring, sampling, survey
Trinity House	MV Mair	1974	47	24	6.4	1000nm	Coastal	Survey, buoy/beacon handling, support
Trinity House	THV Patricia	1982	39	86.3	13.8	21	Regional	Survey, sampling, buoy/beacon handling, support
Trinity House	MV Alert	2006	15	39.3	8	3000nm	Coastal	Survey, buoy/beacon handling, support
Trinity House	THV Galatea	2007	14	84.2	16.5	35	Regional	Research, survey, sampling, buoy/beacon handling, support

Table 19 - The integrated UK fleet

3.3 Coastal, regional and deep sea fleet operations

The MCSS review of coastal and regional vessel operations carried out for the Cefas, Marine Scotland Science and AFBI vessels, (also referencing Environment Agency, English Heritage, JNCC, Natural England and the Countryside Council for Wales), identified a network of activities covering acoustic surveys, monitoring and sampling around the UK and regional waters. The report outlined that Cefas Endeavour, Corystes and Scotia operations in 2013 comprised around 70% fish stock assessment and monitoring of contaminants in the marine environment, 20% directed towards understanding marine ecosystem functions , and 7% responding to climate change and its interaction with the marine environment. These operations are predominantly operating in UK waters, but all operations are regional UK locations. The RRS James Cook and RRS Discovery predominantly operate outside UK waters, but between 2016 and 2019 (4 year period) around 22% (or around 327 days) of operations at sea were in UK waters albeit some of this on passage to deep water operations.

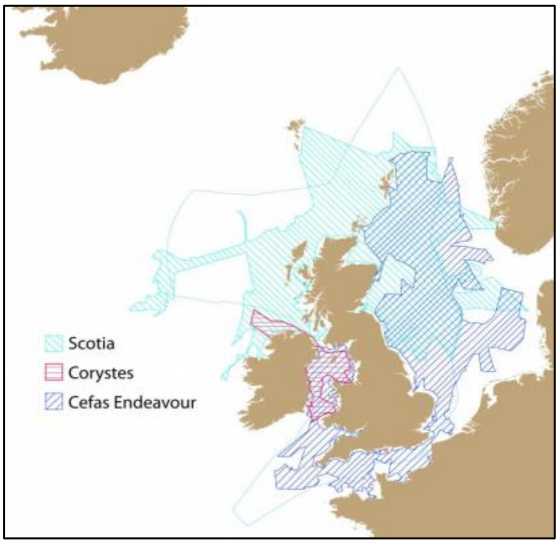


Figure 26 - Regional operations from the 2013 MSCC report

Twelve out of the fifteen vessels referrenced in this report are fully engaged in UK coastal and regional operations, as well as a proportion of the Global class ship operations; this area of operation presents opportunties for ratinalisation through the adoption of emerging autonomous ship technologies.

For the NERC marine science programme the NZOC report has identified an increasing tendency towards an integrated, diversified, survey, monitoring and sampling capability, operating within a networked ecosystem of traditional ships, and autonomous and remote operating systems. As this approach continues to develop it will provide a transformation in the way science is delivered across UK operations from coastal to deep water; this approach will be further enhanced as un-crewed marine autonomous surface ship (MASS) technology becomes more advanced.

The coastal and regional operations in particular will benefit from the UK and EU infrastructure development that will support commercial coastal and regional shipping operations targeted at GHG emission reductions for the UK transport sector. This will drive developments in coastal infrastructure which can be leveraged to support the development of the UK science, survey and monitoring MASS aspirations.

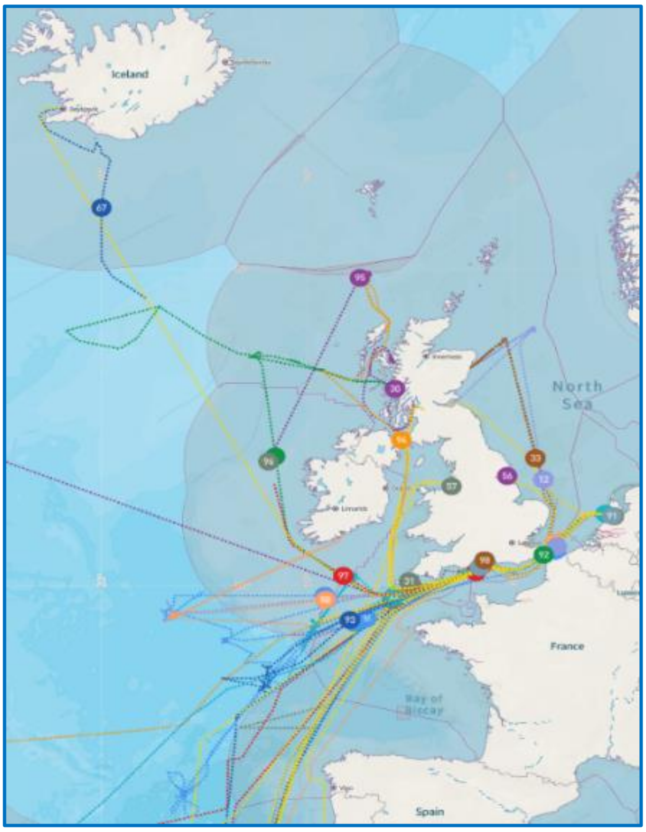


Figure 27 - RRS Discovery & RRS James Cook regional activities 2016-2019

The zero carbon highways and motorways of the seas initiatives mentioned earlier in this report would require the substantial investment necessary in vessel design, shore and maritime infrastructure to support the development of zero-emissions, autonomous shipping. This initiative would in turn provide the infrastructure to support the integration of marine autonomous surface ships (MASS) into the marine science environment as part of a diversified marine science fleet concept.

Figure 28 - RRS Discovery & James Cook passages 2016-2019

As MASS (and MAS) capability develops in the short to medium timeframe an increasing amount of coastal and regional activity will be able to be carried out using un-crewed autonomous surface ships and sub-surface autonomous platforms.

The developing capabilities of MASS and MAS will in turn increasingly present opportunities for efficiency in fleet structure as new ways of working are embedded into organisations operating remits, particularly for coastal and regional operations. It is highly likely that the necessary next stage analysis of the collective UK coastal and regional activity across the fleets will indicate that there is significant scope for an integrated UK programming stratagy. This can lead to a rationalised fleet structure operating on the integrated/diversified fleet concept discussed within the NZOC project, comprising crewed and un-crewed surface ships and marine autonomous systems operating within an integrated programme.

The projection to a centrally coordinated national UK un-crewed surface fleet (MASS), together with the fleet of Marine Autonomous Systems (MAS), available to be programmed jointly in support of the various UK operators programmes, (in parallel to, or independently of the traditional crewed ships), presents an option to facilitate a more efficient and comprehensive presence for survey and monitoring in the UK and regional waters as compared to traditional operations using crewed vessels only. This approach will in turn support the progress towards further efficiency of scale of fleet structure.

The NZOC report has identified a need to understand the key development areas in which sensor and instrument development for MASS and MASS systems needs to develop to better support the integration of these autonomous assets into a diversified fleet. The high level of coastal and regional operations carried out across the broader UK fleet presents an important area which needs to be reviewed urgently as part of this. A coordinated and collaborative approach to the broader UK fleet, and the development of an integrated MASS and MAS capability in support of the broader UK research, survey and monitoring enterprise is clearly a fertile environment for future activity. Based on the age of the UK fleet and the likely imminent renewal plans for a many of the vessels, this review needs to be carried out at the earliest opportunity.

3.4 Fleet age profiles and impact on fleet renewal strategy

The following table shows a breakdown of the UK fleet by age and operating region. The planned dates for taking ships out of commission and/or replacement would need to be confirmed by the various ship operators, but it is clear that there are a number of ships at, or approaching replacement as of 2021, and by 2035 *there is almost a complete fleet replacement plan required*.

UK ships age as of 2021

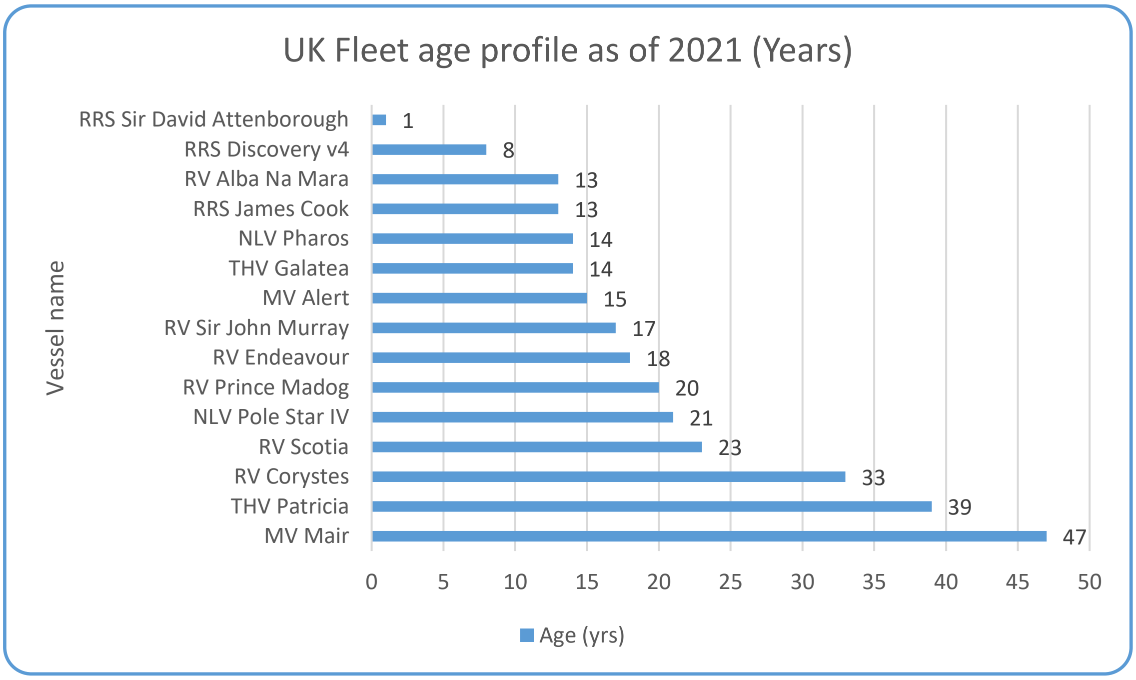


Figure 29 - UK ships arranged by their primary operating area (age as of 2021)

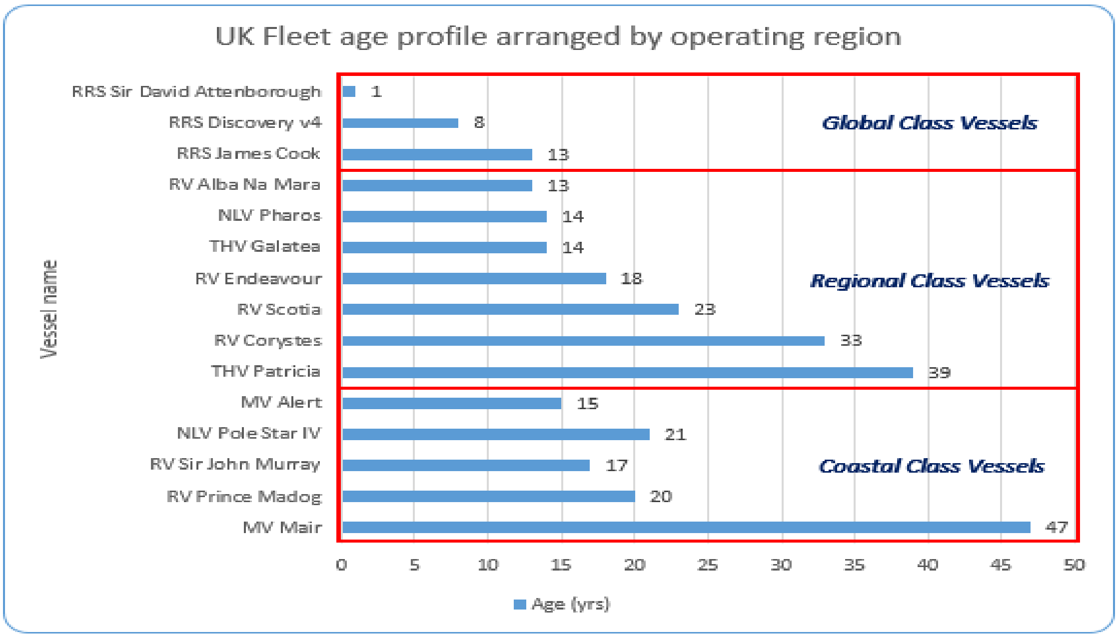


Figure 30 - UK Fleet age Profile by operating region

When looking at the UK fleet based on their primary operating areas, the age profile of the fleet shows the entire coastal and regional survey, monitoring and support fleet is at or beyond the typical notional replacement age of 30 years at the 2035 NZOC milestone. A number of these vessels will already be planning for replacement as of 2021, with a number of them likely to begin their replacement concept design stage within the next 5 years.

The scale of the UK fleet renewal programme will be substantial, and it seems inevitable that the financial cost of this endeavour will drive the requirement to consider options for new and efficient ways of delivering national survey, monitoring and sampling remits across the fleet(s), and options for rationalisation of fleet structure. Adoption of MASS and MAS in the next decade and beyond will provide alternative options to traditional surface ships particularly coastal and regional operations, and coordinated programming across platforms will also certainly increase deployment efficiency and identify further options for rationalisation.

The age profile below shows that if there is serious intent to look to rationalise and/or integrate the broader UK fleet to maximise the opportunities for efficiency of operations, it is critical that the fleet wide review process starts by 2022 at the latest. This will ensure the minimal number of ship replacements designs are progressed independently resulting in the opportunity being lost to include them within a broader UK fleet assessment.

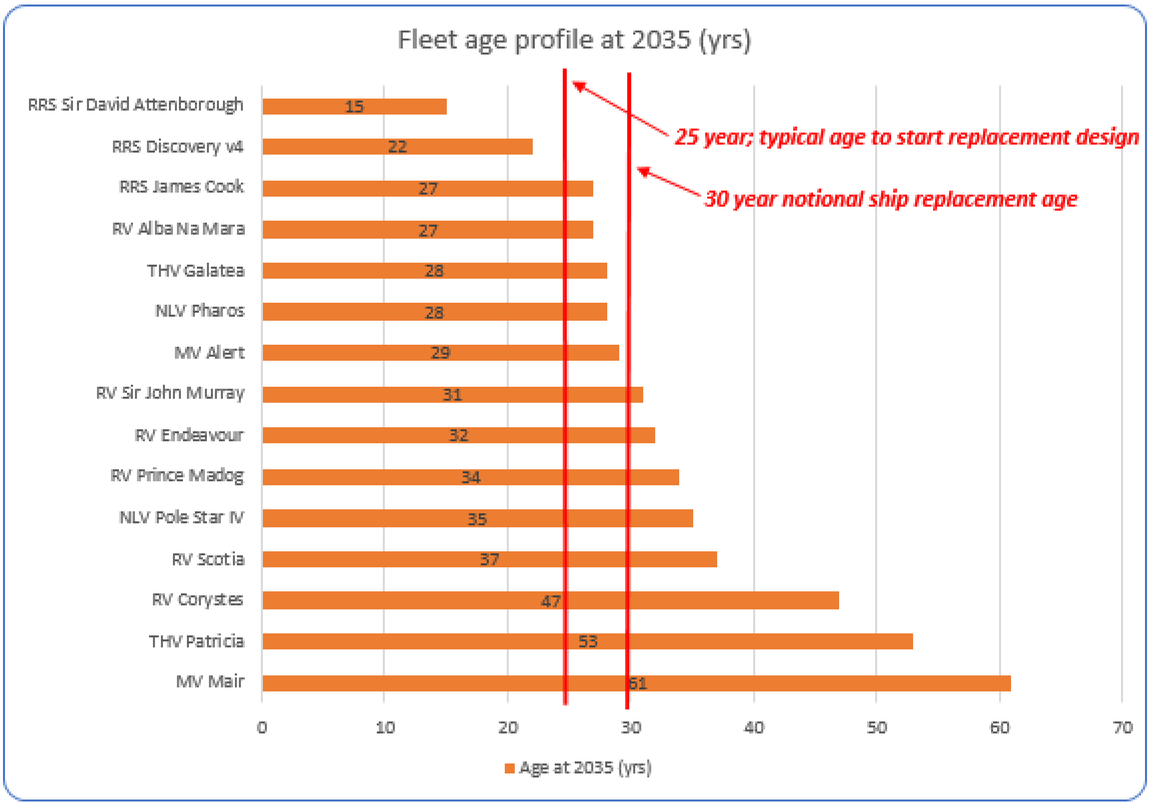


Figure 31 - UK Fleet age profile in 2035

3.5 Science support equipment – national and individual organisational based equipment pools

The delivery of marine science requires the use of a wide range of ship fitted and portable equipment for the different research, survey, monitoring or deployed equipment intervention activities carried out across the different UK organisations. This equipment represents a significant financial and resource management investment across the UK enterprise. It is assumed there is significant commonality in the type of equipment used across the different operational disciplines and organisations and likely significant crossover of assets held and operated across the UK. The authors of this report are not aware if a survey or audit of the ship fitted, portable and exchangeable equipment held by the various UK organisations has been carried out to date, but such an assessment would be a key requirement to understand what options may be available for collaboration for equipment use as well as ships, which is a as important as the ships themselves. Including both ship fitted and portable equipment as part of the assessment of a ship wide UK fleet evaluation would identify the options for interoperability of equipment across ships as well as potential for efficient inventory management.

There is potential for greater efficiency of operation and/or potential for common asset management of portable, exchangeable equipment, but there are also a range of constraints which need to be understood for any potential exchangeable equipment sharing activities as part of an expanded collaboration across UK organisations.

Equipment can be platform specific or have complex time consuming and expensive platform integration requirements. Much of the heavy, complex equipment needs to be supported by teams of experienced and trained technicians which need to accompany the equipment during use. Different equipment types have varying preparation costs and timelines, and equipment logistics often build in pre and post project time lags over and above as sea requirements. Due to the wide variety of equipment used across the marine science environment there would be no ‘one size fits all’ option for exchangeable equipment sharing, but a survey of exchangeable equipment across the UK organisations will potentially identify key areas of commonality which could present opportunities for future collaboration across exchangeable equipment as well as ships.

There is a significant range of equipment held across the UK by different organisations. It is probable that a limited number of organisations hold the greater proportion of equipment, and likely that the UK national Marine Facilities (NMF) operates one of the main equipment pools within the UK, that said, there will also be a range of specialist equipment held within different organisations UK wide. It can be assumed that there is already a level of organisational collaboration and sharing of equipment across the UK organisations on a bilateral case by case basis, and these existing equipment sharing programmes should be further be explored. An example of national asset sharing process is operated by NMF which is a national provider of exchangeable equipment across the UK science community, mainly for deployment of equipment for the NERC marine facilities programme, but also more broadly for UK science operators (within its operating terms of reference). The various UK equipment sharing processes and operating protocols should be further assessed to see how UK organisations could approach best practice for equipment sharing and exchange. There may well be options to also review the duplication of equipment assets across the UK operators to determine if there is any efficiency of scale across a more collaborative working model.

3.6 Collaboration: options and proposals:

3.6.1 Common programming and scheduling tools

Common programming and scheduling tools can underpin future collaboration efforts and needs to be seen as a central priority of future collaborative initiatives.

Adoption of common, integrated fleet programming tools would enable consistent data gathering across the fleets enabling the sharing of information in real time, which in turn can provide the knowledge for resource and policy managers to determine the key areas of change and development to support future collaboration initiatives. This would be an important step to provide the cross organisational information necessary to understand the operating profiles and capacities of the various operator's vessels as well and exchangeable equipment. It would provide the information to develop the options for collaboration and coordination relating to programme planning, delivery and asset management.

An example of an integrated ship and equipment scheduling system is the Marine Facility Planning system (MFP) developed by NERC and NIOZ (Royal Netherlands Institute for Sea Research, Netherlands), which is an integrated web based marine planning, scheduling and programme management system used as the primary system for programme management of the NERC fleet. It is now also used by many organisations worldwide as their primary marine science fleet programming and scheduling system. The MFP can be scaled for small operators (single coastal ship operator), up to large mixed fleet operations for many ships. The system can be configured for individual operators to have programming control over their own fleets whilst also enabling consistent information and data sharing across linked organisations in real time. Adoption of the MFP across the UK operators would enable visualisation, data sharing and common analysis tools across the fleet operators, providing the interface at the operations level, as well as the strategy planning level to support collaboration, and future decision making.

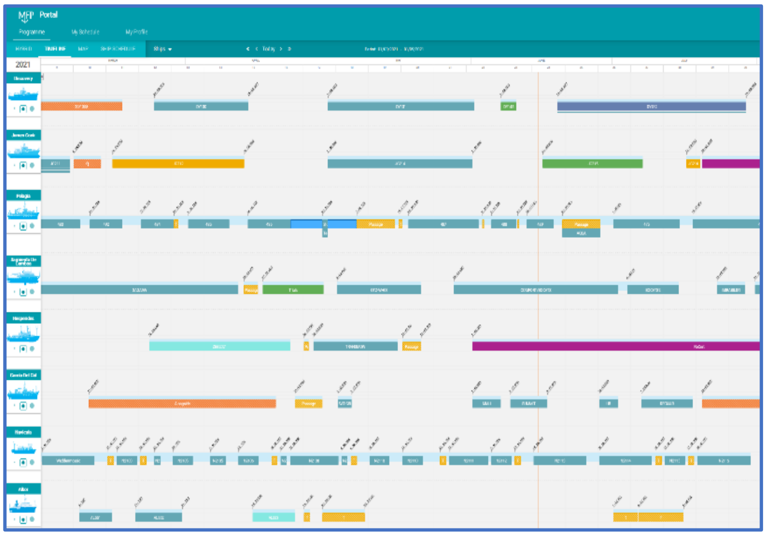


Figure 32 - MFP annual programme showing UK, Spanish and German ships

Common programming and scheduling systems would provide consistent ongoing intelligence into the operational profiles and programming of the various operator's vessels. This would enable informed decisions to be made on operating efficiency, options for ship time exchange, and opportunities for use of MASS and MAS to augment or replace some of the existing activities. This will be particularly relevant to the coastal and regional vessels which make up the bulk of the fleet operations and the majority of the ships across the respective fleets. The NZOC project has focussed heavily on the potential impacts and benefits of MAS and MASS for NERC fleet operations, both regional and deep sea. Applying the same focus across the broader UK fleet will likely provide significant benefit to the UK fleet capability. The greater part of the UK fleet is targeted at coastal and regional operations which is where the early advances will be made in MASS capability both in the current and the next decade. There are significant opportunities to harness this technology in the areas of survey and monitoring in particular, and increasingly the more complex sampling activities as commercial operators develop this area of their operations and these technologies become more widely available. Gathering consistent and reliable information on fleet operations is a key requirement to identify the common activities to develop this adoption of emerging technology.

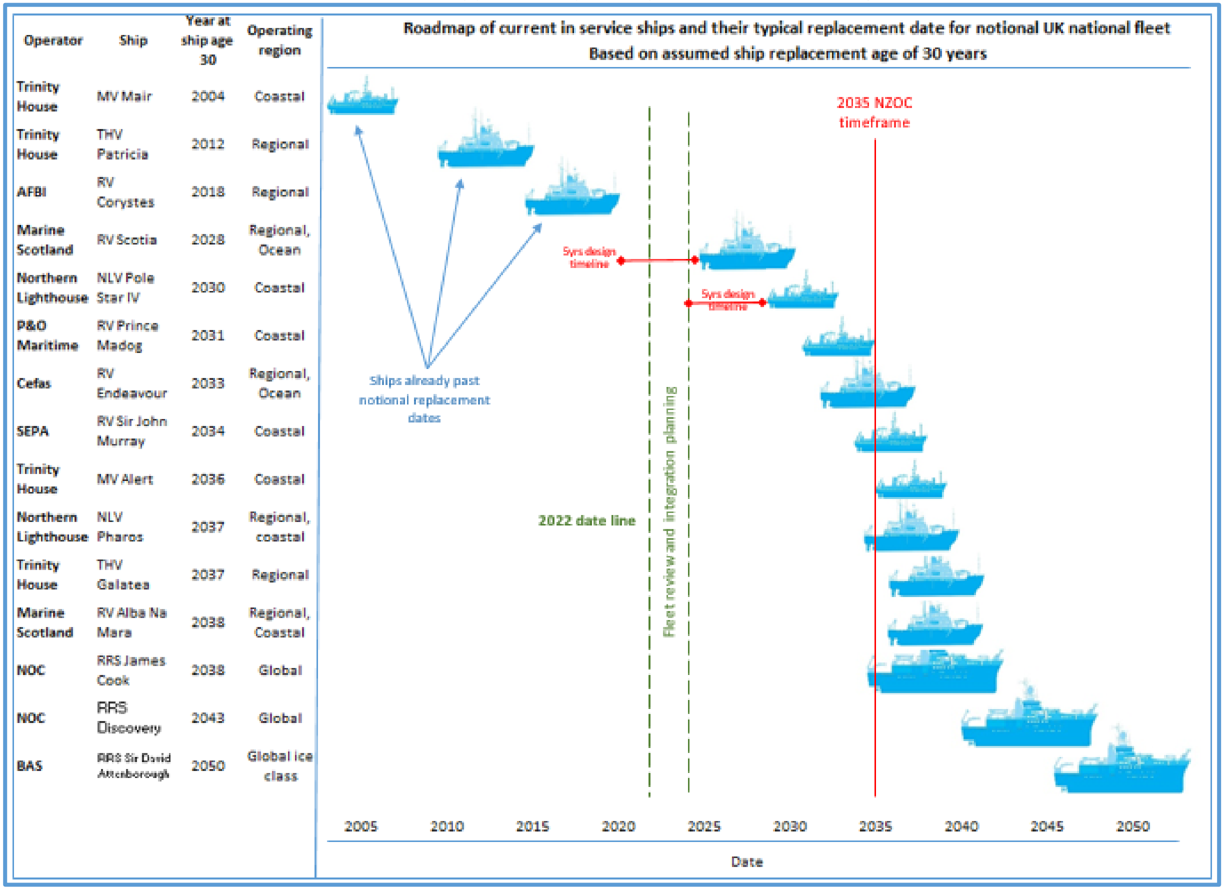
3.6.2 Fleet renewal roadmap

Previous reports proposed collaboration on cross organisational engagement for fleet renewal, this area of collaboration is also seen as a critical requirement by this report. Review of the renewal timelines would identify options for designing in fleet efficiency through assessment of common cross fleet requirements and equipment interoperability, with the potential to build in cross organisational exchange of similar tasks across the fleet, supporting the concept of ship and equipment exchange and joint scheduling. A well-defined fleet renewal roadmap will identify the fleet renewal milestones in advance that can then be targeted to assess and implement strategic interaction between funding bodies and fleet operators over appropriate timescales.

Figure33 is an example of a simple graphical fleet renewal timeline of the six international Ocean Facilities Exchange Groups (OFEG) partners. A road map for an integrated UK fleet renewal plan alongside a clear understanding of the fleet’s operational profile gained from use of the MFP will further enable informed decisions to be made on the fleet renewal strategy. A cross organisational approach to fleet renewal can enable an assessment of the required capabilities of individual ship replacement designs from an ‘integrated fleet perspective’, supporting efficient fleet design, interoperability of equipment between operators, and potential for integration in areas such as common long term design and build contracts, fleet maintenance contracts, and joint fleet operations.

Figure 33 - OFEG fleet renewal time-line

Example fleet renewal time line for the broader UK fleet are outlined below
Based on a typical 30 year operational vessel life:



Operator	Ship	Year at ship age 30	Operating region
Trinity House	MV Mair	2004	Coastal
Trinity House	THV Patricia	2012	Regional
AFBI	RV Corystes	2018	Regional
Marine Scotland	RV Scotia	2028	Regional, Ocean
Northern Lighthouse	NLV Pole Star IV	2030	Coastal
P&O Maritime	RV Prince Madog	2031	Coastal
Cefas	RV Endeavour	2033	Regional, Ocean
SEPA	RV Sir John Murray	2034	Coastal
Trinity House	MV Alert	2036	Coastal
Northern Lighthouse	NLV Pharos	2037	Regional, coastal
Trinity House	THV Galatea	2037	Regional
Marine Scotland	RV Alba Na Mara	2038	Regional, Coastal
NOC	RRS James Cook	2038	Global
NOC	RRS Discovery	2043	Global
BAS	RRS Sir David Attenborough	2050	Global ice class

Figure 34 – Notional UK fleet renewal time-line

3.6.3 Science support equipment

A survey or audit of the ship fitted, portable and exchangeable equipment held by the various UK organisations should be carried out across the UK organisations to understand what options may be available for collaboration for equipment use. An understanding of the UK wide inventory of ship fitted and portable equipment would identify;

- the options for interoperability of equipment across ships,
- the potential for more efficient inventory management in areas such as duplication of assets,
- options for sharing equipment,
- asset renewal strategies, and/or common procurement efficiencies,
- areas where emerging technology such as MASS and MAS can be adopted,
- areas to target new ship design to support interoperability of equipment across a more integrated, collaborative fleet operating model.

Any existing UK equipment sharing processes and operating protocols should be assessed to see how UK organisations could approach best practice for equipment sharing and exchange.

3.6.4 Joint UK research fleet working group

To develop and support the process of collaboration and cooperation between the various UK fleet operators there needs to be a dedicated forum for communication and administration operating at the right level across the organisations. This forum would be tasked to define, initiate, implement, and progress the practical steps necessary to underpin the mechanisms which need to be put in place for information gathering, evaluation of the options for collaboration, and producing the implementation roadmap.

Adopting an informal unstructured approach to collaboration across the UK fleet operators will likely continue to result in piecemeal exchange of information (and data) on vessel operations, operating profiles, and scheduling metrics over an unacceptable and extended timeframe. A dedicated joint research fleet working group comprising informed, operationally aware members from the various fleet organisations would provide ownership and accountability for the process.

The working group would have clear terms of reference, have members drawn from the respective fleet operators, with initial primary tasks comprising:

- Implementation of common systems across the fleet operators adopting an internet based programming, scheduling and reporting system,
- Production of a UK fleet renewal roadmap.
- Formal cross organisational communication, developing an understanding of each other’s organisational capabilities, and options for cross organisational exchange of knowledge and assets.
- Assessing the adoption of new technologies such as MASS and MAS to augment/replace existing deployments.
- Exchange of information and knowledge on ship design and the adoption of next generation fuel options to implement the emissions reduction measures required by the UK government for the next generation of ships.
- Evaluate fleet renewal and current commercial milestones as part of a structured strategic approach to fleet renewal coordination, asset sharing and eventually the potential for future rationalisation of vessel operators and fleet integration.

A joint working group of UK fleet operators with strategic focus on collaboration, cross organisational engagement and coordination of fleet renewal would be the first step in developing the necessary relationships to move the collaboration process between the UK ship operators forward. A structured and informed approach applied to collaboration across the UK fleet, focussing on the key criteria of changes providing *‘equal or greater capability’*, can enable change to be enacted over planned timescales ensuring the delivery requirements of each organisation are not unduly impacted. Adoption of common scheduling and reporting systems at the earliest point will enable key information to be efficiently, objectively and accurately captured in a timely manner, providing a major keystone in the information structure needed to evaluate options for collaboration and activity exchange. The production of an integrated fleet renewal road map will provide the intelligence to assess cross organisational options for future fleet structure particularly when reviewed in conjunction with fleet operational data from the MFP.

3.6.5 Integrated UK fleet renewal programme – New generation of UK survey & research fleet

The adoption of common scheduling and programming tools across the different fleet operators will progressively provide the information on duty load cycles of ships across the fleet, their geographical operating profiles, as well as detail of the type of activity and the equipment used to deliver each project. Working alongside fleet operators this information would allow a fleet working group to determine the optimum size, structure and design criteria for a national fleet to support the diverse UK operations for global regional and coastal activities.

Considering the age profile of the UK fleet, and the fact that the greater proportion of the fleet will require renewal within the 2035 time scale, there is an unprecedented opportunity for a national fleet renewal plan. This could enable a structured shipbuilding plan that can benefit from the economy of build scale which can be realised from the potential for repeat builds. The option to build more than one ship of a core design has potential financial benefit (cost reduction), and also the potential to progressively build on the design to enhance and improve from an initial build. If this level of organisational cooperation can be achieved, it is an effective and efficient approach to fleet renewal.

Based on the ships reviewed for this report and the previous MCSS report the current extended fleet is considered as 3 global class, 7 regional class, and 5 coastal class ships, but there may well be other ships that can be considered as part of the broader national UK fleet not identified in this report. For the purposes of this report the 15 ships are arranged into generic classifications based on the UNOLS research ship classification of geographical operating criteria of Global (multi-ocean), Regional (territorial waters and up to shelf edge), and Coastal operations. There are substantial differences between the UK ships designs, size and capabilities, and it is clear that the classification applied here is generic and does not fully account for each ship design and operating capability. The significant difference in ship designs across the UK fleet operators is more to do with the fleet's ad-hoc development over the decades. Despite the diverse range of designs across the fleet the generic 'global', 'regional', 'coastal' classification is still an effective method to capture the core geographical operating mode of the ships based on their operational requirement at this initial stage.

It is clear that if there is to be an effective UK government fleet capability necessary to support the UK obligations for the deep sea marine science research programme, environmental monitoring, survey, fisheries and coastal navigation, there is going to need to be a comprehensive fleet renewal plan and build programme in place throughout the next two decades. This will either take place as discreet projects within each organisation developing ship designs internally for their specific organisational needs, or it could be a broader integrated approach encompassing the wider cross fleet synergies which would lead to a more efficient fleet structure and cross organisational engagement in use of assets, and more effective adoption of emerging autonomous technologies. Either way there will need to be a major ship build programme. The integrated approach has the potential to provide significantly greater benefit for a strategic fleet structure encompassing cross organisational interoperability and integration of MASS and MAS.

An integrated fleet renewal approach would initially be a significant undertaking. This integrated fleet renewal approach has likely not been undertaken in the UK for many decades, if at all. But individual organisations undertaking their own fleet renewal programmes is also a significant undertaking. The integrated approach would need significant ground work for funding alignment, project administration and organisation, but the downstream benefit for efficiency could be significant once a structure is in place. An integrated national fleet renewal plan also has significant potential for engagement with the UK industry and UK ship building sector.

For the purposes of this report it would be premature to propose a fleet size and structure as the necessary information is not yet captured (at least not by this report), to determine the overall operating requirements across the various organisations. That said, it is considered that there would be scope for fleet rationalisation particularly with the integration of MASS and MAS into a coordinated fleet operating structure. As with a national approach to a crewed surface fleet, a UK wide approach to a national MASS fleet supporting cross organisational activities would provide an efficient advanced capability for the UK research, survey and monitoring enterprise.

3.6.6 Overview – scheduling tools, joint working group, fleet renewal planning

There is no reason that the fleet working group, fleet renewal plan, and implementation of common scheduling and reporting systems across the ship operators could not be fully in place by the end of 2022, with the setup of the working group and completion of the fleet renewal plan the initial priorities.

The primary objectives would be; implementation of common scheduling and reporting systems across operators, production of a UK fleet renewal schedule, information gathering, relationships building, and the identification and evaluation of the options for collaboration across respective programmes.

The above starting point seems simplistic for such a complex task of understanding different organisational operating practices, technical capabilities, and organisational sensitivities. That said, this approach is essentially how the Ocean Facilities Exchange Group developed its complex and detailed understanding of operational practices necessary to successfully support the ship exchange programme across six international fleet operators, and the process has been seen to be very effective. The approach proposed here builds and exceeds the OFEG model in a more formal way, through a process of practical, operational engagement. The OFEG group have operating and exchange protocols in place for ships and equipment across international operators, these are uncomplicated, straightforward operating practices designed to effectively protect, but support the collaboration and exchange between partners.

The adoption of the correct tools to capture and exchange the broad meta-data needed to understand the fleets operational capabilities and models, will provide the information needed to make the strategic decisions related to fleet size, capability and organisational structure. As mentioned earlier, this report is focussed as an operational project, with a view to evaluating options to re-align UK fleet capabilities through efficiency of operations and adoption of new technologies to provide ‘equal or greater operational delivery’.

Financial pressures and decisions at the funding level also need accurate and reliable information to make informed decisions, and this financial aspect of the process would also be supported by this practical operational approach supported by consistent cross organisational information gathering and exchange.

Initial evaluation of the broad capability of the UK fleet suggests there is significant potential for improved cross organisational efficiency. The provision of effective programme and operational data across the UK fleet from the systems such as the MFP could confirm if this is the case and to what extent. NOC and BAS already apply a ‘joint scheduling’ function to programme planning overseen by NERC (as the fleet and programme owner), with both fleet operators having operational ownership and responsibility of their own fleets. Fleet deployment information is jointly available to both operators and funding body; this concept can be extended to a greater number of UK ship operators as part of the initial phase of coordination and collaboration.

It is clear looking at the operating areas of the coastal, regional, and deep sea ships that there is significant overlap between the various programmes operational requirements on a geographical basis. Looking to the development of un-crewed autonomous vessels in the current decade, there are significant opportunities to employ un-crewed autonomous vessels to support a proportion of the coastal and regional activity, supporting this programme of activities in an integrated manner across the UK fleets. During the 2022 – 2030 timeline there is also significant opportunity to look at existing and developing MAS capability to also support aspects of the coastal and regional programmes across the UK operators. There is an opportunity to consider a model of a fleet of un-crewed autonomous vessels (MASS) operating as a central UK capability, across the UK enterprise, alongside the fleet of MAS, providing a constant presence from a permanently deployed fleet of MAS and MASS for the coastal and regional component of the UK research, survey and monitoring programmes.

This focus on coastal and regional operations would enable the crewed ships to be programmed in the areas in which they are most efficient at operating. It would also enable the development of a fleet structure to be targeted more efficiently in an increasingly integrated way where the MASS and MAS can deliver a component of the coastal and regional programmes, working alongside crewed vessels where necessary, also operating independently of crewed ships depending on the project requirements. Crewed vessel operations in these regions will still be necessary and would then be programmed as required for intervention to fixed and autonomous assets, activities requiring more complex equipment and human intervention outside the capability of MAS and MASSs, or activities requiring the greater sampling, and multi discipline activities only larger crewed ships can provide.

The MSCC report reviewed fleet collaboration and operating scenarios across the UK fleet operators (not including Trinity House or Northern Lighthouse), and concluded collaboration on programming and scheduling, and progress on integrated operations are key areas for development along with evaluation of the options for cross organisational collaboration for ship procurement. Reviewing the broader UK fleet regional operating profiles and remits, it is clear that there is scope for greater exchange of assets and improvements through joint programming initiatives.

From an operational perspective effective evaluation of the options for cross organisation collaboration, and review of fleet structure, can only be made on the basis of;

- an understanding of each operators fleet capability to deliver their core remit as ‘discreet fleets’ in their own right;
- an understanding of the survey and sensing requirements of each operators fleet activities to target MASS and MAS capabilities to augment or replace current crewed surface ship activities;

- an effective understanding of the ‘task vs resource’ loading across the integrated fleet;
- and following above, an understanding of the fleet as an ‘integrated fleet capability’ assessing the overall fleet in context of the potential for efficiency of scale.

Carrying out the above analysis across the ship operators as a single integrated project can ensure any proposed structural changes are not to the detriment of the responsibilities of the various organisations, and they each continue to effectively deliver their core remits. The options for collaboration from this report align closely with aspects of the 2013 MCSS report and offer practical approaches to moving this forward. The timescale of the NZOC project looking to the replacement of the RRS James Cook, coincides at a critical time for the shipping sector with rapid development of autonomous technology and focus on reduced emission fuels. These factors, along with the adoption of integrated web based planning tools, provide a range of opportunities to move the collaboration, and programme rationalisation effort forward which were not available at the time of the 2013 MSCC report.

Implementing common scheduling and reporting systems across the fleets and developing an integrated fleet renewal road map, will inform a structured approach to efficient scheduling and programming, and support an integrated fleet renewal plan and options for rationalisation of fleet operations.

A more integrated approach to the broader UK marine science and marine governance enterprise via a designed evolution into a coordinated entity with clear communication channels, will enable the collective assets to be more effectively and efficiently developed, managed and deployed, magnifying the benefits of individual operators by working across organisations.

These partnerships will provide greater opportunity and weight to represent the individual (and collective) requirements to funding bodies (government). The more integrated approach will also provide benefits to UK industry through via a consistent approach to fleet design and build programmes and maintenance programmes.

3.6.7 Potential scope for further international collaboration

The main mechanism for international collaboration for the UK Global Class ships is the Ocean Facilities Exchange Group (OFEG) concept which has been in place since 1996. NERC was one of the founder members of this process and has been fully engaged in its development and operation since its conception. OFEG is a collaborative venture between the NERC (Natural Environment Research Council, UK), IFREMER (Institut Français de Recherche pour l’Exploitation de la Mer, France), BMBF (Bundesministerium für Bildung und Forschung, Germany), the NIOZ (Royal Netherlands Institute for Sea Research, Netherlands), the CSIC (Consejo Superior de Investigaciones Científicas, Spain), and the IMR (Institute of Marine Research, Norway). Different countries joined at different points in time since 1996, and the partnership is targeted at the deep sea global ships, but operations are targeted at deep sea, regional or coastal depending on the various operators programme requirements.

The collaborative partnership is designed to cooperate with exchange of ship-time, and exchange of large items of marine science equipment, and scheduling joint expeditions when the opportunity arises. The process allows national science communities to access to a wider range of facilities and equipment other than their own countries assets, and potentially save on long passage legs between areas of scientific interest. As the broader international fleets have different global areas of operation, the partnership works by exchanging ship time between organisations, allowing scientists access to a wider range of geographical areas in a given year. Ship time is exchange through a ‘barter process’ with equivalent reciprocation between partners over time, resulting in no money needing to change hands. The partners form a permanent working group, comprising the managers and planners of the respective fleet of scientific research ships and major marine facilities.

Although the underlying principal is that no money changes hands, the arrangement does not provide “free” ship time. For every cruise on another organisation’s ship, the beneficiary organisation must mount a full cruise on one of its own ships in return, and to an equivalent ‘value’. The operating costs still fall to the ship owners, and each organisation has an appropriate scheme of ‘banking the reciprocal balance of days owed’ to support the process. An equivalence points system has been agreed for the value of each of the ships, to ensure like-for-like ‘value’. Points are allocated per ship or equipment day used.

The OFEG barter process is an extremely efficient and effective initiative in operation for over 2 decades. It is critical that this partnership continues and is supported, and potentially seen as a model for further collaborative partnerships to increase international collaboration.

The UK also has bilateral agreements with Irelands’ Marine Institute (MI), and the US National Science Foundation (NSF). These agreements are direct one-to-one relationships with the UK, but are also administered via the OFEG barter concept. As the global marine research fleet capability develops across international partners, there is increased scope to develop further collaborative relationships.

The adoption of the Marine Facilities Planning system by many countries worldwide presents an opportunity for international partners to share their national programme information on a common web based platform; this will increasingly present further opportunities for collaboration and asset exchange. Many (if not all) of the countries operating global and ocean class ship are members of the International Research Ship Operators forum, and this forum can be a key mechanism for progressing international collaboration efforts in the future.

It is assumed that a number of our partner organisations worldwide will be reviewing their options for efficient geographical operations that could be supported by collaborations across international partners. Most, if not all international operators are part of the International Research Vessel Operator (IRSO) forum, an increasing number of which are adopting the Marine facilities Planning (MFP) system to support their programme operations. This presents a real opportunity to develop international collaborations through the IRSO forum.

NERC has high level interaction across the main international research vessel ship operators within Europe via the OFEG mechanism. This partnership can be leveraged to further enhance cooperation and should form a key component of NERCs approach to efficient geographical collaboration with our closest partners. NERC/NOC can also take a lead role initiating a review of collaborative options via the IRSO forum to assess the appetite for more formal arrangements between IRSO partners potentially along the lines of the OFEG concept, via bi-lateral arrangements such as those between the NERC, MI and NFF, or other arrangements that may be determined through a formal approach across the IRSO community. There is also a significant potential for the UK to engage with the European Research Vessel Operator (ERVO) group, which takes a coordinating role for the small to medium research vessel operators within Europe. NERC has always been a partner within ERVO, but as the NERCs main marine programme remit operates global class vessels operating internationally (via NMF and BAS), the engagements with ERVO has been very limited over the years. If there is to be higher levels of collaboration, asset sharing and engagement across the UK marine research, monitoring, and survey organisations in future years as recommended by this report, the ERVO forum would be highly relevant to the UK small, medium vessel operators. This can potentially provide some of the benefits to both UK and EU partners that the global class, international ships have through access to the OFEFG forum.

3.7 Collaboration: Conclusions

UK collaboration -

- The main UK operators considered in this report manage the broad UK marine obligations for marine science research, environmental monitoring, survey, fisheries stock assessment, and marine navigation management. They collectively operate around 15 different vessels; twelve of which are fully engaged in UK coastal and regional operations, the Global class ships predominently operate deep sea and internationally, but also carry out a proportion of regional operations.
- During the past decade there have been at least three reviews and reports which addressed the area of UK vessel operators, fleet utilisation, collaboration and cost/programming efficiency. Three of these plus the NZOC report are identified below. These have identified a range of common observations and recommendations, and common areas for development and collaboration;
    - 2013 - Marine Science Coordination Committee (MSCC): ‘UK Marine Research Vessels - An assessment and proposals for improved co-ordination’
    - 2019 - European marine Board: ‘Next Generation European Research Vessels – Position paper 25’
    - 2021 – Cefas: ‘The future of the UK National Monitoring fleet capability’
    - *(2021 – NZOC: ‘Net Zero Oceanographic Capability’)*
- Examples of common recommendations from reports are paraphrased below;
    - Common scheduling and programming systems
    - Asset sharing
    - Joint strategic fleet renewal roadmap
    - Adoption of next generation low to zero fuel options and EEMs
    - Adoption of MASS and MAS to augment/replace existing deployments.
    - Review portable and exchangeable equipment held by the various UK organisations to identify; options for interoperability across ships, duplication of assets, options for sharing equipment, asset renewal strategies/common procurement efficiencies, new ship design to support interoperability

- The UK fleet age profile shows most if not all the vessels within the coastal and regional survey, monitoring and support fleet will be at or beyond a typical replacement age at the 2035 NZOC milestone. Operators will already be planning replacements as of 2021, others beginning their replacement designs within the next 5 years. The age profile shows that if there was a serious intent to coordinate, rationalise and/or integrate across the UK fleet to maximise efficiency of operations, a fleet wide review process would need to start by 2022 at the latest. This would ensure the minimal number of ship replacement designs are progressed independently of a broader strategic UK fleet assessment.
- There is going to need to be a comprehensive UK wide fleet renewal plan and build programme in place throughout the next two decades, either as discreet projects within each organisation, or an integrated approach encompassing wider cross fleet synergies. The integrated approach has the potential to provide significantly greater benefit for a strategic fleet structure encompassing cross organisational interoperability and integration of MASS and MAS.
- An integrated fleet renewal approach would initially be a significant undertaking, with this level of coordination unlikely to have been undertaken in the UK for many decades, if at all, but individual organisations undertaking their own fleet renewal programmes is also challenging. The integrated approach would need significant ground work for funding alignment, project administration and organisation, but the downstream benefit for cost effectiveness and efficiency could be significant once structures are in place. An integrated national fleet renewal plan also has potential for substantial engagement with UK industry.
- Analysis of the collective UK coastal and regional activity will likely indicate that there is significant scope for an integrated UK programming stratagy. This can lead to a rationalised fleet programming structure operating on the integrated/diversified fleet concept, comprising traditional and un-crewed surface ships and MAS operating within an integrated programme. As MASS (and MAS) capability develops an increasing amount of coastal and regional activity will be able to be carried out using un-crewed autonomous surface and sub-surface platforms. The developing capabilities of MASS and MAS will increasingly present opportunities for efficiency in fleet structure as new ways of working are embedded into organisations operations.
- Adopting an informal unstructured approach to collaboration across the UK fleet operators will result in piecemeal exchange of data and information on vessel operations, operating profiles, and scheduling metrics over an unacceptable and extended timeframe inducing further delay. A formal approach via a dedicated joint research fleet working group comprising informed, operationally aware members from the various fleet organisations would provide ownership and accountability for the process.

International collaboration -

- The main mechanism for international collaboration for the UK Global Class ships is the Ocean Facilities Exchange Group (OFEG) concept which has been in place since 1996. NERC was one of the founder members of this process and has been fully engaged in its development and operation since its conception. This partnership should be approached with renewed importance to evaluate further opportunities to enhance cooperation, and to maintain and promote OFEG as a key component of NERCs strategy for efficient international collaboration with our closest partners for deep sea, international operations in particular.

- NERC/NOC can take a lead role initiating a review of collaborative options via the IRSO forum to assess the appetite for more formal arrangements between IRSO partners potentially along the lines of the OFEG concept, via bi-lateral arrangements such as those between the NERC, MI and NFF, and other arrangements that may be determined through a formal approach for greater collaborative engagement across the IRSO community, particularly with focus on the adoption of emerging technologies such as zero carbon fuels and autonomous shipping.
- NERC has always been a partner within the European Research Vessel Operators group (ERVO), but as the NERCs main marine programme remit operates global class vessels operating internationally (via NMF and BAS), the engagements with ERVO has been very limited to date. If there is to be higher levels of collaboration, asset sharing and engagement across the UK marine research, monitoring, and survey organisations in future years as recommended by this and previous reports, the ERVO forum would be highly relevant to the UK small, medium vessel operators. This can potentially provide some of the benefits to both UK and EU partners that the global class, international ships have through access to the OFEG forum.

Collaboration; Recommendations

1. Set up a formal UK fleet working group between the various UK fleet operators with accountable members; this would be a dedicated forum for communication and administration operating at the right level across the organisations to develop and support the progress of collaboration and cooperation.
2. Begin a UK fleet wide review process by 2022 at the latest to ensure the minimal number of ship replacements designs are progressed independently resulting in the opportunity being lost to include them within a broader strategic UK fleet assessment.
3. Implement common programme planning systems across ship operators enabling information sharing in a consistent and efficient way enabling evaluation of operating profiles, asset use and capacity availability.
4. Produce a UK wide joint strategic fleet renewal roadmap to inform planning, finance and organisational timelines for fleet renewal collaboration.
5. Survey/audit of the ship fitted, portable and exchangeable equipment held by the various UK organisations to identify; options for interoperability across ships, duplication of assets, asset renewal strategies/common procurement efficiencies, areas for MASS and MAS adoption.
6. Adoption of next generation low to zero carbon fuel options as a central tenant of fleet renewal strategy to implement the emissions reduction measures required by the UK government for the next generation of ships.
7. Adoption of MASS and MAS as a central part of fleet renewal strategy to augment/replace existing deployments during the current and next decade.

8. Assess the potential for enhanced OFEG collaboration with EU partners to review new areas of collaboration
9. Take a lead role initiating a review of collaborative options via the IRSO forum to assess the appetite for more formal arrangements between IRSO partners, via bi-lateral arrangements such as those between the NERC, MI and NFF, or other arrangements that may be determined through a formal approach across the IRSO community, with particular focus on adoption of emerging technologies such as zero carbon fuels and autonomous shipping.
10. Review NERCs limited engagements with ERVO with a view to higher levels of engagement. The ERVO forum is highly relevant to the UK small, medium vessel operators. As part of greater collaboration across UK organisations, engagements with ERVO can potentially provide benefits to both UK and EU partners that the global class, international ships have through access to the OFEG forum.

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