National Oceanography Centre

NZOC: Net Zero Oceanographic Capability

Summary Report

Contents

Foreword

"Knowledge of the oceans is more than a matter of curiosity. Our very survival may hinge upon it."

President John F Kennedy, March 1961. Message to Congress

We know that the ocean has greatly slowed the rate of climate change, but in doing so it has warmed, acidified and lost oxygen. Alongside those changes, sea levels are rising and ocean currents are in flux.

Understanding how fast these changes are happening, what their impact upon marine ecosystems might be and the future risks to a healthy and biodiverse ocean is predicated upon marine scientists continuing to analyse this most complex of ecosystems. More positively, the Fourth Industrial Revolution might provide solutions that allow us to achieve that understanding without adding to the problem but technology alone will not accomplish this. Sustained global ocean observations using autonomous platforms, allowing us to peer into the seas like never before, can provide an unprecedented level of data. Hovever, this data must be designed to meet the broadest possible range of needs across national and regional boundaries.

The UK's current observing system is impressive, but due to fragmented and patched together funding, it is fragile, too often works in isolation and too frequently the full costs of delivering user ready datasets are not supported. Restructuring how data collection is funded, coordinated and delivered would shift this ecosystem to one that supports the UK's world-class oceanographic research base. It does, however, present a major transition and one that in many areas will skip a generation of technological advances if it is to meet the required timeframe. Despite this, the gains will be significant for marine science and the broader user community if we can structure a system which allows the UK to extract maximum information value for investment in observation capability.

Under the UK Presidency, the G7 Climate and Environment Ministers have made ambitious commitments to climate action and addressing biodiversity loss – including accelerating the clean energy transition, improving resource efficiency and promoting a circular economic approach. In particular, the Ministers committed to keep a limit of 1.5 degrees temperature rise within reach and achieve net zero emissions as soon as possible - by 2050 at the latest. They recognised the importance of innovation and multilateral collaboration.

[2]G7 **Ocean Decade Navigation Plan (2021)** www.gov.uk/government/publications/g7-climate-and-environment-ministers-meeting-may-2021-communique/g7-ocean-decade-navigation-plan

[3]G7 **Future of the Seas and Oceans Initiative:** www.g7fsoi.org

Foreword

The UN Decade of Ocean Science for Sustainable Development articulates the need for a Net Zero Oceanographic Capability – "a once in a lifetime opportunity to create a new foundation for the scientific community, governments and civil society to strengthen the management of our oceans and coasts". Through an agreed G7 Ocean Decade Navigation Plan[2], G7 members committed to collaborate to advance collective work on ocean science, ocean observing and ocean action. The Navigation Plan recognised the ongoing work of the G7 Future of the Seas and Oceans Initiative[3], agreeing to three new priority activities to collectively advance efforts in Global Ocean Indicators, Digital Twins of the Ocean and Net Zero Ocean Capability.

This report demonstrates the important contribution the UK can make in advancing a Net Zero Ocean Capability and could act as a launch pad for the G7 to share best practice, and collaborate on technological development. The Digital Twin Ocean and Global Ocean Indicator will also contribute to the goals of Net Zero Ocean Capability of ensuring maximum information value and utility for investment in ocean observing, as we improve efficiency on the path towards Net Zero emissions.

While Oceanography started out as a voyage of discovery and still remains so, understanding the ocean is increasingly recognised as essential to supporting a sustainable relationship with the natural environment. Thhis is due to the fundamental role the ocean plays in our weather and climate system, as hosts to important ecosystems, biodiversity and food sources, and the growing maritime economy such as shipping, energy generation, and tourism. Almost 250 years after HMS Challenger set out on the expedition that laid the foundations for the field of marine science, the UK has the opportunity to play a leading role in the transition of the research ecosystem that supports this expanding field of research. By leveraging its expertise in marine science, robotics and autonomy, sensor development, global data transfer networks, artificial intelligence (AI) and machine learning (ML) and supported by its expertise in marine policy and regulation, the UK can maintain its position as a world leader.

Professor Sir Ian Boyd

Executive summary

This report seeks to identify 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.

The aim is to support UKRI's objective to be net zero by 2040 and its ambition to "be a leader in environmental sustainability for the sector". It must also recognise that the research infrastructure needs to continue to support scientists measuring climate change and inform the wider efforts to meet the UN's sustainable development goals.

The headmark for enacting a measurable change is 2035 which, whilst ambitious, recognises that novel technology and systemic changes often take longer than originally planned (thus the stretch deadline is 2040). It also takes advantage of planned replacements of large research infrastructure e.g. the RRS James Cook and shortly after the RRS Discovery within that timeframe.

By supporting UKRI's ambitious target, **the report deliberately aims to be audacious and forward-looking and to act as a catalyst for others to engage in the necessary transformations.** The report does not address build/decommission issues nor does it consider the full range of scope 2 and 3 activities as related to the CO2e footprint associated with the current infrastructure.

Executive summary

OSNAP (Overturning in the Subpolar North Atlantic Programme) 2013-2018

The UK OSNAP glider missions provided unprecedented details of the circulation over the complex topography across the Eastern Boundary. Between 2014-2018, 12 of the 15 planned glider missions were completed, producing a unique and fascinating data set. For the first time, the OSNAP programme was able to measure a key part of the AMOC at subpolar latitudes. The glider missions supported ship-based and fixed moorings data sets across a multi-national research programme.

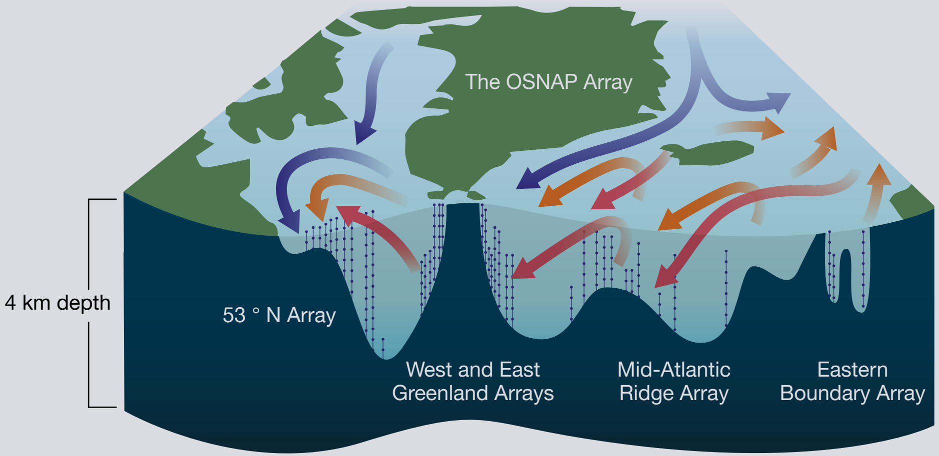


Fig 1 – The use of autonomous gliders to replace ship-based measurements.

Taken in one bite, a net zero oceanographic capability represents a fundamental shift in the way oceanographic research has been conducted over the last 250 years. The incremental nature of technology-based transition requires a clear articulation of the intent (as set out in UKRI's sustainability strategy) but also the flexibility to move forward with numerous technologies at different speeds and thereafter adapt as necessary.

Users of oceanographic information will continue to need access to accurate, trustworthy data and to capability that enables novel experimentation. Traditionally, that has been supported by the use of multiple calibrated ship-deployed sensors, verification via ship and shore laboratory analysis and teams of technicians/scientists available 'on-site' to adapt processes/equipment to enable novel experimentation.

Automation of much, if not all, of this is possible but requires a huge increase in the number of accurate, reliable and trustworthy sensors that can replicate scientific processes currently performed by a human. Those sensors have to be carried to the parts of the ocean that scientists wish to investigate, and be able to relay that data in raw or processed form and in real or near real-time as much as possible.

Executive summary

Therefore, the vision presented at this point is of a re-wired ecosystem which no longer has the large, multi-role research ship at its centre, but which accepts that a large, lean-crewed, green fuelled platform (a vessel very different in design than that available today and capable of deploying large and energy intensive equipment whilst also acting as a hub within the wider ecosystem) will be a key enabler for marine scientific research.

If this premise is accepted, it provides the basis for the necessary transition as it exposes a fundamental challenge: given our current level of understanding, no other viable energy source is as power-dense as Marine Gas Oil (MGO). Work package 3 suggests the most likely replacement for MGO is ammonia, which is 1/3 the power density by volume (i.e. it will take up 3 times more space on a ship to deliver the same amount of power). Therefore, to maintain the current endurance and power available on a global-class research vessel, space currently taken up by people and scientific equipment will have to reduce significantly. This can be achieved by taking capability off the ship and increasing the use of autonomy on the ship alongside 'smarter' planning of the research infrastructure. To deliver this step change, effectively missing out a generation of technological development, significant investment in sensors, autonomous platforms, ship-based robotic systems and the planning and data flow tools will be required.

This report combines the findings of 6 separate work packages and a number of independent reports commissioned under the NZOC banner.

The work packages (WP) are as follows:

WP1 Future Science Requirements

WP2 Future Policy and Regulation

WP3 Future Ship Technologies

WP4 Future Marine Autonomous Systems

WP5 Future Sensor Systems

WP6 Future Data Ecosystems

It sets out immediate, short, medium and longer-term recommendations within the context of the UK Research and Innovation (UKRI) sustainability strategy and subject to the definition of 'net zero' as detailed later in the report. Where possible, because this is an international endeavour, it aligns with the UN sustainable development ambitions to "promote a more targeted and effective information flow as well as innovative ways of conducting and using ocean science". Amongst a number of UN objectives, key initiatives applicable to this review include:

a. Increase scientific knowledge.

b. A comprehensive digital atlas of the ocean.

c. Comprehensive ocean observing systems for all major basins.

d. Data and information portals.

e. Capacity building and accelerated technology transfer.

Executive summary

Notwithstanding the increased momentum towards the automation of data collection, **people are expected to remain at the core of the endeavour and are critical to enabling the transition.** Mechanical, electrical and electronic engineers are required to design and build the sensors and platforms; software engineers are required to design and build the underpinning data ecosystem and **marine scientists/end users must be present throughout to define the requirement and test the output.**

Industry will take on and solve many of the technical challenges: low earth orbit satellites, cloud-based data pools, renewable battery technology, vessel collision avoidance technology and engines that use green fuels. Regulation of autonomous platforms, new fuels and safety systems will mature and be adopted internationally, driving forward innovation and reducing costs. Scientists will adapt to accessing data in different ways and handling amounts of data that can confound non-specialists but, with training and use of supporting systems, and the application of AI and ML, will open up new opportunities for research. Cyber security will increasingly influence how novel technologies are implemented, but should not present a barrier with appropriate standards and investment.

The transition from the current oceanographic capability to one that is net zero therefore requires:

a. Immediate, significant investment in developing the scientific sensors that can be fitted to autonomous platforms, floats, crawlers etc and will remove the need for scientists working in ship-based laboratories.

b. Continued investment in the development and operation of autonomous platforms that, operating in swarms and as part of a wider observing network, will replace capability currently available only on research ships.

c. A focus on linking the observing network to data portals that can be accessed by multiple users (this links closely to the Natural Environment Research Council (NERC) Digital Strategy).

d. Considered alignment with the UK's ambitions regarding sustainable shipping and a 'fast-follower' strategy adopted to take advantage of commercially developed technology that enables 'green' research ships.

Executive summary

Shifts in an ecosystem can exacerbate or reduce imbalances, bake-in or wash away inequalities, further restrict access or remove all barriers and thereby reduce or improve inclusion. The opportunity to improve Equity, Diversity and Inclusion (ED&I) across oceanographic science and the infrastructure that supports it will require steadfast action.

In the same way that the UKRI sustainability strategy sets out a clear aim of "embedding environmental sustainability across all investment decisions", UKRI should explicitly embed ED&I in the same way. In broad terms, the general shift to increased autonomy and robotics is a double-edged sword: the 'oceanographic model' of long periods at sea on research ships adversely impacted those who could not access that level of infrastructure and could not give that level of personal commitment. The shift to remotely operated and fully autonomous infrastructure reduces the entry-level costs and the personal impact. However, technological barriers remain and the increasing importance of software/AI/ML and the analysis of huge amounts of data raises other barriers not currently prevalent.

By aiming to be a net zero organisation by 2040, UKRI/NERC have placed themselves in the vanguard of the transitions necessary to realise this ambition. This date is not aligned with other national and international targets (e.g. the UK Climate Change Act and its commitment to 2050), and that presents a risk which should be acknowledged and addressed in any NZOC strategy. Targeted investment in key areas that will support the necessary transition, a proactive approach to partnering with other areas of academia (nationally and internationally) and with industry and clear, prescient regulation of the associated technologies (fuel, autonomy, AI) will be needed.

Key findings and recommendations

The majority of the recommendations made in this section should be implemented by 2025 which aligns with UKRI's sustainability strategy timelines and complements the UK government's environmental sustainability reporting period (Greening Government Commitments).

These recommendations lay the foundation for ongoing reductions in CO2e emissions from the current research infrastructure alongside supporting the transition that a future NZOC will require. Collectively, they aim to embed sustainability across key parts of oceanographic research.

Key findings

KF1.1

Scientists are increasingly using Marine Autonomous Systems (MAS) to collect data.
Scientists are often conservative in their fieldwork as they risk failing to capture data if they use equipment or techniques that are unproven, i.e. mature in accordance with the Framework for Ocean Observing concept of readiness levels. Notwithstanding that statement, there is evidence of substantial interest and uptake of MAS, mostly ocean gliders, for marine research alongside initiatives such as Argo. The WP1 research suggests the UK has a lead in the use of MAS (Brannigan, 2021) and over the last 5 years has been publishing results based on data from gliders at 2-3 times the global average. Recent investments by UKRI/NERC, e.g. Oceanids and NEXUSS CDT, will support further innovation in this area. Out of the 44 survey respondents across the marine research sector, 34 currently use autonomous technology in their work(77%).

KF1.2

Marine science is increasingly multidisciplinary and the global marine science questions, drivers and applications demand multidisciplinary approaches.
Another key trend identified by WP1 is the representation of research expeditions supporting multidisciplinary research as identified by the Principal Investigator (PI). Out of the 37 cruises (Cook and Discovery) identified since 2017 where cruise discipline was reported by the PI, 25 (68%) were classified as relating to two or more disciplines, and 16 (43%) were classified as relating to three or more disciplines.

The UK is leading in the use of MAS and over the last 5 years has been publishing results on data from gliders at 2-3x the global average

Over the last 50 years the percentage of UK publications with international partners has increased

10% of the global market share of marine geoscience research is published by UK authors

WP1 Future science requirements

Key findings

KF1.3

One aspect of multidisciplinarity that is often critical is the time constraint that imposes upon collection of the data: any future infrastructure must be able to operate in a co-ordinated manner that enables multiple data sets to be captured in tandem. Given the challenge of automating some data collection activities, this co-ordination will have to extend across ship and MAS platform operations.

KF1.4

International collaboration will always be necessary. A long-term trend identified by WP1 is the level of international collaboration as seen in the publication data; over the last fifty years, not only have the number of authors per paper increased in the fields of oceanography and marine geosciences, but also the percentage of UK publications with international partners (predominantly USA, but also strong representation from Germany, France, Australia and Spain). Collaboration across both operators and scientists will underpin efficient use of research vessels, ship-deployed equipment, MAS and Maritime Autonomous Surface Ships (MASS) in future which will unlock part of the net zero challenge.

KF1.5

Investment in both technical development and ongoing operation of cutting-edge infrastructure remains necessary. The UK has a strong history of world-leading marine science, and remains one of the top countries globally for oceanographic research. For example, a recent meta-analysis of online databases revealed that whilst the global share in oceanographic (including biology and fisheries) and marine geosciences papers has declined over the last fifty years with the worldwide expansion of scientific publishing, UK researchers are still responsible for approximately 10% of the market share (Mitchell, 2020). Today, the UK plays an important role in global networking and observing strategies, and development of autonomous technology and models. Collaboration is increasingly key for efficient use of ships, equipment and emerging technologies, and in leveraging access to study locations, and is likely to play an important role in achieving net zero goals.

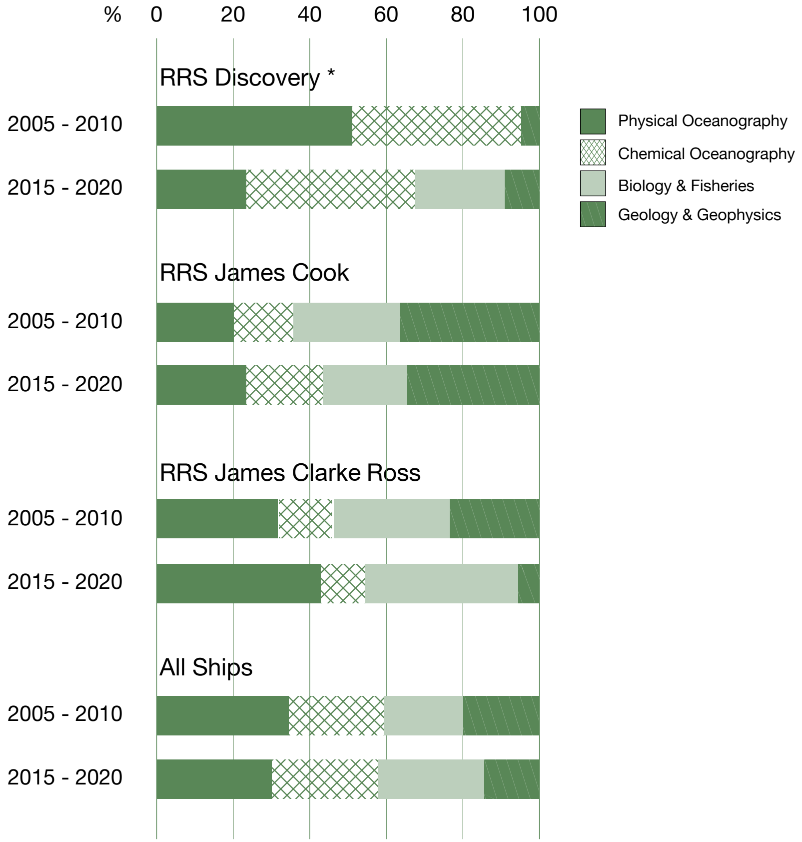
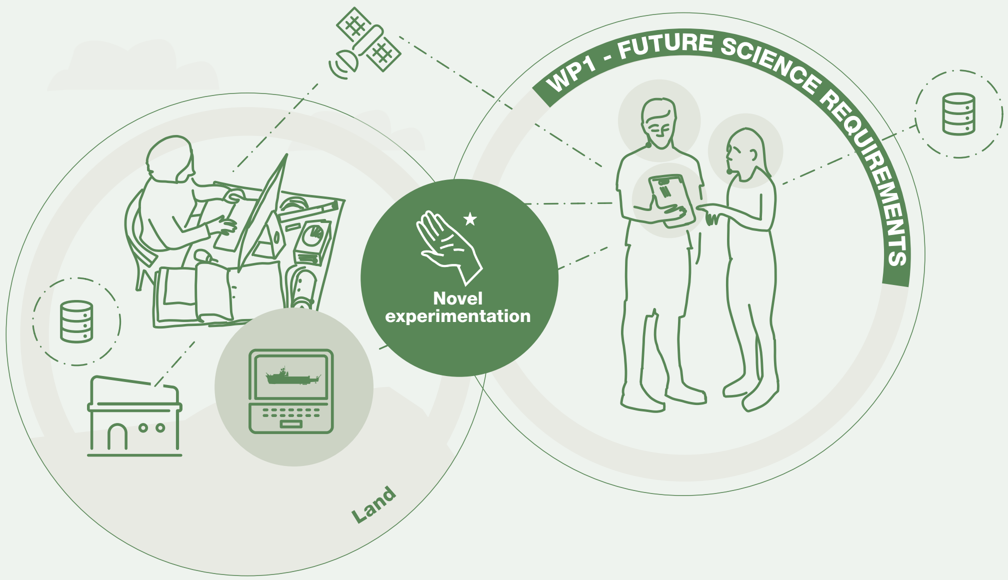


Figure 2: The main research discipline, assessed from cruise reports, for each of the main UK research vessels from a period of 2005-2010 and 2015-2020. *Note for the RRS Discovery that this summary includes both Discovery ships III and IV.

WP1 Future science requirements

Key recommendations



KR1.1

An expert panel should be set up to evaluate the priority technology development areas to support future UK marine science, particularly regarding sensors. Alignment with international standards should be maintained at all costs. This should be considered a live document and reviewed regularly.

KR1.2

Ship use should be prioritised to encourage collaborative efforts to gather and make available FAIR data (meeting principles of findability, accessibility, interoperability and reusability) that supports both the UKRI Sustainability Strategy and priority development areas.

KR1.3

Available bandwidth on research vessels should be significantly increased to support remote participation and outreach activities wherever possible.

KR1.4

Scientists should be embedded within the technology development efforts rather than passive recipients of newly developed technology. Furthermore, both observational scientists and modellers should be involved to advocate for optimum value from the data and to set part of the groundwork for the shift to a digital twin of the ocean.

WP1 Future science requirements

Key recommendations

KR1.5

A high-level training needs analysis should be conducted to consider how marine scientists learn the skills necessary to engage with data collected via an NZOC.

KR1.6

Careful but deliberate investment in an equitable, diverse and inclusive marine science community able to take advantage of how new technology can remove barriers should be considered. As an immediate priority establish a practice of monitoring ED&I on the path to Net Zero to evaluate expected consequences and safeguard against unforeseen consequences.

KR1.7

A framework for collaborating with industry that enables scientists to quickly and easily take advantage of technology under development and overcomes the challenges of sharing of data to support both partners aims should be developed.

KR1.8

The G7 and UN Decade of the Ocean initiatives should be used as springboards to identify and grow the UK contributions to global observing and work with key partners to capitalise on agreed net zero recommendations.

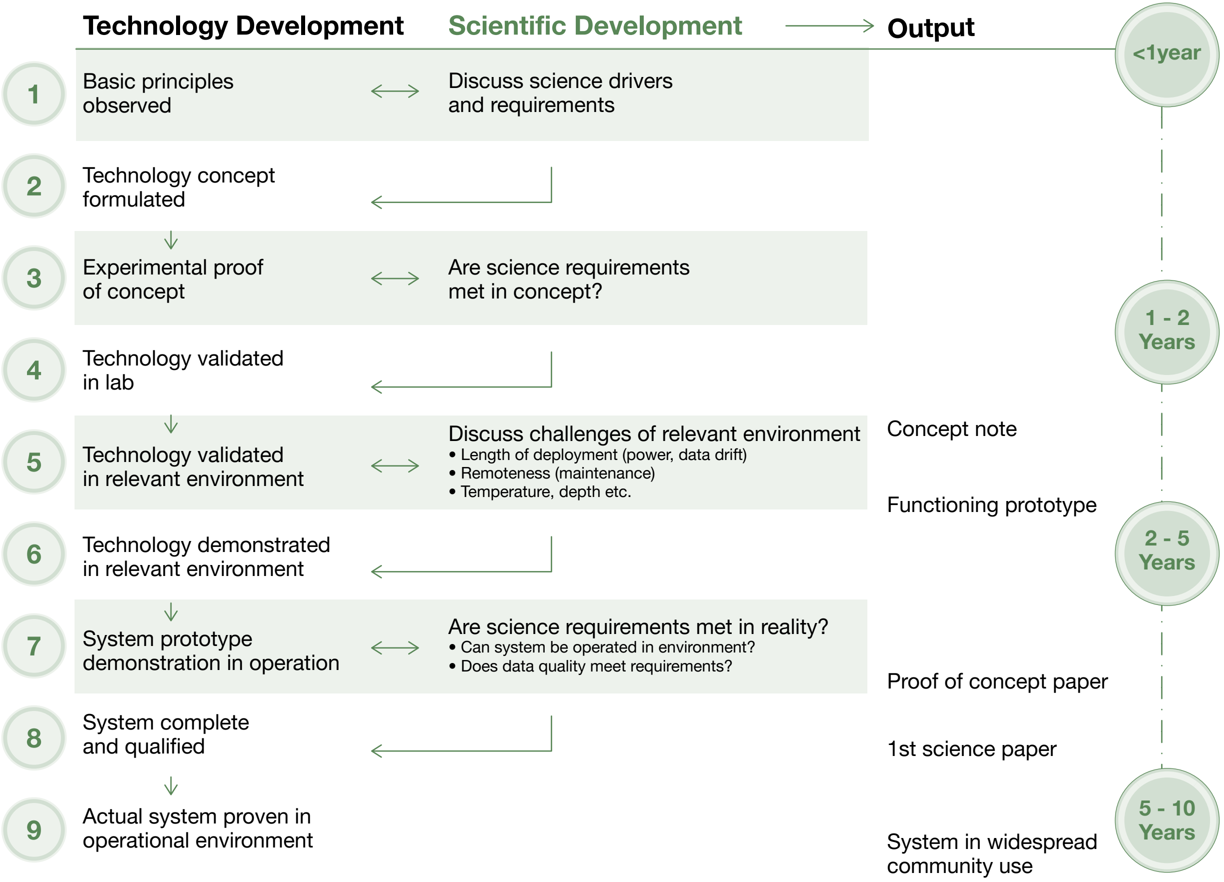
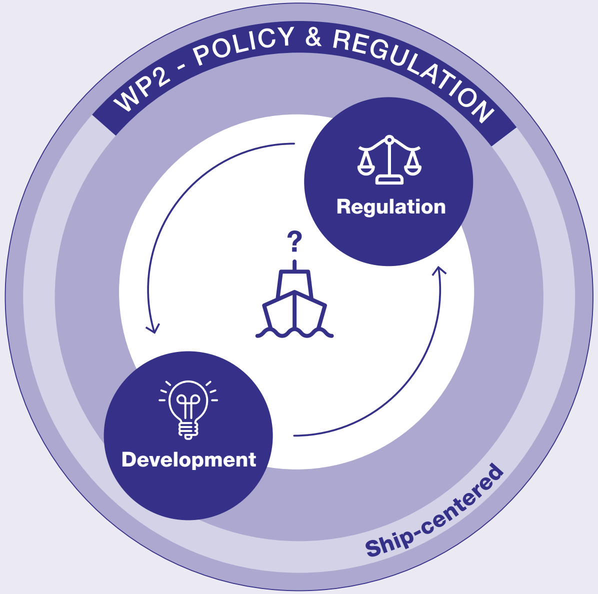


Figure 3 – Technology Readiness Levels (TRLs as defined by Horizon 2020) in the context of a novel marine sensor, with embedded technology developments and scientific discussions, and suggested timeframe of scientific outputs.

WP2 Future policy and regulation

Key findings



KF2.1

Delivering a sustainable blue economy benefits everyone. The transition to a sustainable blue economy requires that scientific data should sit alongside economic and social data and be available to inform and support government policy, compliance and sustainable use of the ocean and coastal areas.

KF2.2

Securing clean, healthy, productive and biologically diverse seas and oceans is a long-term priority supported by the Marine Policy Statement, International Ocean Strategy, the 25-year environment plan (2018) and a commitment to increase MPA coverage within the UK EEZ to 30% by 2030. As a result, the evidence needed for the selection, designation and future monitoring of MPAs is likely to increase significantly. This will have to accommodate activities that increase the uptake of CO2 by the natural environment, support carbon capture and storage as well as the likely expansion of the offshore energy sector.

The transition to a sustainable blue economy requires that scientific data should sit alongside economic and social data to inform/support the sustainable use of the ocean.

Clear, standardised regulation is needed for uncrewed/ autonomous systems, net zero shipping, new fuels and data sharing.

Ocean plastic pollution is likely to be a key policy issue. Any NZOC will need to pre-empt the focus on ocean plastic in marine policy.

Key findings

KF2.3

Policy makers will adopt a 'natural capital' approach across all aspects of the marine ecosystem. Considering the marine environment as an asset that sits on the UK national balance sheet enables increased value through sensible, sustainable management to be recognised. This approach supports decisions being taken that consider trade-offs between different policy options that impact that natural capital in different ways.

KF2.4

Marine policy and compliance will drive increasing inter-disciplinary alliances across scientific, social and economic disciplines. A sustainable blue economy will require data that spans these areas to be collected and made available to all users in an accessible and effective way. Future infrastructure should recognise that data needs of this shift to more holistic ocean governance.

KF2.5

Ocean plastic pollution will remain a key policy issue. It looks likely that the process to develop a global agreement on reducing single use ocean plastic pollution will be initiated at the UN Environment Assembly in February 2022. Any NZOC will need to be aware of this activity and pre-empt the focus on ocean plastic in marine policy.

KF2.6

Despite the plan for legally binding carbon budgets that include shipping, and a desire for shipping to reach net zero, there is very little practical direction for those building, designing and operating net zero ships. The positive aspect of this lack of direction is that a less constrained regulatory landscape does allow for freedom of approach and experimentation. There is no foreseeable reason why net zero platforms will not be compliant with UNCLOS.[1 However, there is the possibility that this could result in some incoherence, for example, Coastal States denying access to their waters and ports based on a perceived non-compliance with their approach to net zero regulation. The UK government has not indicated it will introduce a carbon offsetting and reduction scheme for shipping.

KF2.7

Uncrewed or autonomous systems still face a challenge in terms of their ability to comply with legislation, due to a lack of clarity regarding the interpretation of terms including 'vessel', 'crewed', 'manned' and 'on board', however, this is being addressed in a number of fora. The International Maritime Organization (IMO) and Maritime and Coastguard Agency (MCA) are leading this work. It is highly unlikely that legislation and regulations will be interpreted and applied in such a way that they are not relevant to those commanding and operating uncrewed vessels from ashore.

[1] The United Nations Convention on the Law of the Sea 1982.

Key findings

KF2.8

Uncrewed government owned and operated research vessels greater than 24m should be able to seek Diplomatic Clearance (DIPCLEAR) using established procedures in Part XIII of UNCLOS, however, there is no documented evidence of Coastal State practice in this area.

KF2.9

The difference in permission regimes for spaceborne sensors compared to shipborne sensors has yet to be resolved. Potential resolution of this issue could result in a restriction in use of spaceborne sensors to collect ocean data in other States' maritime zones.

KF2.10

There is currently very little regulation of new fuels, although the IMO has made some progress towards providing safety guidance on new and alternative fuels, and the MCA intends to address the use of lithium batteries by workboats. Still to be addressed is how current legislation and regulation might inadvertently block new fuel options from becoming a reality.

KF2.11

Underpinning legislation and regulation are likely to be required to support global involvement in oceanographic science data sharing. The challenge to date seems to have been global coordination of this information, accessibility and championing the requirement.

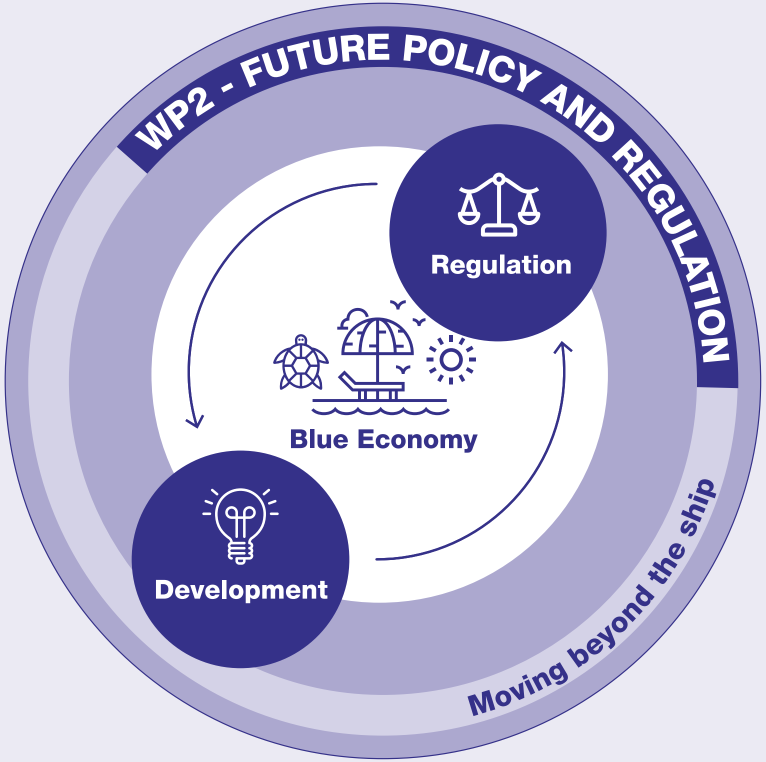
KF2.12

The theft or piracy of small uncrewed vessels from both the surface and subsurface of the sea, cannot be prevented but can be protested if we know who has taken the vessel.

KF2.13

Insurance of net zero vessels may be challenging, therefore, if possible NZOC should be underwritten by the government. Increasing levels of automation and the use of AI would also add to the difficulty in finding a commercial marine insurer.

Key recommendations



KR2.1

The benefits accrued from an improved societal relationship with the ocean should be considered in future investment decisions.

KR2.2

A public-facing knowledge platform on ocean health should be established to support public engagement with critical ocean issues.

KR2.3

Consideration should be given to mandating that any future NZOC is capable of supporting the transition to a sustainable ocean that includes social and economic outcomes as well as a healthier ocean environment. **Should include capability to generate the evidence needed for the selection, designation and future monitoring of Marine Protected Areas (MPAs).**

KR2.4

A future NZOC should seek to design-out the use of non-recoverable, single-use equipment (plastic or otherwise).

KR2.5

The UK's NOC should represent the UK marine science community and work closely with the Foreign Commonwealth and Development Office (FCDO) to ensure future capability is able to access desired marine areas in compliance with the relevant UNCLOS articles.

Key recommendations

KR2.6

The UK's NOC should represent the marine science community and work closely with government on future versions of the Marine Policy Statement with particular reference to NZOC.

KR2.7

The UK's NOC should represent the marine science community and work closely with the Department of Transport and MCA to ensure that the IMO MASS scoping exercise is analysed with a view to determining its impact upon any NZOC solution.

KR2.8

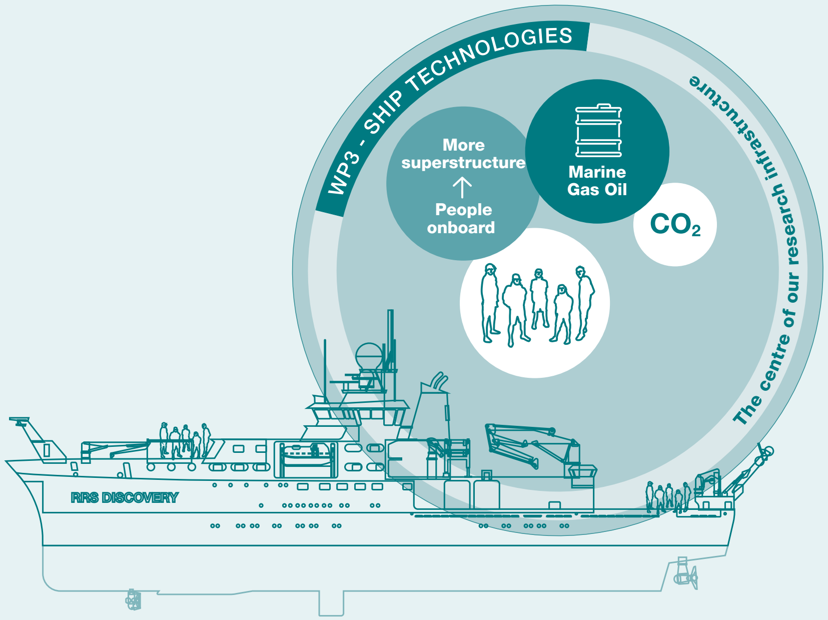
The coordinated collection and use of data should be a priority for NOC (representing the UK science community), Department of Transport (DfT), Department for Business, Energy and Industrial Strategy (BEIS), Department for Environment, Food & Rural Affairs (DEFRA) and FCDO.

KR2.9

Those engaged in NZOC marine and maritime autonomy, led by the MCA, should discuss AI regulation as a priority to establish consistency with other industries.

WP3 Future ship technologies

Key findings

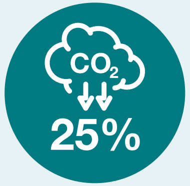


KF3.1

There are opportunities to reduce the CO2e footprint of the current vessels across a range of Energy Efficiency Measures (EEMs) which could reduce CO2e emissions by up to 25%. These include: route optimisation, hull form optimisation, wind assistance technologies, advanced hull coatings, speed reduction, main engine improvements, auxiliary systems improvements as well as modification to allow ships to 'plug in' to green shore electrical supplies and even sustainable food policies. In the medium term (5-10 years) consideration might be given to using lower-carbon ICE fuels, e.g. biodiesel, if their cost, availability and quality permits.

KF3.2

Nuclear and non-fuel based alternative energy options are attractive from a carbon emissions perspective and are seeing a resurgence in Research and Development (R&D). However, nuclear power, e.g. Small Modular Reactors (SMRs), still faces a range of regulatory, public perception and political challenges, and is currently very high cost. Wind and solar are limited to being considered as useful EEMs as they can't meet all of the propulsive and energy requirements of a research ship, its complex operating profile and dynamic positioning requirements.



Using a range of Energy Efficiency Measures could reduce CO2 emissions by up to 25%.

We must identify opportunities to invest in the latest 'green ship' technology and be prepared to trial this on smaller, coastal class vessels.

There is potential to deliver a world-leading oceanographic survey fleet capable of supporting UK development of zero-carbon fuel systems, enhanced autonomy and increased inter-connectivity with MAS platforms.

WP3 Future ship technologies

Key findings

KF3.3

Alongside these technological innovations, a coordinated, international system of bartering (modelled on the Oceans Facilities Exchange Group system) presents an opportunity to significantly reduce passage legs but will take time and concerted effort to achieve. This option may require some vessels to be semi-permanently based away from their home countries to ensure even coverage given the limited availability of research vessels outside of Europe, North America and China/Japan/South Korea/Australia/New Zealand. The challenges to setting up and sustaining
this should not be underestimated and the UK should focus on better co-ordinating its national assets as a priority.

KF3.4

The data collected from research vessels should be maximised at all times to justify the CO2e footprint. Bathymetry, underway sampling and meteorological sampling should be collected at all times. This is quick and easy to implement but requires funding to enable data processing, storage and use.

KF3.5

In addition, telepresence and high-speed data transfer should be considered the norm and allow shore-based science parties to interact with ship-based scientists and technicians.

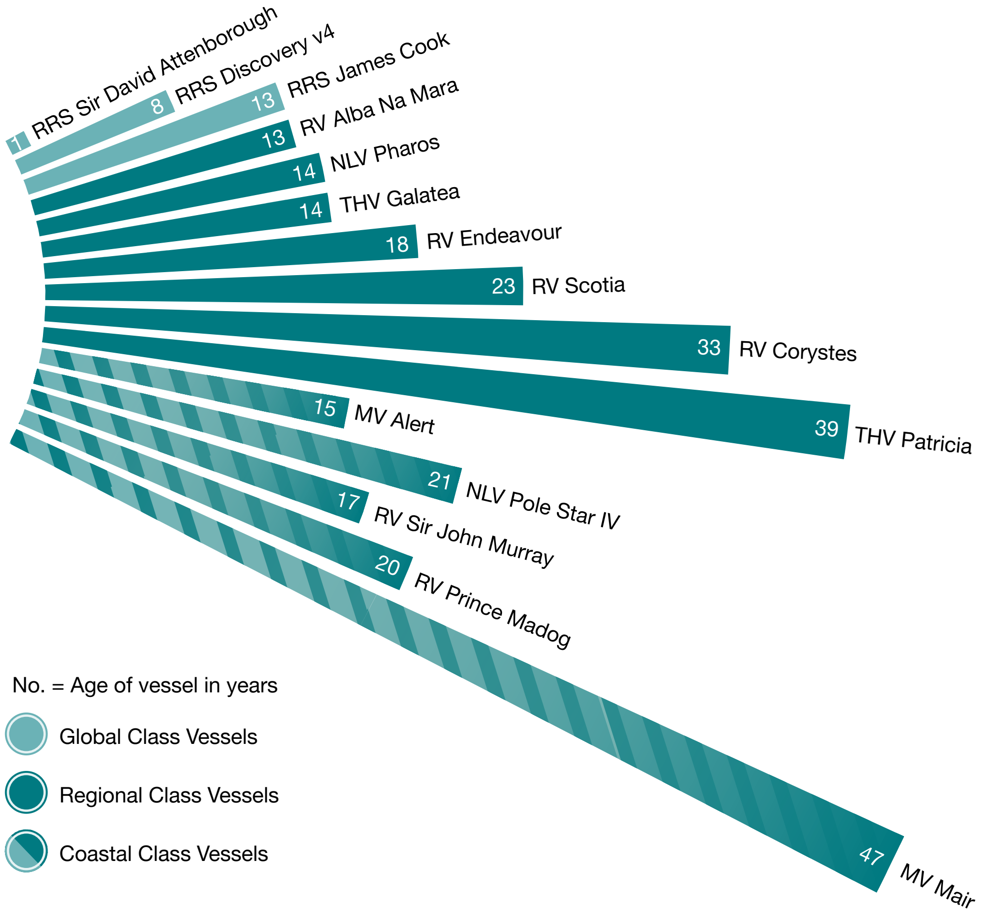


Figure 4 – UK Research fleet - age of current vessels

WP3 Future ship technologies

Key findings

KF3.6

When considering the UK mix of polar, global, regional and coastal research and monitoring vessels as well as the Royal Navy's Multi-Role Oceanographic Survey Ship it is apparent that **there is potential for a UK shipbuilding programme that could enable inter-operability, reduce risks and therefore costs by using common/modular design techniques and deliver a world-leading oceanographic survey fleet capable of supporting UK development of zero-carbon fuel systems, enhanced autonomy and increased inter-connectivity with MAS platforms.** This would support the UK's Maritime 2050 strategy.

KF3.7

Future global-class research vessels will probably use an ammonia/fuel cell or H2/fuel cell combination. These options will fundamentally alter the design of the vessel as they are less power dense. To avoid increasing the size of vessels, the proposed solution is to reduce the space required for personnel and capability, specifically that capability that can be delivered by MAS platforms. **This will require the current trend in automation of ship navigation, pilotage and general operations as well as operations specific to research vessels, e.g. over-boarding systems and winches, to be accelerated and proven.**

KF3.8

Identify opportunities to invest in the latest 'green ship' technology and be prepared to trial this on smaller, coastal class vessels. Partnerships with industrial partners could make this more affordable, particularly with respect to fuel technology where investment in the supporting logistical systems will be necessary. NERC could leverage its entire fleet to mitigate the risks associated with this.

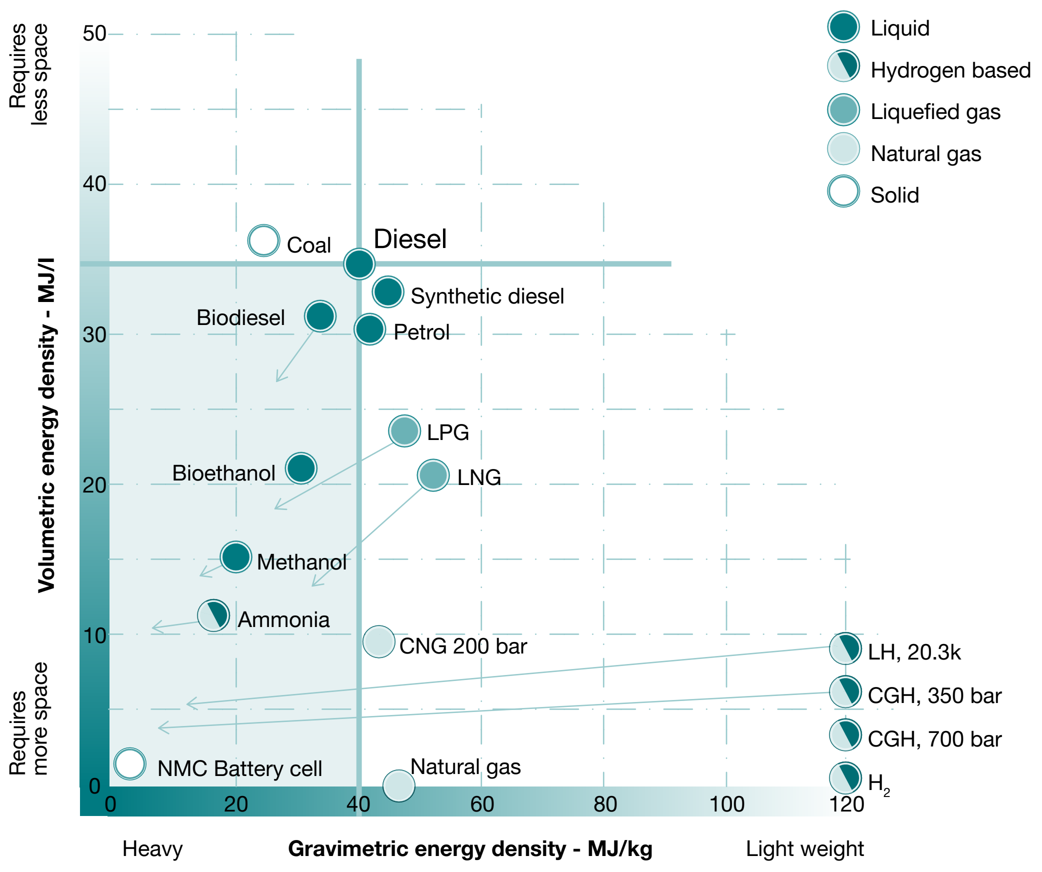
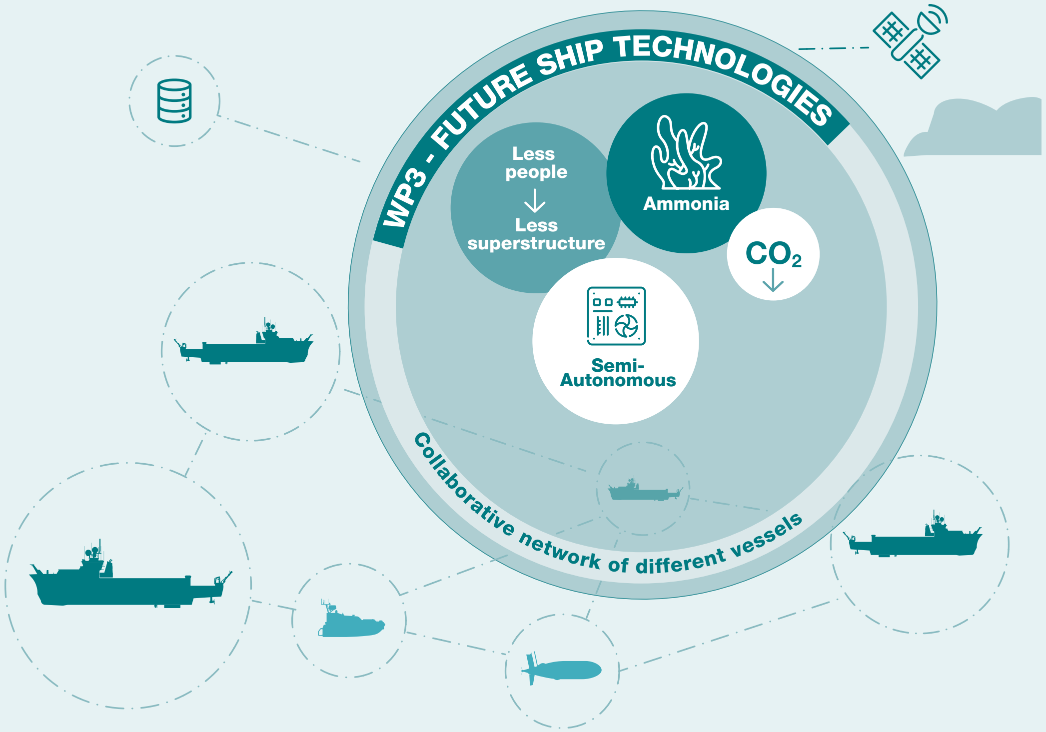


Figure 5 – Energy densities for different energy carriers. The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only)

Key recommendations



KR3.1

The prioritisation criteria for bids for NERC ship-time should be reviewed **so that 'sustainable planning' across the Marine Facilities Planning (MFP) becomes a key aim.** In support of this:

a. Continue to invest heavily in supporting the OFEG bartering scheme and seek to replicate wherever possible, particularly across the UK research fleet.

b. Consider 'campaigns' that place a research ship in one part of the ocean for an extended period.

c. Shift the refit timings of at least one of the 2 blue-water research vessels so that use of the ship during the summer period (normally calmer weather) around the UK can be maximised.

KR3.2

NERC's research ships should be modified to allow them to take advantage of 'green' shore supplies where available and upgrade the alongside berth at NOC so that electricity can be made available whenever the ships are there (on average 40 days per annum).

KR3.3

Design reviews of each vessel should be undertaken to consider how they may be adapted to reduce their fuel use, e.g. use of kites when on passage, hull shape. This review would sensibly assess if/how the vessels might use biodiesel in future. At the very least, the issue with the RRS Discovery's thruster head boxes should be resolved thereby improving energy efficiency by the 12% originally envisaged.

Key recommendations

KR3.4

Sustainable supply chains that support the marine science programme should be prioritised.

KR3.5

Continuous, underway sampling via NERC's research vessels should be funded to maximise data available to scientists as well as supporting global initiatives such as Seabed2030.

KR3.6

Significantly improved telepresence and high-bandwidth capability on the research vessels should be funded and PIs incentivised to increase connections with shore-based science parties.

KR3.7

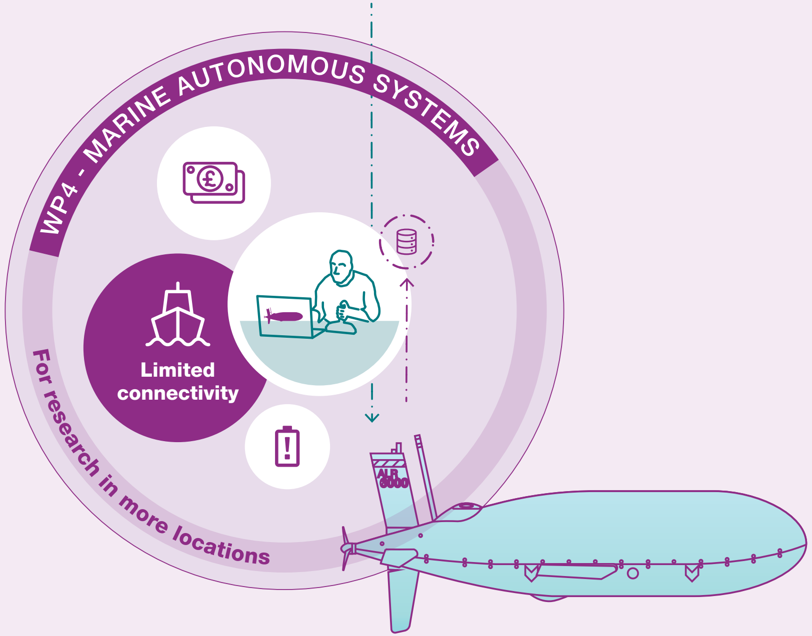
Opportunities to automate ship operations, e.g. CTD casts, should be identified and development of those capabilities funded. This will initially deliver minimal CO2e savings (reduced technicians flying to join research expeditions - they will be replaced by additional scientists). However, it ensures the technology is available and reliable if future, lean-crewed vessels are built.

KR3.8

Opportunities to invest in the latest 'green ship' technology should be explored and the UKRI should be prepared to trial this on smaller, coastal class vessels. Partnerships with industrial partners could make this more affordable, particularly with respect to fuel technology where investment in the supporting logistical base will be necessary. NERC could leverage its entire fleet to mitigate the risks associated with this.

WP4 Future marine autonomous systems

Key findings

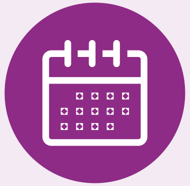


KF4.1

The marine autonomous systems market is developing rapidly. Over the last few years, there has been a significant increase in investment in the offshore energy, ocean science and defence sectors that has been driven by the need to reduce costs, improve data quality, and add new capabilities. These drivers are not expected to decrease, and so it is likely that the market will continue to grow and the technology development will continue to advance rapidly.

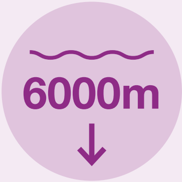
KF4.2

Persistent underwater autonomy is currently an active area of research, and recent work has been focusing on extending autonomous operations from days to weeks. The main obstacle to long-term missions is dealing with the uncertainty of an ever-changing environment. Marine robots need to deal with high variability across large-scale spatiotemporal dimensions while reacting to a locally dynamic and uncertain environment.



Persistent underwater autonomy is currently an active area of research, and recent work has been focusing on extending autonomous operations from days to weeks.

There is a growing trend where multiple platforms are working together as a system of systems (a "swarm") to enable more complex data gathering.



There is a push to increase the glider depth rating to 6000m, however, the limited commercial interest in deep rated gliders has meant that there are currently no commercially available systems.

Key findings

KF4.3

There is a growing trend where multiple platforms are working together as a system of systems to enable more complex data gathering. These 'swarms' can be a homogeneous set of vehicles all acting together to form a measurement network, an example being autonomous ocean bottom seismometers. Alternatively, the vehicles can create a heterogeneous 'fleet' where different vehicles undertake different functions. Fleets allow for parallelisation of missions, intervehicle support for longer deployment times, adaptability to in situ mission changes, and effective use of vehicles based on their specificities.

KF4.4

Another area of intense research has been risk-aware planning. Operations of AUVs in coastal regions, as opposed to deep water, expose AUVs to the risk of collision with ships and land.

KF4.5

The use of ocean gliders has steadily increased within the academic and defence sectors since the early 2000s. Their relatively low cost means they are often operated by science teams focused on ocean physics and are becoming an integral part of the Global Ocean Observing System (GOOS). Alongside the under-ice developments, gliders are continuing to be developed (e.g. Teledyne Webbs recent Slocum G3 release) and refined with the addition of new sensors (e.g. the RBR Legato CTD) and operating capabilities (e.g. Teledyne rechargeable batteries). One area of development is the push to increase the glider depth rating to 6000m, however, the limited commercial interest in deep rated gliders has meant that there are currently no commercially available systems.

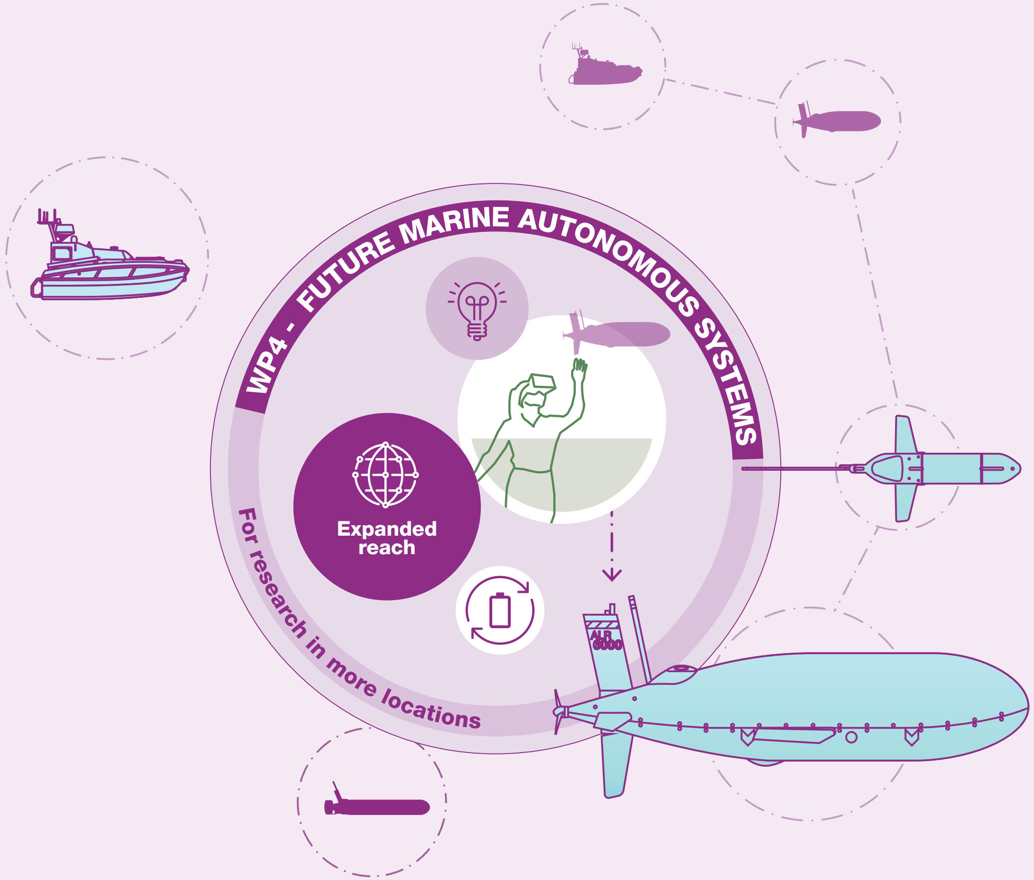
KF4.6

Complementing glider operations are the new long-range AUVs. These platforms offer a similar range to gliders but can carry increased sensor payloads at higher speeds. Thus, they have a more comprehensive range of applications from Ocean Physics, through nutrient and carbonate system measurements, to seafloor mapping (either optically or acoustically).

KF4.7

Alongside the sampling issues, MAS platforms cannot currently launch and recover fixed platforms to the seabed, something that is relatively easy from a crewed ship. The most significant limitation is the deployment and recovery of moorings. Alongside moorings, MAS platforms cannot easily launch and recover landers or other bespoke seabed experiments. Thus, moving to a purely MAS based solution would significantly hamper the opportunity to deploy these sorts of experiments.

Key recommendations



KR4.1

The "brains" of marine robots are critical to their ability to undertake more complex behaviours and thereby increase their capabilities. Hence, the NOC-developed Onboard-Control-System (OCS) and shore side Command and Control (C2) systems will need to be further developed. Specific areas of development include the Automated Piloting Framework (APF) of the C2, which allows machine-based control of the long-range fleet. The C2 will be further extended with integration of new platforms, development of a PI portal, creation of fleet planning tools and refinements of data flows.

KR4.2

New autonomy behaviours will also need to be developed within the OCS to support safe under-ice operations. The OCS will be further extended with integration of new sensors, refinement of the backseat driver interface, and integration into new platform types.

Key recommendations

KR4.3
There is a need to operate near boundaries and on the seafloor, so work should be undertaken to further develop hover capable and crawling vehicles. These additions to the fleet would increase the range of science missions that marine robots can undertake and hence increase their use in observing the ocean.

KR4.4
Launch and recovery systems from Unmanned surface vehicles (USVs) (for gliders and autonomous underwater vehicles (AUVs)) should be developed at pace for greater flexibility in the use of MAS platforms to support oceanographic research by increasing endurance and data transfer options.

KR4.5
Marine battery/fuel cell technology will underpin much of the expansion in use of MAS platforms and should be a priority for UKRI/NERC (InnovateUK) working in tandem with industry.

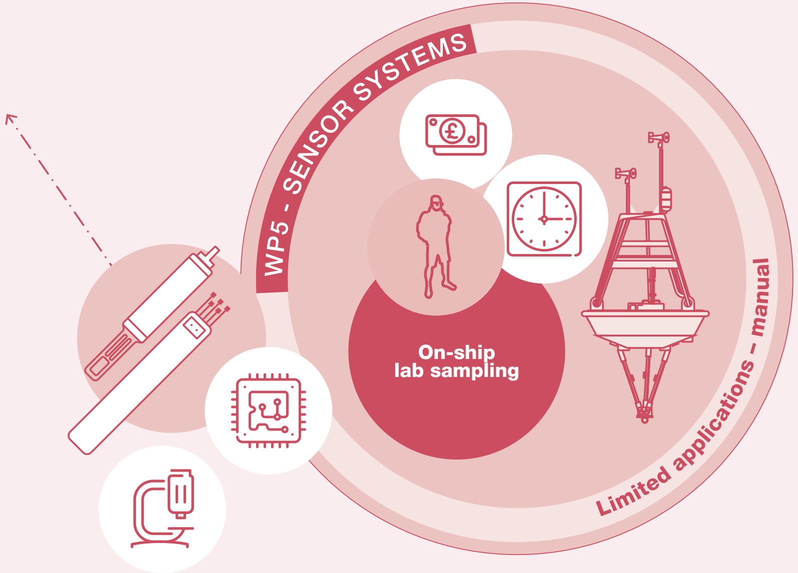
KR4.6
NERC should expect to double the size of the autonomous fleet it supports every 5 years. A total fleet comprising over 200 gliders, 25 long-range AUVs, 2 short-range AUVs and the associated USVs as well as smaller AUVs deployable by hand should be available within the NMPE by 2035.

KR4.7
Remotely operable ROVs should be introduced into the NMEP to remove personnel required onboard vessels and to increase their availability. This is possible with increased bandwidth on vessels.

KR4.8
Research into sustainable solutions to overcome marine biofouling should be funded.

WP5 Future sensor systems

Key findings



KF5.1

The current rate of measurement technology development, though excellent in the UK and in pockets globally, is slow relative to the ambition of the oceanographic community, with **only 5% of the requirement addressed by new measurement technologies in the last 10 years**. Without intervention or drivers from emissions reductions, this trend is likely to continue with an additional 5-10% of the measurement requirement addressed by 2035.

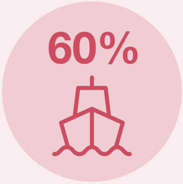
KF5.2

The scoping review has identified a list of 68 categories of user requirements. Research vessels currently address 60% of the total requirements for oceanographic research whereas MAS platforms could at best address 40%. **There are 61 specific technology developments that could address this gap** (with an estimated cost of £100M+).

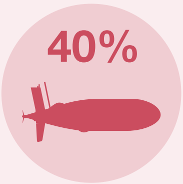
KF5.3

There remain a small number (10 out of 68) where there is not a clear or cost-effective pathway to meeting user requirements without a research vessel. The WP5 report identifies possible solutions which might be described as stretch targets.

Only 5-10% of the measurement requirement will be addressed by 2035 without intervention or drivers from emissions reductions.



Research vessels currently address 60% of total requirements for oceanographic research.



MAS platforms address 40% requirements for oceanographic research.

Key findings

KF5.4

Adaptation and “marinization” of innovations made elsewhere has been a successful strategy and numerous projects are ongoing of this character. Examples include: AI and ML for image processing, classification and/or taxonomy; application of molecular assays such as PCR and genome sequencing.

KF5.5

The gaps between requirement and novel, non-ship dependent sensors are currently significant and will require an increase in investment to upscale research and development, including new analytical scientists, engineers, technicians and additional capacity, e.g. laboratories. Whilst dauting, the majority of the requirements are soluble with technology that is known or envisaged within the NZOC timeframe. The UK is currently a world leader in measurement systems and success in this area would ensure that position is retained.

KF5.6

The increasing trend to mass automation will require sensor development independent of platform type (green research vessel, MASS, MAS). Those sensors should be deployable across all platform types to safeguard future options and maintain flexibility across observing systems.

KF5.7

Currently, sensors not linked directly to research vessels or vessels of opportunity are providing data sets to end users that are different to those previously provided by ship-based research. These data are currently used together with results from ship-based measurements to ensure accuracy, but now provide more data than ships do. For example, programmes such as Argo provide persistent and global synoptic measurements, and AUVs can explore under ice-shelves: neither possible with ship-based measurements. These add to our understanding of the ocean but have not yet replaced the extensive and adaptable measurement, sampling and experimental capabilities of ship-based methods (e.g. for biological sampling and experimental determination of rates) nor have they as yet been designed to do so.

Key findings

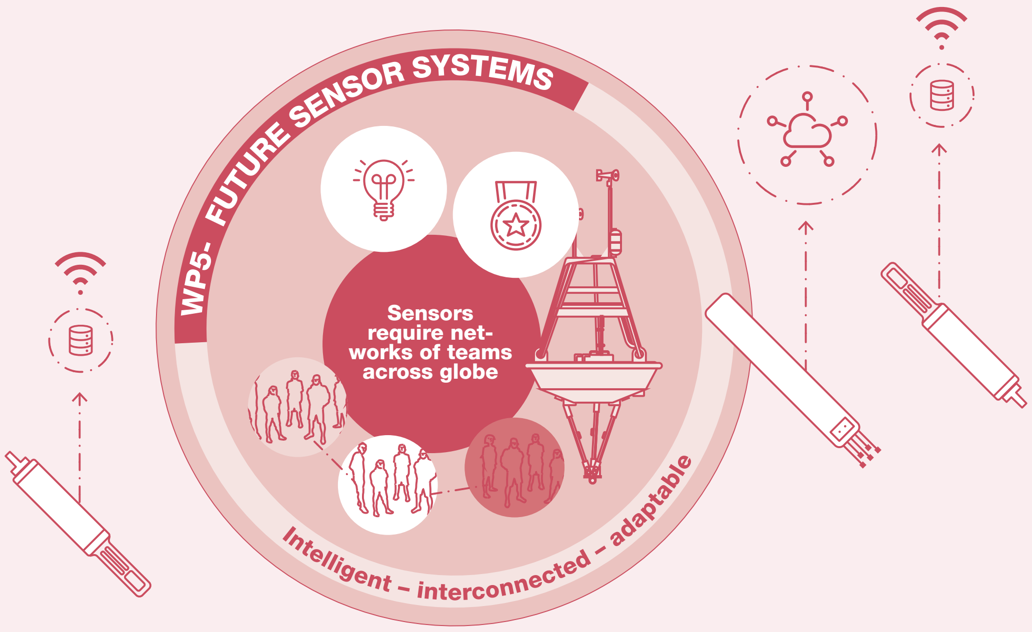
KF5.8

Modern, multi-role research vessels are extremely adaptable and provide platforms (literally and metaphorically) for scientists across all disciplines to work collaboratively, leading to cross-working and productive serendipity. The replacement of these beneficial characteristics with non-ship capability requires a similar level of planning and focus. With appropriate technology it could allow a vastly increased science party to 'join' the research expedition at specific points and collaborate with colleagues from across the world. As MAS platform endurance increases, expeditions could feasibly last months with virtual science parties overlapping.

KF5.9

The user community is justifiably concerned that any transition may impact the quality of data they are able to obtain. Key concerns include inability to collect key variables, interruption or suspension of long-term series and time wasted in comparing old with new data sets. A cautionary approach requires a high level of new sensor maturity, its easy availability and its use being well understood. **This requires novel sensors, samplers and other autonomous measurement systems to be developed and tested alongside current systems/processes and then commercialised in a cost-effective manner. A significant programme of side-by-side development and trials, both with fully engaging users, will be required to enable this.**

Key recommendations



KR5.1

A major, long-term Oceanographic Measurement Systems Development Programme should be established with a research hub and spoke model.

A single coordinating hub is essential and should be a centre of excellence in measurement systems. It's coordinating role should be to support external (spoke) organisations, and satellite hubs (for example focusing on a particular technology, such as acoustics, or animal tagging) by providing support from existing technological solutions (e.g. robust electronics, sensor components, data and software systems) to reduce development effort and accelerate delivery. It should also assist in the interface between users, their requirements, and the specifications of the solutions developed.

The hubs (coordinating and satellite) should also promote and develop the use of modularity, common interfaces and best practice in design, metrology and data system. Spokes should support innovation and be aimed at capability gaps. The development programme would work on sensor development for both MAS platform and green or lean-crewed research vessel options. Opportunities to collaborate with international partners should be actively sought to avoid duplication.

WP5 Future sensor systems

Key recommendations

KR5.2

An expert panel should be set up to refine, within 6 months, the statement of measurement and sampling requirements drafted in this report, which the development program will address and meet. Alignment with international standards should be maintained as a live document and reviewed regularly.

KR5.3

An expert panel should be set up to report within 6 months on standardised design parameters, modules, and interfaces which would guide sensor developers in the hubs and spokes, enable efficiency and as far as possible a 'plug and play' approach to platform integration.

KR5.4

An executive for the coordinating hub or expert panel should be convened to, within 6 months, refine the technology development roadmap based on currently understood requirements and to establish mechanisms to adapt this for changes in requirements and research / technology opportunities.

KR5.5

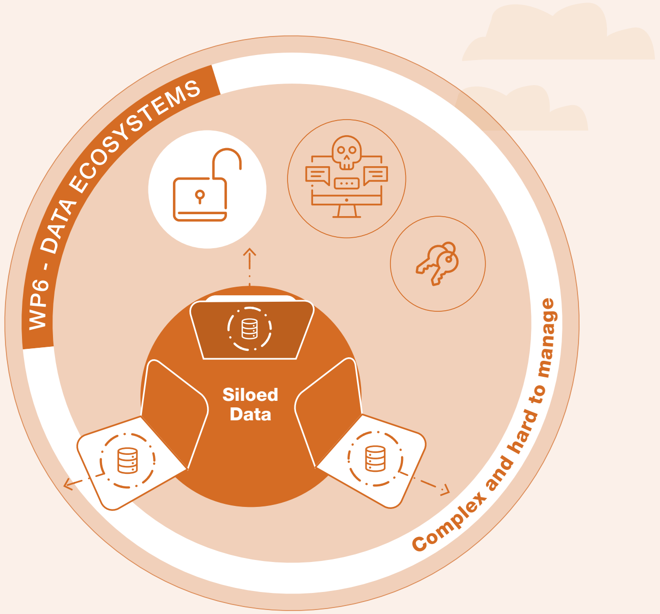
That a working group is established to manage the effect of new measurement systems on platform design: both MAS and green ships. Many of the measurements required could be delivered with MAS but would need platform (vehicle) characteristics that are different to current capability. Equally, green ship requirements may be eased by new measurement systems developed for autonomy. Strong consideration should be given to working across research councils and other funders on the sensor development necessary to support the increased use of autonomy in the marine sector and use of the current developments that support other sectors.

KR5.6

'Sideways' development of sensors - collaboration with industry on sensor R&D, overseen by InnovateUK, should be prioritised.

[4]Including parameter, sampling frequency, metrology performance (accuracy, precision, drift, interferences etc.), spatial / temporal data density required including, amount of data required, and assessment of requirements to coordinate multiple measurements (as is common practice currently). 5e.g.: increased sensor size, weight and power; the ability to deploy moorings or drilling / coring devices; the ability to carry large volumes of samples; the ability to interact with in situ experiments and sample manipulations (e.g. incubations).

Key findings



KF6.1

The flow of data associated with a research expedition, from planning to capture, processing, storage and use is well described but remains mostly manual. This results in a significant overhead on both the science party and NMF in managing the data alongside increased chance of lost data either through poorly linked metadata or a failure to follow data logging protocols. **An end-to-end approach to data associated with research expeditions and/or MAS platform missions is required.** It is possible to achieve this by 2030 with data management processes that incorporate quality and metadata controls and enable the transfer of data to data portals that allow access across a broad community of users.

KF6.2

Given the costs associated with the collection of oceanographic data, improving access through adherence to the FAIR principles must be a priority. As the volume of data collected increases, the systems used to support FAIR data must be scalable. Alongside the increase in volume, the percentage of data that is available in real-time or near real-time will increase and so the systems must be configured to support 'live' data streams.

An end-to-end approach to data associated with research expeditions and/or MAS platform missions is required.

F.A.I.R.

Improving data access through adherence to the FAIR principles must be a priority.

2030

Microsoft, IBM, and others, are developing technology infrastructure that are moving towards net zero that would support any data ecosystem UKRI/NERC might require, with ambitions to be net zero by 2030.

WP6 Future data ecosystems

Key findings

KF6.3

ML and AI will support better use of data. However, for that to be realised improved data management and data workflow processes will be required.

KF6.4

The National Digital Twin Programme (NDPt) skills and competency framework outlines the critical roles needed at an organisational level to support the integration of data into a digital environment. There are a number of skill sets that are not presently well-represented across UKRI/NERC, yet will be increasingly in demand as the digital dependency of research infrastructure increases.

KF6.5

Research expedition and mission planning would benefit from the use of data sciences approaches. **In due course, the integration of modelling, data collection, data sciences and informatics could enable 'digital twins' of the research domain.** These digital twins, receiving real-time observations assimilated into models and providing input to machine learning algorithms will support the research expedition to revise plans and take advantage of the ability to react to observations.

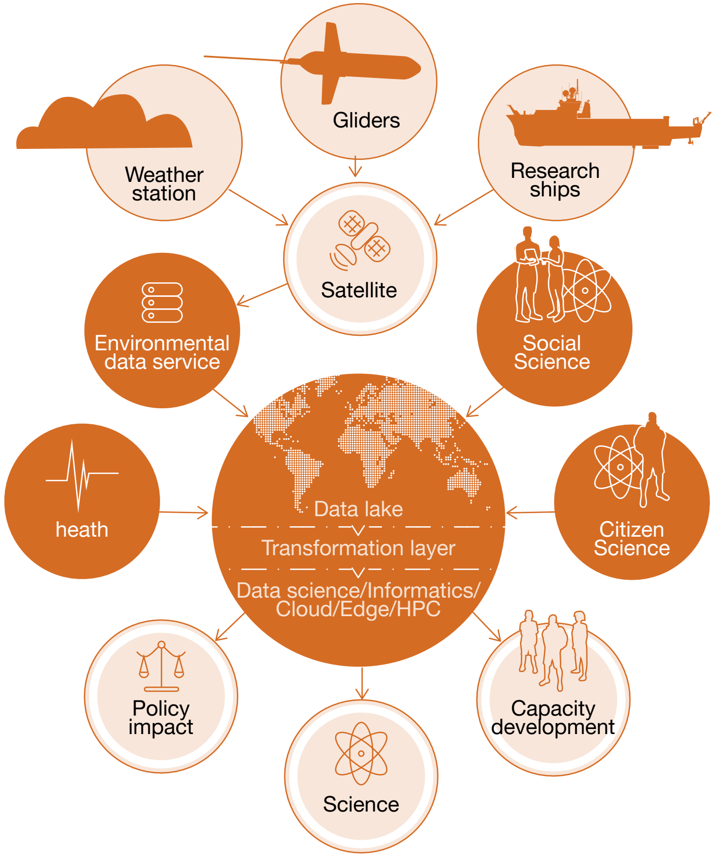


Figure 7 – Data flow that creates value and better supports the use of data by scientists, government and the wider economy

Key findings

KF6.6

Communication infrastructure, including low-earth orbit satellites, will continue to rapidly improve and provide options for continuous, high-bandwidth communication systems. Any data ecosystem will be reliant upon the hardware and therefore vulnerable to technology failure. **Resilience is possible in most areas of the ecosystem, however cyber-attacks will present a continuous threat and processes/ systems able to detect, protect, respond and recover from an attack will be essential.**

KF6.7

As the marine sector adapts to increasing autonomy, enabled by increased use of smart, connected sensors, there are opportunities to engage with other marine users to share data and information more effectively. **This will require an international effort to ensure data standards are the same or compatible but opens up huge opportunities for data collection.**

KF6.8

The use of autonomy in collecting data for UK geo-intelligence remains a high priority for the Ministry of Defence. Their recently published Digital Strategy places data use and exploitation at the centre of their thinking. There are overlaps between the data ecosystem the Royal Navy will require and the data ecosystem able to support a net zero oceanographic capability. Partnering in development areas such as command and control of autonomous assets would be beneficial.

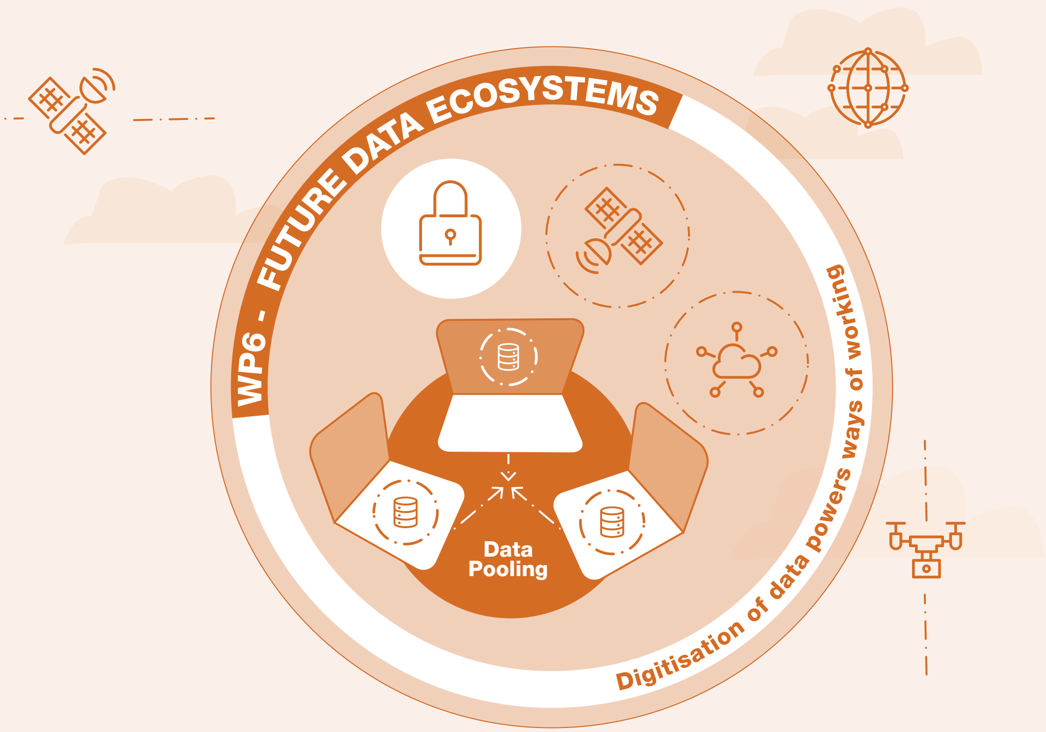
KF6.9

Microsoft and IBM, amongst others, are developing technology infrastructure that are moving towards net zero and would support any data ecosystem UKRI/NERC might require, with ambitions to be net zero by 2030. Engaging with technology companies that have strong net zero ambition and well-developed data ecosystem approaches may provide opportunities to develop a future NZOC.

KF6.10

The NZOC data ecosystem will need to be resilient to any unauthorised access or harmful intent by authorised users, not only to mitigate against cyber attacks but also to ensure that data is appropriately access managed. Where possible, data will be freely available, but **General Data Protection Regulation (GDPR), Intellectual Property Rights (IPR) and security concerns will all need to be addressed through appropriate data access management and licensing.**

Key recommendations



KR6.1

Develop a 'data skills' strategy that details how UKRI/NERC will support a plan for training the future generation of scientists and engineers/operators capable of developing, operating and using a digitally-enabled, net zero infrastructure. Promote and invest in Research Software Engineer careers across UKRI/NERC.

KR6.2

Ensure that all future activities that support the NZOC data ecosystem concept align with national and international best practices and follow the guidelines laid down in the NDPt framework. This will safeguard against the risk of incompatibility at a later stage.

KR6.3

Further develop the data flow architecture that allows data to flow from planning (MFP website) through capture, processing, storage and use with the aim of delivering FAIR data to multiple users across science, government, defence and business. Setting out the strategy for achieving this and prioritising development opportunities should be completed within 12 months.

Key recommendations

KR6.4

Scope a scalable data lake architecture capable of managing data from the widest spectrum of platforms (satellites, research vessels, MAS platforms, floats, moorings etc) and commission a pilot project to develop expertise in managing the data architecture across cloud, ship and shore-based infrastructure and test the concepts.

KR6.5

Develop a modelling capability that can dynamically assimilate observations in a moving frame (ship-following) at a resolution relevant for observation collection decision making, using modelling tools already well established within the community, e.g. NEMO, ERSEM, NEMOVAR. Use this as a pre-cursor to developing a digital twin of the expedition region to support that specific research expedition.

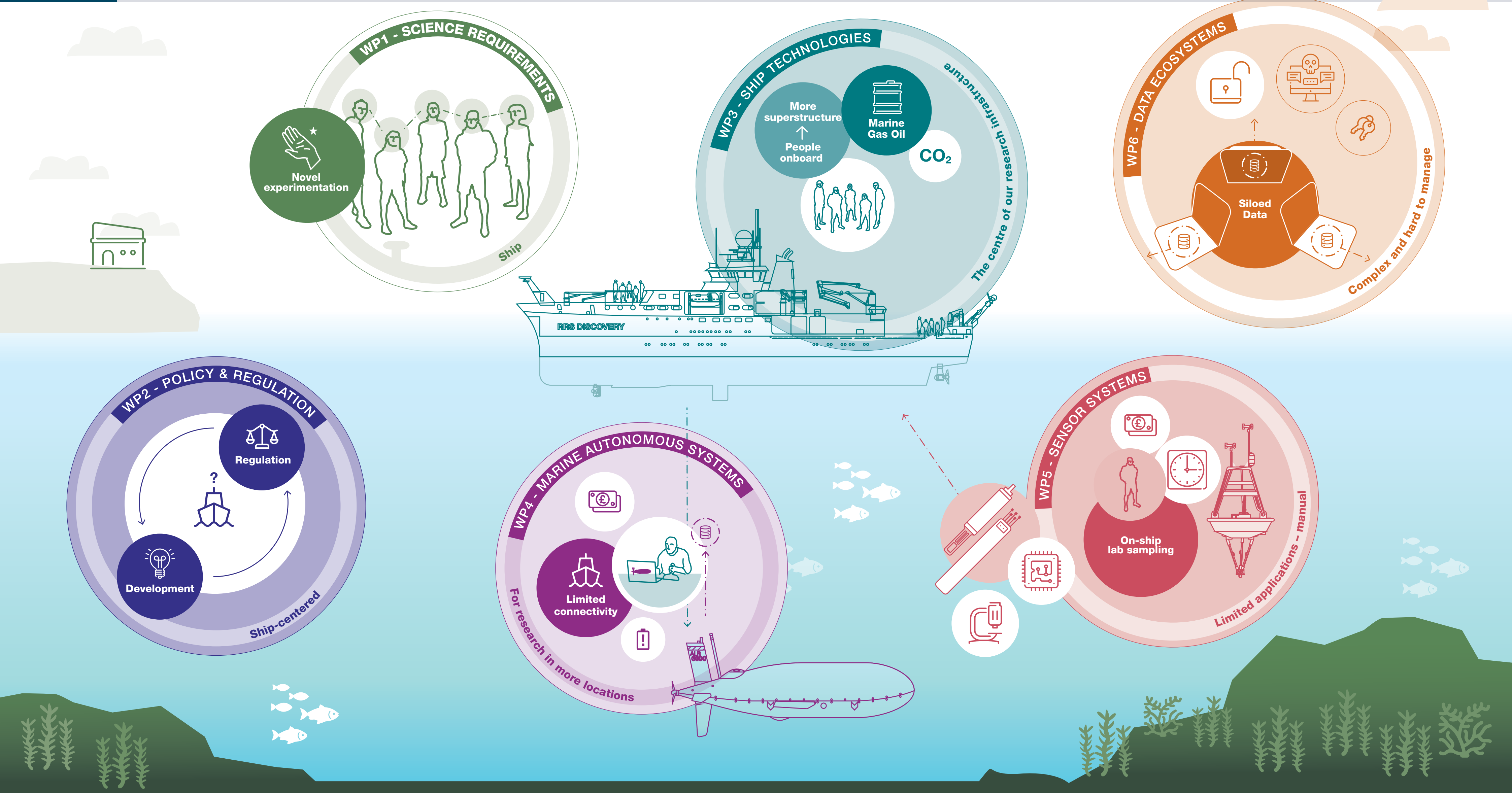
KR6.6

Incentivise, across UKRI (including InnovateUK), **collaborations on the development of novel autonomous planning and optimisation (command and control) systems** to maximise the usage of MAS platforms.

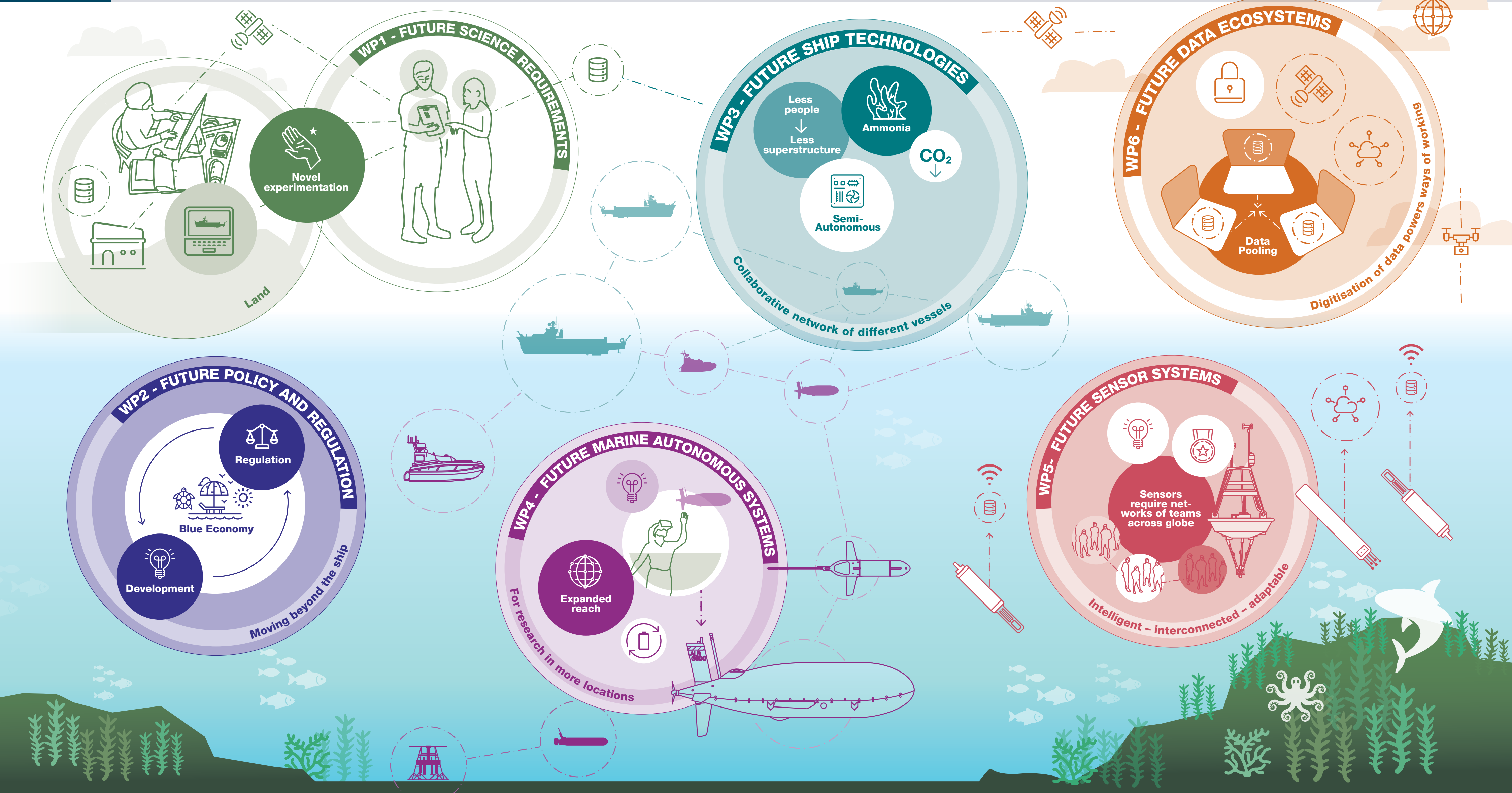
KR6.7

Align with the 'Greening Government: ICT and Digital Services Strategy 2020-25, as the basis for reducing the carbon footprint of an NZOC data ecosystem.

Current *Ships at the centre of current capability*



Automation at the centre of a Net Zero capability



Commissioned reports

Industry Engagement

Public-private partnerships provide a useful mechanism for investment in technology development and opportunities to exploit shared interests rather than compete or operate in isolation, and should be considered as a priority.

UKRI/NERC is not isolated from the potential skills gap that may emerge in the areas of marine autonomy and low-carbon, semi-autonomous and autonomous vessels and should intervene to support UK leadership in these areas.

Moving from a 'data storage' model to a 'data portal' approach that supports multiple users of common data presents opportunities for better exploiting data including monetising information products.

Scientific research into modelling/digital twins can support the wider exploitation of this technology to the benefit of society and industry.

The shift to 'digital' sensors that can both collect data and support marine autonomy will require significant investment and national/international agreement on data standards which should be led by government/international agencies.

Adoption of low or zero-carbon methods should be recognised and rewarded by UKRI/NERC and senior managers.

The UK should take advantage of expertise in marine tech development, operations and regulation and be in the vanguard of developing a net zero vessel able to support scientific research but applicable to other areas e.g. defence, coastal shipping.

Commissioned reports

Ocean Observing Capability from Space

Satellite ocean observations are now recognised as an essential component of the global observing system, supporting forecasting through assimilation. Observations such as sea surface height, temperature, ocean colour, winds and sea state are routinely ingested in near real-time in most operational forecasting systems. This capability is expected to be maintained beyond 2035, mainly through established operational programmes in Europe. Of those, EUMETSAT METOP and the EU Copernicus Space Component (Sentinels) are the two main programmes. One area that has significant potential is the use of satellites to observe large-scale animal migration. NASA's Cloud Aerosol LIDAR and Infrared Pathfinder Satellite (CALIPSO) can monitor animals such as fish, krill and squid rising from the depths to the surface to feast upon phytoplankton on a daily basis.

Science-driven satellite programmes continue to represent a major route for the development and launch of new space missions. The Earth Explorer programme is the European Space Agency's (ESA's) most prestigious mechanism for the selection and further development of science-driven missions. In 2019, the Harmony mission was selected as a candidate for Earth Explorer 10. If successful, Harmony will provide high-resolution observations of surface currents and winds over extreme events and high latitude storms. Two approved missions that present significant opportunity are the Surface Water and Ocean Topography (SWOT) mission and the Plankton, Aerosols, Cloud ocean Ecosystem (PACE) mission. A joint mission between space agencies in the US, France, Canada and the UK, SWOT is expected to launch in 2022 and deliver a step change in understanding of ocean mesoscale dynamics. PACE is a NASA mission due to launch in 2023 and will advance observations in areas such as surface biogeochemistry and ocean/atmosphere carbon exchange.

Operational satellite programmes are characterised by long (decadal) development timelines and slow adoption of innovative technologies. Science-driven satellite programmes are prone to uncertain funding. These long lead-in times and innovative constraints have motivated the emergence of fast track and disruptive space solutions that broadly fall under the umbrella of 'New Space'. New Space relies upon numerous, low-cost satellites working in constellations. This approach has become viable thanks to the miniaturisation of sensors and the availability of low-cost satellite components. Examples relevant to ocean observing include Spire Global Inc and Capella Space who fly constellations of multiple satellites in differing orbital planes to deliver high-frequency observations using GNSS signals and X-band SAR systems. At the time of writing, key gaps in ocean observing capability using satellite technology included:

a. Total ocean surface current vectors, wind vectors and waves as 1-10km scales (these measurements would support understanding of small-scale ocean surface dynamics).

b. High-resolution coastal imaging.

Commissioned reports

Ethics of Marine Robots

Understanding our oceans is key to a sustainable future and combating climate change (Visbeck, 2018).

In some ways, the methods scientists use to study the seas have not changed in hundreds of years. Since the 1700s, researchers wishing to study the seas have chartered ships and sailed to new locations to take physical measurements and collect data. However, in the age of anthropogenic climate change, the need for learning more about our world must be balanced with the even more urgent need to reduce carbon emissions. The scientific study of the ocean is central to ensuring it is protected and sustainably managed, but research comes with its own impacts. These impacts need to be considered, monitored and reflected upon within an ethical framework to ensure research is being as true as it can be to its objectives.

The ultimate aim for ethical marine research is to strike the balance of providing maximum benefit to science, society and environment whilst leaving a minimal negative footprint on the marine realm (Barbier, 2018).

Innovation and technology, including marine robots, have the potential to vastly improve data collection and sharing about the world's oceans. However, in order for the UK's marine research capability to move forward with confidence in the area of marine robots, there remain several aspects that need to be more deeply considered, examined and addressed. Not least, the development of an appropriate ethical frame for emerging research endeavours.

Once such a frame is established, it will allow the development of a set of robust ethical principles. Taking account of societal, environmental and design aspects, these would then help ensure that the UK maintains its world-leading position in marine research and innovation, and facilitates, encourages and supports the development of environmental oceanographic research around the world.

It is recommended that:

a. Each artefact will need ethical assessment, and this will be especially important where we expect high autonomy due to extended durations without human control or through behavioural plasticity.

b. This assessment should be based within an appropriate ex ante framework for ethical foresight analysis.

c. The ethical frame must be clearly determined, in order to justify the conclusions explicitly and in a manner that can be substantiated and supported. It may be necessary to consider other values of 'good' in a global endeavour.

d. This ethical frame should speak to the heart, for its success will depend upon this.

Commissioned reports

Future Capability Training Needs Analysis

The introduction of new technologies to support oceanographic research will continue at an increasing pace. However, cautious optimism should be applied to ensure that those new technologies do not become causal factors in accidents, particularly as oceanographic research often takes place in remote, environmentally sensitive areas where the consequences may be more acute. This mandates a high level of training and experience across the research ship crew and equipment technicians, and investment in ongoing training. There will likely be a mix of mandated, regulated training and certification and bespoke training and accreditation in future.

As automation is increasingly used, gaps will emerge and grow without the investment in training. There is a risk that skills gaps impact support to scientific discovery.

See tables for detail:

Capability	Passage Planning & Route Execution	Command and Control	Berthing & Mooring Operations	Uncrewed Vessel Operations
Timeframe				
Present day until 2025	AL 2 ✔	AL 2 ✔	AL 2 ✔	AL 2 ✶
2025 - 2030	AL 4 ✶	AL 4 ✶	AL 4 ✔	AL 3 ✶
2030 - 2035	AL 4 ✶	AL 4 ✶	AL 4 ✶	AL 3 ✶

✔ Skills exist in present day work force

✶ New skills required in work force

Table 1 – Development of autonomy within capability areas related to Vessel Operations

Commissioned reports

Capability	Pre-Departure Engine Configuration	Performance and Efficiency Monitoring	Failure Diagnosis and Correction	Preventative Maintenance
Timeframe				
Present day until 2025	AL 2 ✔	AL 2 ✔	AL 2 ✶	AL 2 ✔
2025 - 2030	AL 4 ✶	AL 4 ✶	AL 4 ✶	AL 3 ✶
2030 - 2035	AL 4 ✶	AL 4 ✶	AL 4 ✶	AL 3 ✶

✔ Skills exist in present day work force

✶ New skills required in work force

Table 2 – Development of autonomy within capability areas related to Vessel Engineering

Capability	Pre-Launch System Checks	Scientific Sensor Calibration	Launch & Recovery	Maintenance
Timeframe				
Present day until 2025	AL 2 ✔	AL 2 ✔	AL 2 ✶	AL 2 ✔
2025 - 2030	AL 4 ✔	AL 4 ✔	AL 4 ✶	AL 3 ✔
2030 - 2035	AL 4 ✶	AL 4 ✔	AL 4 ✶	AL 3 ✶

Table 3 – Development of autonomy within capability areas related to Scientific Support Vehicle Operations

Capability	Full Field Mission Planning	Remote Monitoring and Intervention	Data Quality Analysis
Timeframe			
Present day until 2025	AL 2 ✔	AL 2 ✔	AL 2 ✔
2025 - 2030	AL 4 ✶	AL 4 ✶	AL 4 ✶
2030 - 2035	AL 4 ✶	AL 4 ✶	AL 4 ✶

Table 4 – Development of autonomy within capability areas related to Scientific System Operations

Commissioned reports

The Future of the UK National Monitoring Fleet Capability

For the purposes of this [commissioned] report, the UK Research Fleet shall be defined to be those vessels with a minimum length of 50m and at the direct disposal of the UK Government and/or its devolved administrations for the purposes of scientific research and monitoring. The 'UK Research Fleet' is therefore:

a. RRS Sir David Attenborough

b. RRS Discovery

c. RRS James Cook

d. RV Corystes

e. RV Endeavour

f. RV Scotia

Niewejaar, et al (2019) found that European research vessels are generally owned by a public body but that management processes differ widely. Nieuwejaar recommended that whilst the European research vessel fleet as a whole has huge potential to be more cost-effective if countries are willing to pool resources, **even the sharing of resources (national pools of equipment, marine technicians and crews) at a national level would introduce significant efficiencies.**

Marine Scotland and AFBNI have recently embarked upon replacement programmes for RV Scotia and RV Corystes. The new vessels will no doubt take advantage of modern energy-efficiency technologies but will inevitably rely upon diesel engines for their primary means of power. The next opportunity to commission a genuinely low or zero-carbon research vessel is either the RV Endeavour or the RRS James Cook (due to be recommissioned in 2031 and 2035 respectively but with options for life-extension measures).

As a 'regional class' vessel the RV Endeavour presents an easier option, with regards supporting infrastructure, for a hydrogen powered or hybrid-hydrogen powered vessel (similar to the vessel being designed and built for Scripps in the US). Government procurement rules and acceptance or risk may be key considerations if this option is to be considered.

Alongside this, both British Antarctic Survey (BAS), NOC and Centre for Environment, Fisheries and Aquaculture (CEFAS) are increasingly using MAS platforms to support research and/or monitoring (NOC maintain and operate the UK's National Marine Equipment Pool and CEFAS have been trialling a CEFAS smartbuoy and USV).

Commissioned reports

Acceptance of data captured using novel sensors deployed via MAS platforms still faces challenges within the associated scientific community. In Jan 2020, a Workshop on Unavoidable Survey Effort Reduction (WKUSER), initiated by the International Council for the Exploration of the Sea (ICES) working group on improving use of survey data for assessment and advice, challenged survey and stock assessment scientists from Europe, Canada and the US to investigate the nature, knowledge and responses to unavoidable reductions in survey effort (ICES, 2020).

WKUSER participants examined methods that can minimise the amount of information lost and identified appropriate methods to accommodate the survey design and objectives, however the use of stand-alone MAS platforms was not factored in, with only the use of modelling and/or technology onboard research vessels considered to increase the volume and/or accuracy of data.

It is therefore imperative that Public Sector Research Establishments (PSREs) and the wider scientific community are exposed to the opportunities that MAS platforms present and that their requirements are used to better inform design and use of MAS platforms.

Cybersecurity

Traditional marine autonomy systems have often failed to consider cyber-security during design phases and have relied instead upon communications between platforms in closed networks. That is no longer possible and **as autonomy becomes embedded in ship, platform and sensor operations, a commensurate increase in cyber security protocols must be adopted: the more connected the systems, the higher the risks.** The anticipated increase in use of autonomous systems on research vessels and MAS platforms opens up 2 discrete issues: increased attack vectors for cyber criminals to exploit and the removal of humans able to intervene to mitigate any attack.

At a high level, adoption of the US National Institute of Standards and Technology (NIST) Cyber Security Framework provides operators with a baseline safety management system that allows risks to be identified and guides operators to consider protocols for responding to and recovering from cyber-attacks. The careful classification of data and its encryption, identification, authentication and authorisation by users remains as important as the physical protection of infrastructure and ensuring that the design of supporting systems and processes are resilient and that backup and restore modes are available in the event of a compromise.

The fundamental cyber security issues are not unique to the maritime domain. **These risks are shared by many other sectors in an increasingly connected world. The maritime domain should aim to stay aligned with these other sectors and take advantage of solutions that are scalable and resilient to future changes.** In the longer-term, AI may provide tools for detecting and responding to cyber attacks however this is not yet available.

NZOC roadmap

NZOC roadmap - key recommendations

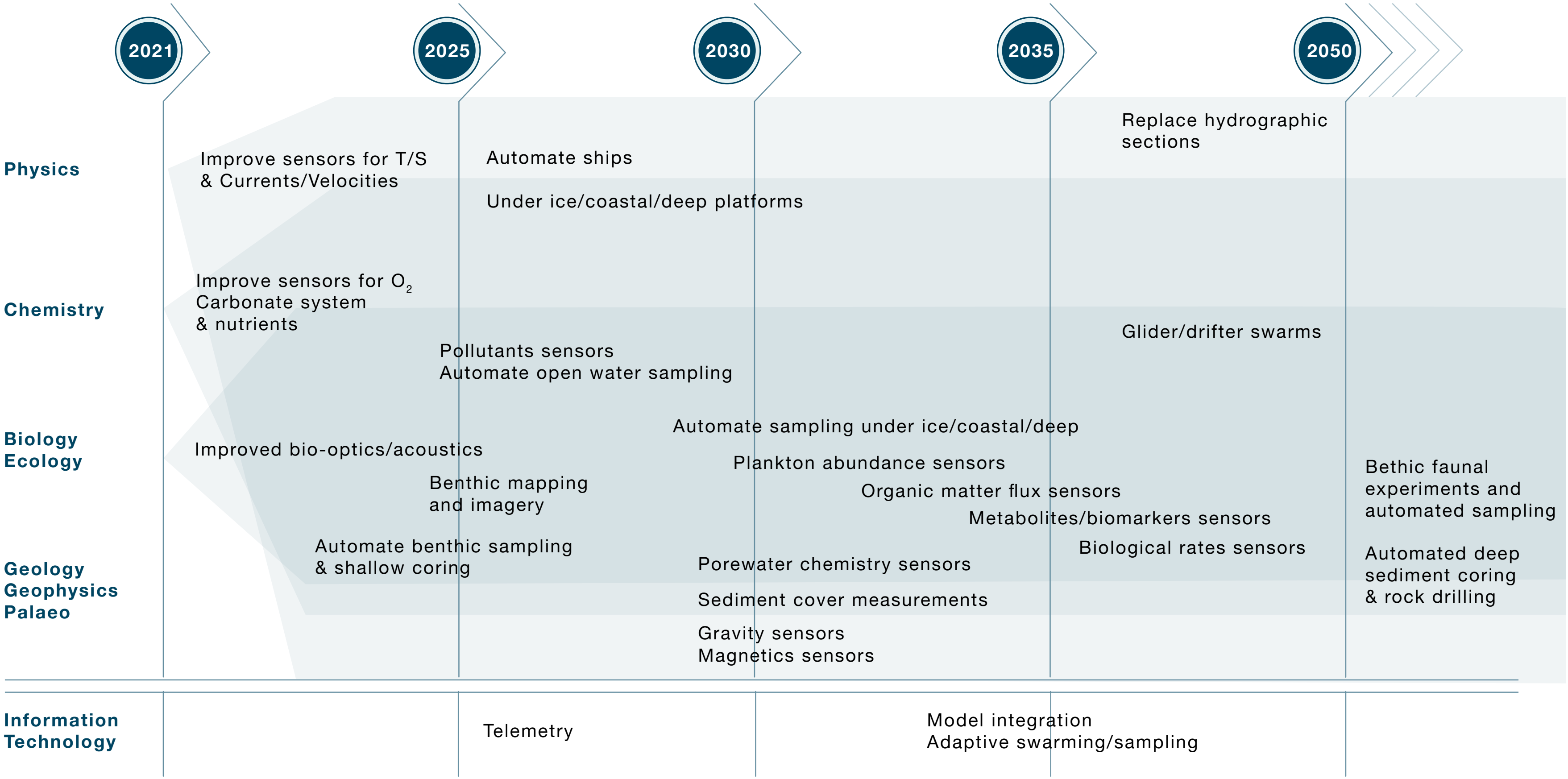


Figure 8: Impact of NZOC roadmap on science disciplines

NZOC roadmap – key recommendations

An approximation of how different marine science measurement strategies might take advantage of the introduction of improved sensor technology, increased numbers of more capable and more intelligent autonomous platforms, improved IT and telemetry and the introduction of AI is shown.

Some areas, e.g. sediment coring, biological sampling and deep crust geophysics, are considered beyond the timeframes required by NZOC and hence would fall back on the use of 'green' research vessels rather than the introduction of improved MAS technology. Progression will depend upon technology developing through Technology Readiness Levels (TRLs) to the point at which they meet the scientific requirements, are reliable, widely available and affordable. Use by scientists will both prove the capability and resolve issues, e.g. grey listed Argo floats with faulty pressure sensors or XBT fall-rate adjustments due to manufacturing changes. Other issues will include:

a. Adjustment to new technologies including learning how to access, use, understand the data streams and align with previous data sets.

b. Adjustment for accuracy and precision between ship-deployed and MAS platform-deployed sensors and methods for addressing bio-fouling on extended endurance MAS platforms.

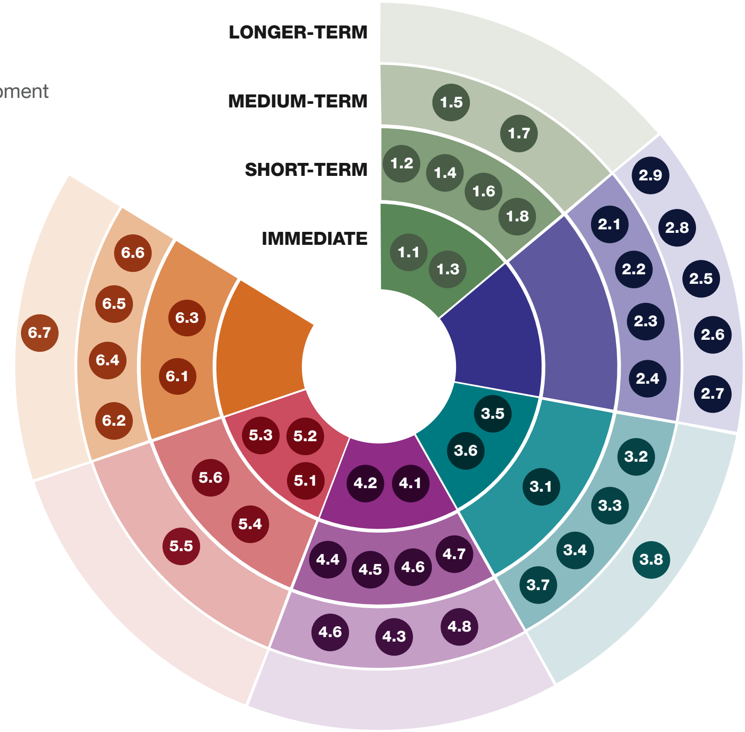
Developments in both sensors and platforms that may be achievable within different timeframes are associated with the different disciplines in the shaded boxes, illustrating that many of the emerging technologies will serve multidisciplinary activities.

Developments in sensor technology for some parameters are well underway, but will require continued improvements and wider usage in the next 5-10 years to achieve acceptance by the marine science community (temperature, salinity, oxygen, nutrients, carbonate parameters, bio-optics). The target accuracies for these parameters are well-known and have been defined by international ocean observing strategies.

Developments in platform technology are likely to see rapid changes in the same timeframe (e.g. automated ships, deep-sea and under ice platforms), but the outcome of these developments and their ramifications for marine science are less well-known. Some sensors are in very early development and are unlikely to be used widely this decade (eDNA, metabolites and other 'omics', pollutants).

Some developments for the broader use of autonomous platforms (e.g. glider swarms, fully remote AUVs with fully automated sampling equipment) require step-changes in order to be effective, both in the approaches to oceanographic observing (e.g. implementation of hydrographic sections) and/or information technology (telemetry, bandwidth, artificial intelligence, model integration and oceanic 'digital twins'). These can be considered the "stretch targets" for the next two decades.

NZOC roadmap



WP6
FUTURE DATA ECOSYSTEMS

6.1 Develop a digital training strategy
6.2 Best practise and NDPt framework
6.3 The data flow architecture
6.4 Multi-platform data management
6.5 Moving frame observation model
6.6 Command and control system development
6.7 Reducing the NZOC carbon footprint

WP5
FUTURE SENSOR SYSTEMS

5.1 Oceanographic Measurement Systems
5.2 Expert measurement and sampling panel
5.3 Standardised sensor parameters panel
5.4 Refining technology development
5.5 Manage new measurement systems
5.6 "Sideways" sensor development

WP4
FUTURE MARINE AUTONOMOUS SYSTEMS

4.1 Develop marine robot capabilities
4.2 Develop OCS autonomy behaviours
4.3 Hover capable and crawling vehicles
4.4 Develop USV launch and recovery
4.5 Develop marine battery technologies
4.6 Autonomous fleet expansion targets
4.7 Add ROVs to the NMEP
4.8 Sustainable marine biofouling solutions

WP1
FUTURE SCIENCE REQUIREMENTS

1.1 Expert technology development panel
1.2 Prioritise FAIR data collection
1.3 Vessel bandwidth and remote access
1.4 Scientists to inform new technologies
1.5 Marine scientist data training plan
1.6 Invest in diversity and inclusivity
1.7 Industry collaboration framework
1.8 UK observations and Net Zero targets

WP2
FUTURE POLICY AND REGULATION

2.1 Invest in improved ocean relationships
2.2 Public-facing ocean health platform
2.3 NZOC and sustainability transitions
2.4 Phase out single-use equipment
2.5 Ensure UK access to marine areas
2.6 Advise government on MPS updates
2.7 Ensure IMO MASS considers NZOC
2.8 Coordinated data collection and use
2.9 AI regulation discussions

WP3
FUTURE SHIP TECHNOLOGIES

3.1 Sustainable planning across the MFP
3.2 Adjustments for "green" shore supplies
3.3 Adapt vessel to use less fossil fuels
3.4 Sustainable supply chains
3.5 Fund continuous underway sampling
3.6 Vessel telepresence and bandwidth
3.7 Fund automated ship development
3.8 Partner and invest in "green ships"

Oceanographic Measurement Systems Development Programme

To achieve a rolling programme of:

1. User requirements refinement and updating
2. Technology road-mapping
3. Technology development
4. Parallel testing and deployment of measurement system enabled MAS / ship with traditional methods.
5. Tapering of ship-based measurement where non-ship systems are acceptable to user communities.

We propose and recommend a significant enlargement of the marine measurement systems activity within the UK. This will expand current world-leading research capability addressing significant gaps in technology capability compared to the scientific and user requirements.

There are risks with this enlargement of capability for efficiency of resource deployment, and therefore delivery of technologies. These risks include: absorptive capacity; rework of existing advancements/ technologies; poor integration of measurement system with each other and with MAS/ships; poor utilisation of existing skills and capabilities; project management; mismatch of roadmaps/timescales; organisational, objective and funding stability.

To address these risks and to meet the objectives, we recommend a hub and spoke model. Whilst the majority of the activity and therefore funding should be focused on technology development, the management model described here should maximise efficiency.

In this model a central coordinating hub has a locus of expertise across a number of areas, but this must include the abilities to address:

- Requirements capture and rolling programme of updates
- Technology road mapping
- Technology innovation and development across at least TRLs 2-7
- Interface design for multiple systems
- Technology modularity to minimise duplication / rework
- Development of both marine measurement systems and autonomous systems
- Coordination of research and engineering development by multiple providers (external organisations and teams of organisations)
- TRL progression and commercialisation / scale up for delivery to user communities
- Value and reliability engineering (including in partnership)

The central hub should interface with and coordinate the activity of spokes (individual technology development partners) and satellite hubs (clusters of technology developers with a locus of expertise best separated, or delivered by an organisation other than the central hub provider).

Oceanographic Measurement Systems Development Programme

To best deliver its coordinating role, it would be beneficial if it were the focus of critical mass in technology development capability. However, no group in the UK is the lead in all of the technical areas required to deliver this programme. Hence, satellite hubs coordinating additional specialist communities and their close collaboration with aspects dealt with by the hub, would be beneficial.

In the current UK community, one could foresee satellite hubs focusing on: animal tagging; acoustic technologies; rock drilling; and ocean bottom seismometers for example.

Each of these satellite hubs would need to ensure their developments were compatible with, and did not duplicate work elsewhere through coordination with the central hub. They would also direct the resources and skills from multiple institutions spanning industry and research / academia, with input from abroad when that enabled efficient delivery. For example, the animal tagging community would benefit from a joined-up programme with providers such as Sea Mammal Research Unit (SMRU)/ St Andrews and CEFAS Technology Limited working with technologists and users in the wider community (spokes) and with input from the **Ocean Tracking Network (Canada).**

The relationship with the (satellite) hubs and their spokes should be collaborative, with them working together to pool resources and expertise to solve technology and research engineering challenges rapidly, efficiently and with high-quality outcomes. This may mean reaching out to other hubs and spokes, e.g. to induct new sensor technologies into the animal tagging programme to address additional requirements (such as animal physiology, measurement of EOVs required for context).

NZOC scoping review

Review scope

Background

To sustain its leadership in ocean science, NERC has invested heavily in 3 large research vessels (RRS James Cook, RRS Discovery and RRS Sir David Attenborough) supported by teams of seagoing technicians and a National Marine Equipment Pool. The Royal Society's Global Environmental Research Committee report on the ocean recognised that "research to address present and future priority ocean issues will require diverse and flexible approached to data collection, making use of new and existing technology and with the data in highly accessible formats". In line with this, UKRI/NERC will need to consider how it replaces the RRS James Cook when it reaches its end of service in 2035. This timeline provides an opportunity to review the current technology roadmap, investigate new technologies and future-proof integrated systems.

Within NERC the 3 large research vessels contribute approximately 70% of NERC's total CO2e emissions. For NERC to support the UKRI sustainability strategy, a plan to reduce CO2e emissions whilst still supporting oceanographic science and a plan to move away from BAU is required. Delivery of world-class marine science with a low-carbon footprint may require the UK to reshape its research capability. To achieve this, significant investment in new technologies, modes of operation and effective partnerships will be required. This transition to a new ecosystem will introduce risks associated with the adoption of new technology whilst traditional technology is phased out.

The NZOC review is expected to deliver on behalf of the UK community and was required to engage with all relevant stakeholders, including the science community, other public sector bodies and regulatory authorities. This was achieved via workshops, direct engagement and/or commissioned reports.

The overall focus on the NZOC review was:

a. To identify the various options for delivering a low-carbon oceanographic infrastructure and recommend how these can best be combined to provide a significant contribution towards meeting UKRI's sustainability strategy.

b. To scope the change that is required to close the gap between the current operating model and the NZOC vision. Any change activities should deliver against:

   a. Development of a robust evidence base including a review of the current landscape to inform and de-risk future NERC investment decisions.

   b. Deliver preferred options for realising a low-carbon oceanographic infrastructure with an outline implementation plan to see this realised by 2040.

   c. Engage with stakeholders to understand the requirements for a future low-carbon infrastructure and the opportunities for co-operation between research institutions and with commercial players.

Review scope

Net Zero Definition

'Carbon emissions' is intended as an inclusive term to refer to all greenhouse gases (GHGs) known to have a negative impact upon climate change as per the GHG protocol. All GHG data and emissions targets included in this report are expressed in CO2-equivalent (CO2-e).

UKRI has stated its intent to "reduce and mitigate all carbon emissions from owned operations, including measurable scope 3 emissions, in line with the Intergovernmental Panel on Climate Change (IPCC) recommendations and the UK government commitment". Furthermore, wherever possible, UKRI aims to achieve 'net zero' sooner than 2040. It is also worth noting that UKRI has outlined a timetable to implement "changing funding and decision-making processes and criteria to raise the standard for environmental sustainability" resulting in practical changes across managed operations to improve environmental performance: this intent moves "beyond compliance".

The NZOC scoping review has not considered the manufacture/construction/disposal elements of UKRI/NERC's ocean research infrastructure. These would need to be assessed separately and appropriate action taken with respect to that project(s). It is acknowledged however, that large-scale procurement activities will inevitably have an environmental impact (from production of steel through manufacture of Li batteries). Any assessment contained within this report only takes account of the operation of the research infrastructure used in support of NERC's Marine Facilities Programme (MFP). In the context of this scoping review therefore, net zero means:

"The elimination or reduction of carbon emissions from all activities carried out in support of NERC's Marine Facilities Programme. This includes scientific research expeditions (ship based), scientific research missions (autonomous platforms) and ancillary activities (supporting logistics, flights and workshop/lab activities). Where it is not possible to eliminate emissions, action to remove the same amount will be required on an annual basis."

This aligns with the accepted definition of 'scope one' emissions – emissions released into the atmosphere as a direct result of a set of activities at an organisation level . Scope 2 and scope 3 emissions have not been included in this review, however this is an area where further work would be recommended. This review does touch on one element of scope 2 emissions, energy used to maintain directly associated data centres, but this is being considered more fully in an associated Net Zero Review for Digital Research Infrastructure sponsored by UKRI/NERC.

[6]https://ghgprotocol.org/

[7]UKRI Environmental Sustainability Strategy – September 2020.

Review scope

A carbon reduction plan would normally identify annual reduction targets based upon a comprehensive programme of energy saving initiatives. This would define annual targets and might take benefit from 'upstream activities' such as purchased electricity being generated from sustainable activities, reduced travel/commuting, greener logistical support etc. The annual targets would inform a 'glide path' to net zero by the target date. The carbon emissions associated with NERC's MFP are, however, locked-in to a certain extent. The research vessels have fuel/efficiency curves which are used to minimise CO2e emissions from each ship, but are limited by the engine design and vessel operation. Whilst investment in vessel efficiency has the scope to reduce CO2e emissions by up to 20%, replacement with greener fuels is the only realistic option for meeting the UKRI/NERC sustainability goal of net zero by 2040.

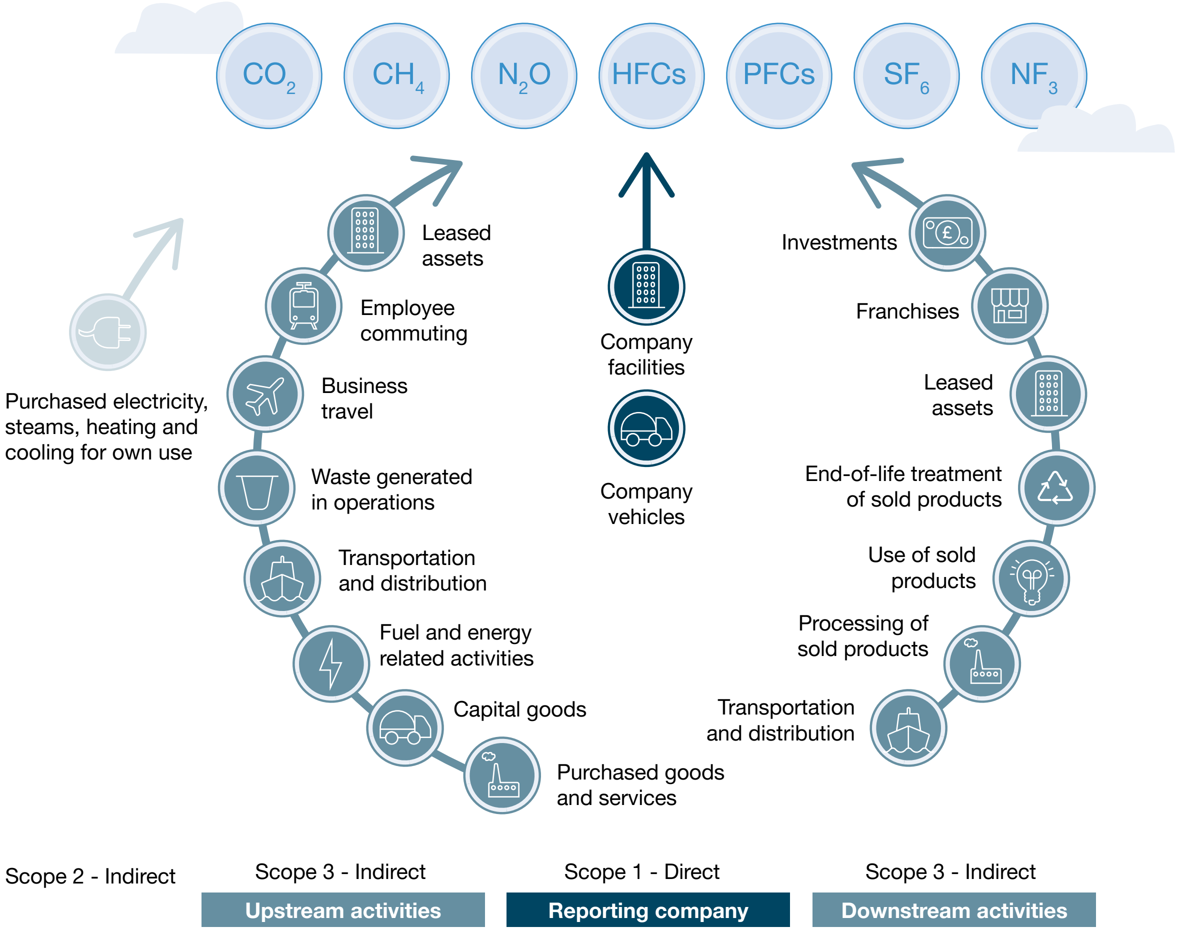


Figure 10: Emission scoping

[8]GHG Protocol standardised frameworks (https://ghgprotocol.org/about-us)

NZOC project management

NZOC Project Team

The NZOC review was set up with 6 primary work packages plus a work package tasked with engaging with industry and wider stakeholders. The work package leads and deputy leads were selected based upon knowledge and experience relevant to the work package, institution (ensuring this wasn't a NOC-centric report) and diversity (where possible – it should be recognised that this is a challenge when selecting from a pool with limited diversity).

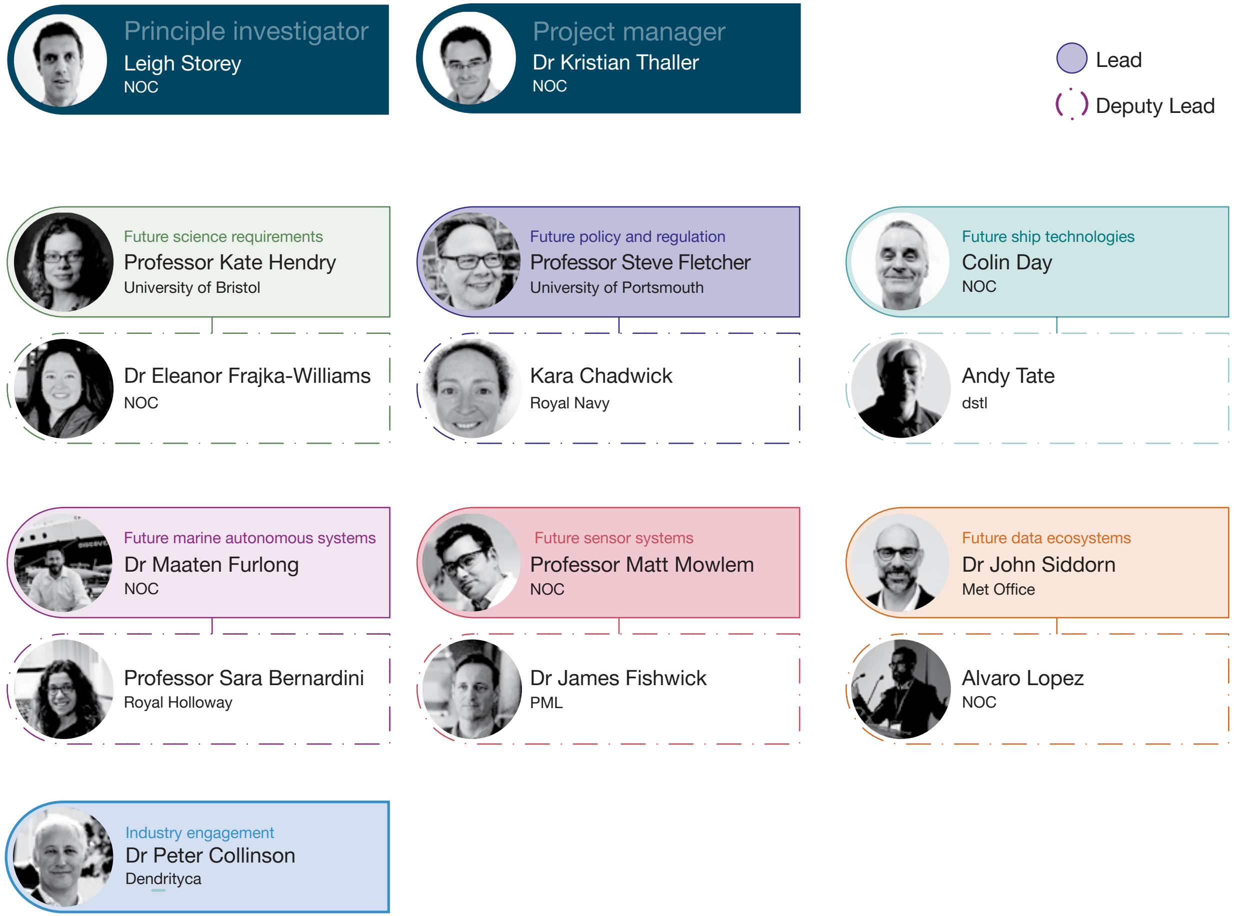


Figure 11: NZOC Project Team

NZOC project management

NZOC Work Packages and Commissioned Reports

The work packages set out to achieve the following objectives:

Work package 1 — Future science requirements

a. Horizon scanning for changes in scientific priorities.

b. Consideration of the impact that not having access to a large research vessel would have on the delivery of science.

c. Identification of science requirements for a future research capability using historic data and stakeholder engagement.

d. Consideration of the interplay between international ocean observing (for all stakeholders/users) and national capability and its effect upon future requirements.

e. Consideration of the impact that not having access to a large research vessel might have on the delivery of science.

f. From a scientific perspective, identifying possible alignment of oceanographic research, development and innovation objectives.

Work package 2 — Future policy and regulation

a. Exploration of trends in UK and relevant international marine policy seeking to understand the likely UK position by 2035 and forecast any changes.

b. Consideration of scientific evidence requirements needed to underpin UK future marine policy priorities.

c. Identification of any aspects of regulation and compliance that may constrain the low-carbon infrastructure options identified across work packages 3-6.

Work package 3 — Future ship technologies

a. Review of the rationale for regional/global class, multi-role research vessels.

b. Identification of current and future emerging technologies, alternative energy options and design approaches that may impact current and future operating capabilities and expected timelines for these.

c. Evaluation of the impact upon CO2e emissions of refitting existing vessels with new technologies.

d. Exploration of the options for reducing the carbon footprint of a future new-build research vessel.

e. Engagement with national and international organisations to assess opportunities for consolidating infrastructure in areas of ship operations and equipment.

f. Consideration of how a zero-emissions, ship-centric infrastructure would impact upon the delivery of science.

NZOC project management

Work package 4 — Future marine autonomous systems

a. Review of the rationale for the use of MAS platforms in oceanographic research.

b. Identification of the technology trends in the MAS sector and how these might contribute to delivery of science by 2035.

c. Identification of the potential for MAS platforms to contribute to a low-carbon infrastructure.

d. Consideration of the CO2e footprint of MAS platforms.

e. Assessment of the expected commercial uptake of MAS platforms and opportunities to collaborate and/or reduce costs by accessing COTS technology.

f. Consideration of how a zero-emissions, MAS-centric infrastructure would impact upon the delivery of science.

Work package 5 — Future sensor systems

a. Identification of technology trends in ocean sensing and sampling and how these might meet the science need in 2035.

b. Evaluation of the opportunities for replacing or increasing the efficiency of ship-based sensor and sampling technologies.

c. Exploration of different models for deploying sensors and samplers and assessing their ability to address science/user needs.

d. Assessment of the expected commercial uptake of marine sensor technologies and the opportunities this will create.

Work package 6 — Future data ecosystems

a. Identification of the trends in data ecosystems, from collection through to processing.

b. Exploration of the use of predictive methods to optimise the deployment of research infrastructure.

c. Exploration of the concept of intelligent MAS platforms and of how AI/ML will impact the future data ecosystem.

d. Assessment of the expected academic/ commercial interest in a low-carbon data ecosystem.

e. Consideration of cyber security issues.

NZOC project management

Industry engagement

a. Support engagement with key industry stakeholders and consider opportunities for future engagement to support NZOC options.

In addition, the following reports were commissioned:

Ocean observing capability from space

a. Examination of spaceborne oceanographic observing capability available in 2020.

b. Consideration of the evolution of spaceborne ocean observing in the 2020-2035 timeframe.

c. Identification of how the use of satellite technology might impact CO2e emissions and ED&I.

Ethics of marine robots

a. Review of ethical issues in marine research/oceanography.

b. Review of ethical issues in AI and robotics.

c. Options for predicting and avoiding/reconciling ethical hazard in marine research/oceanography.

Future capability training needs analysis

a. Review delivery of the current research infrastructure with a specific focus on how advances in technology will impact workforce capability over the next 10-15 years.

b. Identify gaps in capability and develop over time.

Scientific journal and research expedition analysis

a. Conduct an analysis of scientific publications and expedition metadata to consider emerging trends globally and in the UK.

Cyber security and autonomy

a. Review of current cyber risks to the safe operation of autonomous vessels.

b. Analysis of how cyber security systems will have to adapt or improve as the shift to autonomous control increases.

c. Analysis of how cyber security systems might have to adapt to support swarms of autonomous platforms operating in tandem, elements of the 6 work packages as well as the industry engagement and attracted additional stakeholders.

NZOC project management

NZOC engagement and workshops

A key objective of the NZOC project was to capture a diverse range of experience and knowledge from across the broadest range of stakeholders. The entire project was run virtually (this decision was made prior to the impacts of C-19) to support the net zero aspiration and to actively engage with the challenges and opportunities this approach enables. As anticipated, the use of virtual media enabled a wider range of stakeholders to engage but reduced some of the 'depth of engagement' that might have been achieved in person.

The majority of external engagement with the project was routed via a dedicated project website set up in the early stages and hosted on the NOC website. The project website provided a mechanism for potential stakeholders to register for news bulletins associated with individual WPs, see the events schedule, and access online resources such as WP summary videos and workshop outcomes for those unable to attend. In total, 188 stakeholders from 96 separate organisations signed up to interact with one or more work packages.

The workshops were run in order over a 2-month period and covered key elements of the 6 work packages as well as the industry engagement and attracted additional stakeholders.

The events were promoted through direct messaging between WP leads/deputies and known contacts/influencers in the community. WP1 was also supported by a community survey, the findings of which were intended to inform the workshop content and allow individuals unable to attend to contribute. Low response rates to the WP1 survey and increasing understanding about the usefulness of such information meant that surveys were not issued for other WPs. To support the workshop outcomes, the WP leads/deputies also held direct conversations with various community experts who could provide further insight into the conclusions and support the development of the recommendations.

As well as considering the total number of stakeholders involved in the scoping the future research infrastructure, attention was paid to ensuring that there was a balance of representation from science users (academia), industry and public sector organisations.

NZOC project management

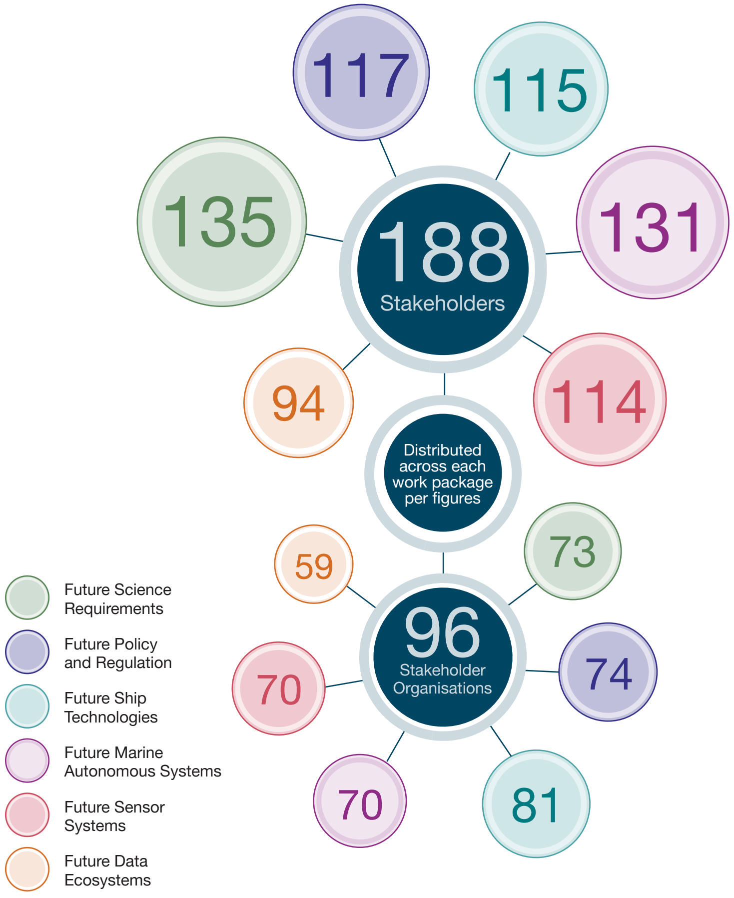


Figure 12: NZOC engagement and workshops

Interaction with the NZOC website peaked in Q1 2021 as communications and workshops were delivered.

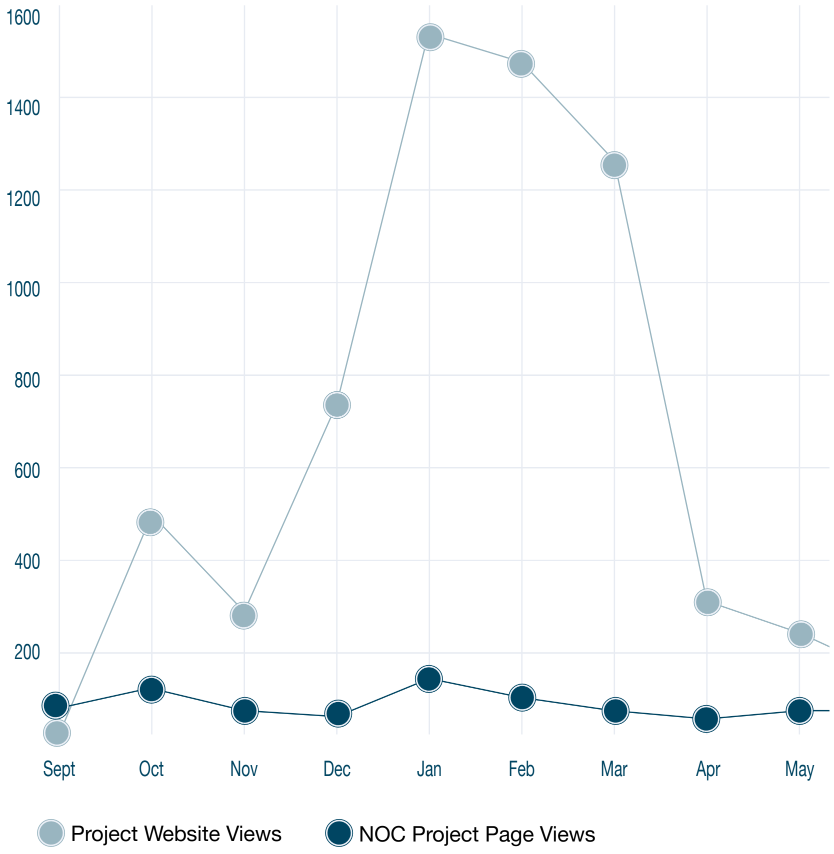


Figure 13: Stacked plot of NOC project page [green] and NZOC website [blue] views by month.

NZOC project management

Figure 14: Number of stakeholders and stakeholder organisations registered to attend the NZOC workshops.

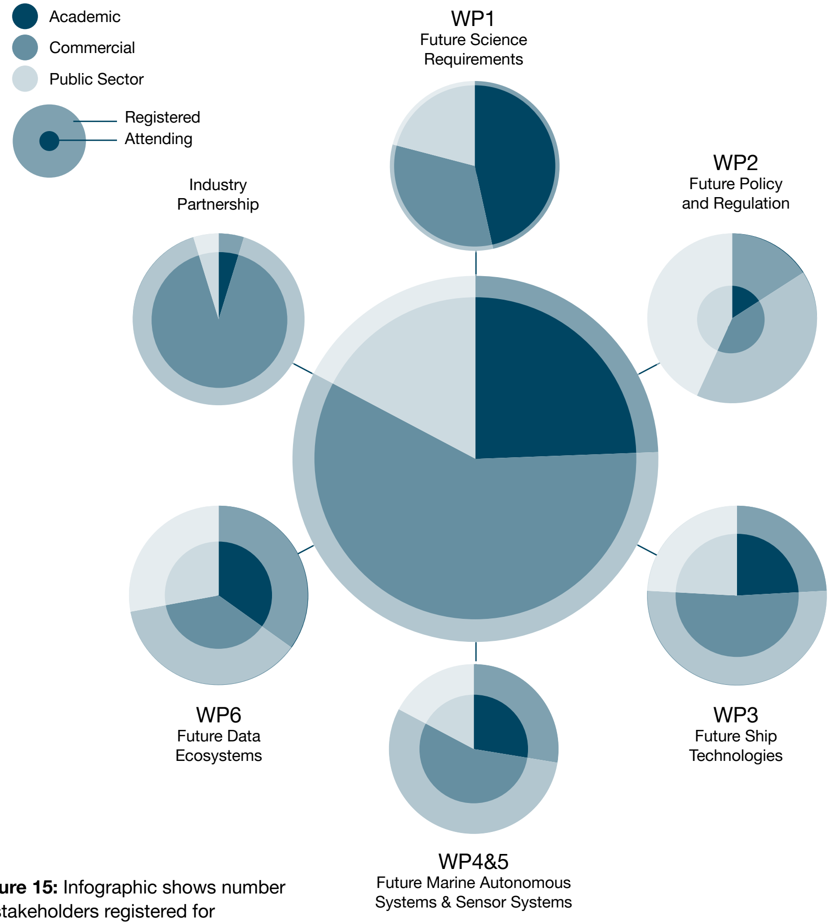


Figure 15: Infographic shows number of stakeholders registered for [filled circle] and attending [dashed circle] the various workshops broken down by stakeholder category.

NZOC project management

Emphasis was also placed on securing representation from the UK and more specifically to identify the carbon savings from having a truly integrated national/international capability.

Figure 16: Global distribution of stakeholders

NZOC project management

NZOC Steering Committee

As part of the NZOC review, a steering committee was set up to provide strategic advice to both NERC and NZOC on behalf of the communities that its members represented. Specifically, the Steering Committee advised on:

a. Improvements to the project deliverables, anticipated outputs and outcomes and recommendations to ensure the project was a success.

b. The strategic direction of the project and alignment with the longer-term, NZOC vision.

c. Opportunities for complementarity with other initiatives, both national and internationally, including funding and impact opportunities.

d. Engagement with the wide range of UK stakeholders and how to articulate that message.

e. Progress against agreed milestones and KPIs.

The steering committee included:

a. Professor Paul Tyler (University of Southampton) – Chair

b. Dr Sophie Fielding (BAS)

c. Professor Chris German (WHOI)

d. Dr Scott Hoskings (BAS)

e. Dr Alan Hunter (University of Bath)

f. Professor Karin Lochte (German Alliance Marine Science)

g. Professor Alex Rogers (REV Ocean)

h. Geraint West (Sonardyne International Ltd)

Equity, diversity and inclusion

The NZOC project was tasked by NERC to embed ED&I throughout the scoping exercise to ensure we were "able to access the best talent and nurture great ideas". Furthermore, as part of the NZOC report, an assessment of the impact upon ED&I that the transition to a NZOC might have was required. It is the accepted view that ED&I policies that support protected characteristics, promote equal opportunities and enable an inclusive working culture are part of any responsible business framework. UKRI has stated that "everyone has the right to be treated with dignity and respect, and to be provided with opportunities to flourish and succeed in a supportive environment". In considering the ED&I impacts of any future NZOC the project has measured the following:

a. Who is impacted and in what way: positively, negatively or disproportionately?

b. Who is missing from the assessment?

c. What are the barriers to achieving equity, diversity and inclusion?

Given the scale of change required and the pace at which that change has to happen it is likely that unintended consequences will emerge. It is for that reason that the recommendation below (taken from work package 1 key recommendations) is so important.

Carefully but deliberately invest in an equitable, diverse and inclusive marine science community and take advantage of how new technology can remove barriers. As an immediate priority, establish a practice of monitoring ED&I on the path to net zero to evaluate expected consequences and safeguard against unforeseen consequences.

The transition to a NZOC presents the opportunity to deliver significant ED&I benefits, however, the realisation and impact of these will depend on the approach that is taken. Critical to making the future research infrastructure more accessible and inclusive will be a focus on the measurement of ED&I impact at all stages of the transition. Opportunities for greater inclusivity should be identified at the concept stage such that key design decisions subsequently support greater ED&I. Alongside that, active steps should be taken to broaden participation when new capabilities are commissioned, e.g. providing shore infrastructure to enable virtual science parties to participate in research expeditions.

Equity, diversity and inclusion

The most notable area of opportunity for greater inclusivity is equitable access to data, i.e. participation on a research expedition is not required and hence that major barrier to access is removed. Progress towards the NZOC envisaged in this paper will support this process. Among the groups most able to benefit will be:

a. Those with disabilities who are physically or by reason of not passing a medical check able to join research ship expeditions.

b. Those with caring responsibilities (a consideration disproportionately affecting women in science).

c. Those who for reasons of religious belief are affected by the timing or remote location of trials.

d. Those who, for whatever protected characteristic, find themselves uncomfortable at being confined in close proximity for multiple days/weeks with other staff.

e. Those who, for whatever protected characteristic, feel unsafe during mob/demob in overseas jurisdictions.

The breadth of initiatives associated with NZOC means completing the 'standard' UKRI Equality Impact Assessment (EqIA) isn't practicable. However, from reviewing the UKRI EqIA form, it is apparent that if it were used in the assessments of proposals or strategic programmes then the barriers presented by 'ship-centric' infrastructure would be exposed. This then might drive initiatives such as 'virtual science parties' which align with reducing the carbon footprint of a future NZOC.

Finally, raising awareness of these issues such that everyone involved in oceanographic research understands the difference between equality and equity and how that impacts those involved and precludes others should be a priority.

Barriers to change

Barriers to change

Key barriers include:

There are multiple, overlapping barriers to implementing the shift in an oceanographic research ecosystem necessary to deliver a net zero oceanographic capability by 2040. The most challenging of these is the misalignment with the internationally agreed target of achieving carbon neutrality by 2050 as recommended by the IPCC and supported by the UK government. This is further exacerbated by the IMO's current greenhouse gas strategy (published in 2018) that commits to nothing and 'envisages' a reduction of 50% by 2050.

The current rate of technology development is such that like-for-like replacement of diesel-powered research vessels with low or zero carbon alternatives is considered to be very challenging by 2040, but also that the increased use of MAS platforms will not completely support the 'maintenance or enhancement' of the capabilities currently delivered by those vessels.

Given current technology development trajectories, the aim must be to continue to reduce emissions wherever possible and replace the fuels used on research vessels at the very earliest opportunity. That will require targeted investment in supporting infrastructure and an acceptance of risk and increased operating costs.

a. The cost of transition whilst continuing to operate legacy infrastructure. This should not be under-estimated. The cost of many of the mitigation actions to reduce the CO2e emissions on the research vessels is estimated to be in the £Ms. Investment in technology development and replacement of older technology will cost £100Ms (note a modern global class research vessel costs £100M+).

b. Access to a skilled workforce necessary to support the transition in a highly competitive market. Costs will include paying a market premium and training of current staff. At some point in the future there may be costs associated with operating and then decommissioning old technology (ships), operation of a hybrid capability and trials of a new, green technology all at the same time.

c. Behavioural shifts away from high carbon aspects of research infrastructure including sharing of data, sustainable food policies, sustainable travel policies, sustainable meeting policies and reward and recognition of leadership in this area.

d. Regulation and compliance will hold back investment until the market is clear on what is required – this issue spans new fuels, new engines, ship autonomy and operator qualification. This issue is exacerbated by the digitisation of the ocean as data standards will have to be internationally acceptable if automation is to be expanded. Data standards for scientists are one side of this, the other is the requirement for research vessels/MAS platforms to be able to operate in EEZs/harbours around the world and interact with digital monitoring and management systems.

[9]The initial GHG strategy envisages, in particular, a reduction in carbon intensity of international shipping (to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by

Barriers to change

e. Cyber security considerations may delay the uptake of new, digitally-enabled technology until they are proven to be resilient in the face of cyber-attacks.

f. Biofouling of sensors and platforms that remain in the water for extended periods remains a problem for large-scale moorings and is a growing problem for MAS platforms as their endurance increases.

g. Lock ins. Examples of potential lock-in categories (adapted from Klitkou et al., 2015) in marine science include institutional learning effects, essentially where complex knowledge and skills cumulate through the evolution of methodologies ("process X has always been done this way, and we know how to do it well"); informational increasing returns, where particular technologies or approaches gain greater attention through promotion, for example, in high-impact publications ("Group or Laboratory Y do it this way, so we should too"); network externalities, where particular approaches are used to be consistent with other national or international groups ("if we do it a different way, our data will not be comparable with any other group"); collective action where 'norms' or customs emerge ("the community agrees that process X should be done this way, and no one will believe us if we try a different way").

h. One specific example of a possible 'lock-in' situation is the global Argo float array. At present, Argo floats are an economical way of measuring ocean properties (temperature, salinity) in the top 2000m. However, they are not designed to be recovered and end up on the seafloor (roughly 750 floats per year). While this is an acceptable near-term solution, in 100 years the accumulation of litter may no longer be acceptable. The availability and low cost of Argo floats means that resources are put into maintaining the Argo array, rather than into developing an autonomous vehicle that could supply the purpose of the Argo array, but would be recoverable at end-of-life.

i. From the survey of marine scientists, 47% of respondents identified that the inability of autonomous platforms to measure their parameter of interest was a barrier to further uptake. This issue was expanded in the workshop, with the 'sensors' sections above outlining areas where developments could be made. Also from the survey, 29% of respondents noted that they could not move to using autonomous platforms because it would disrupt the continuity of long-term datasets. This issue was also discussed in the workshop, highlighting the need for overlap between traditional approaches and new approaches to safeguard the value of these records. Smaller proportions of respondents identified poor reliability, calibration and accuracy, access to technology and cost as barriers to uptake. In querying marine scientists about what it would take to get new sensors into more widespread use, a majority identified that the primary area for improvement would be access to the sensors ('availability or ease of access') with 63% of respondents citing this as a barrier. Other identified barriers to using new sensors included 'reliability' (60%), and accuracy, precision or calibration (47%).

2030, pursuing efforts towards 70% by 2050, compared to 2008); and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008.

Risks

Risks

Risks

The least risky option for UKRI/NERC if it is to meet the requirement to maintain or enhance its current capability whilst supporting the transition to net zero by 2040, is to continue to operate its current infrastructure whilst building up net zero capabilities to the point at which they are able to reliably replicate the capabilities currently available to marine scientists in all respects. This is too simplistic an approach however and some risks should be accepted to allow UKRI/NERC to take advantage of older assets needing to be replaced and new technologies becoming more widely available. An NZOC ecosystem dependent upon multiple platforms/data streams, rather than centred upon research ships, has some risks associated with how we plan science and how we access the data. WP3 identifies how the planning processes can be improved and scaled to manage 100s of platforms. WP6 considers how those data streams can be stored and made available to multiple users as well as showing how the development of better models (digital twins) feeds back into better planning which itself can reduce carbon emissions. An interlinked, multi-modal ecosystem does remove one major risk inherent in the current model as research vessels currently present single points of failure.

Key risks:

a. Short-term funding for development of the necessary technologies. NERC has a good track record of making long-term (5+ years) investments in the development of marine autonomous platforms (using Industrial Strategy Challenge Fund funding most recently) and in investment into the adoption of commercially available technology (using NERC National Capability large-scale research infrastructure funding as advised by the Marine Facilities Advisory Board). The challenge now is to link up funding opportunities so that they align with the desired carbon pathway. This is considered a risk that NERC can successfully manage.

b. Availability of suitably qualified and experienced personnel. This risk sits across every thread of NZOC and as the commercial and defence sectors accelerate their adoption of net zero technology remuneration may become a key factor. More positively, individuals continue to be drawn to the challenge of developing technology that supports ocean research and the key role it plays in understanding climate change. This is a risk that NERC can reduce with funding and communicating the impact NZOC can have more widely.

c. Supply chains are at risk from geopolitics, material scarcity and cyber-attack. This is not a risk NERC can actively manage so should plan in flexibility wherever possible. The global shortage of microchips is a good example of this. Longer-term funding allows relationships with key suppliers to be developed.

d. Siloed development projects. The pace of change required to meet the 2040 deadline is such that co-ordination is imperative. UKRI & NERC have made efforts to improve this across research councils and those should be continued. Allocation of funding to develop technology should require a clear statement of how it aligns with other technologies being developed e.g. sensors that can be integrated into multiple platforms or data storage that supports FAIR principles.

2030, pursuing efforts towards 70% by 2050, compared to 2008); and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008.

A ‘Landscape Laboratory’ and intelligent marine observing system

A ‘Landscape Laboratory’ and intelligent marine observing system

The NZOC scoping review announcement of opportunity asked for ‘clear strategies for the infrastructure becoming a long-term, adaptable facility such that obsolescence does not occur, particularly with a view to this investment forming the first phase of the ambition to create a “Landscape Laboratory” as outlined in the UKRI Infrastructure Roadmap report’.

That report defined landscape laboratories as ‘enhanced, integrated networks of sensors that could be designed to measure a range of interconnected physical, chemical and biological processes that define our environment and that we depend upon for our water and food supplies and protection from natural hazards’. These measurements would need to be collected at appropriate spatial and temporal scales.

The NZOC ecosystem envisaged is significantly more adaptable once fully implemented, but the transition presents risks to specific scientific disciplines (see WP1 report for more detail) and to the responsiveness of the ecosystem if research vessels are replaced too early in the transition (ships as floating laboratories present the opportunity to conduct experiments that otherwise would not be possible).

The strategy of rapidly building up sensor development capability alongside the current trajectory envisaged for autonomous platforms and then specifically testing the new capability against the current capability meets this remit.

Wrapped around that, more integrated planning and the enhanced data ecosystem outlined in WP6 ensures it is a network of sensors rather than a series of siloed missions. This links well with the Intelligent Marine Observing System also described in the UKRI Infrastructure Roadmap. That observing system is focussed upon UK coastal and shelf-sea areas providing real-time data generation, processing and analysis. Here again the NZOC ecosystem envisaged is adaptable enough to support this objective and doesn’t have to meet the mid-ocean challenges of deep water and extended endurance.

Recovery of autonomous platforms becomes much easier and the time/cost to re-deploy and be on-station is significantly reduced. Coastal and shelf-seas observing networks should be considered as test beds for full ocean depth/basin observing systems and linked to the ‘natural capital’ approach described in the WP2 report.

Final thoughts

Final thoughts

As Principle Investigator for this project I continually circle back to 3 key elements of the transition to a net zero oceanographic capability:

Considering the research infrastructure as an ecosystem is helpful when describing the complexity inherent in deep water oceanography and the transition to increased use of autonomy. However, multi-role global class research ships have an inherent flexibility and resilience that is difficult to replicate with current or near-future technology. They are therefore likely to remain a component of the future ecosystem but harnessing the latest 'green' technology.

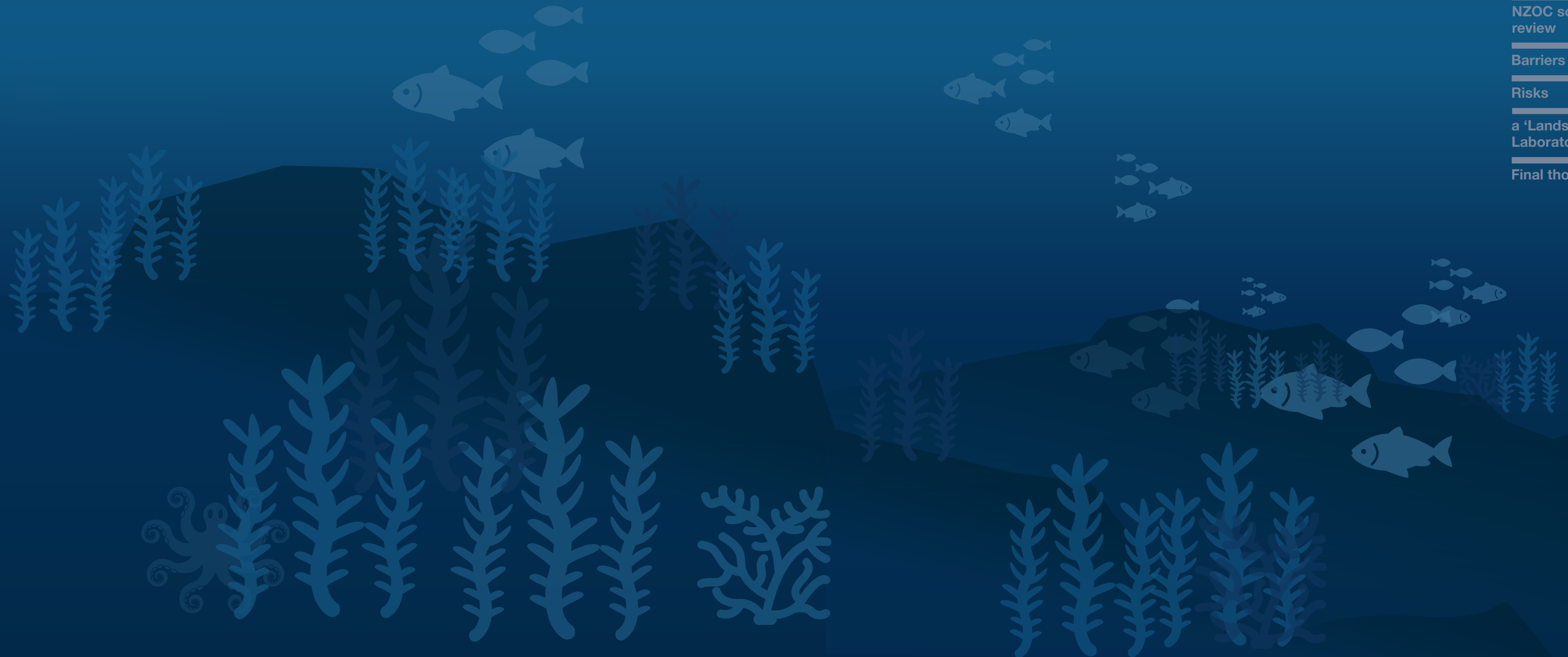
Humans and machines will interface in ever more complex ways with machine learning and artificial intelligence playing a major role in enabling its success. That interface presents numerous challenges associated with knowledge, training, regulation, operation and the sensors that support it. It is not without risk and appropriate safeguards will be necessary.

A more connected, technology-enabled ecosystem is at greater risk from cyber-attack and resilience in the face of that risk should be considered at every stage.

"I would like to recognise and thank those that led and supported the analysis contained within the NZOC reports. Despite a tight timeline, a broad scope and the substantial personal and professional impact of a global pandemic, they remained focused on engaging with as wide a range of stakeholders as possible and bought their own expertise to bear upon the NZOC challenge. They are a remarkable group whose knowledge and passion has been evident throughout."

Leigh Storey

Appendix



Appendix

Work Package 1
Future science requirements

Work Package 2
Future policy and regulation

Work Package 3
Future ship technologies

Work Package 4
Future marine autonomous systems

Work Package 5
Future sensor systems

Work Package 6
Future data ecosystems

Commissioned Report –
Ocean Observing Capability from Space

Commissioned Report –
Ethics of Marine Robotics

Commissioned Report –
Future Capability Training Needs Analysis

Commissioned Report –
The Future of the UK National Monitoring Fleet Capability

Commissioned Report –
Cybersecurity

Collaborators

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ROYAL NAVY

PML | Plymouth Marine Laboratory

[dstl] The Science Inside

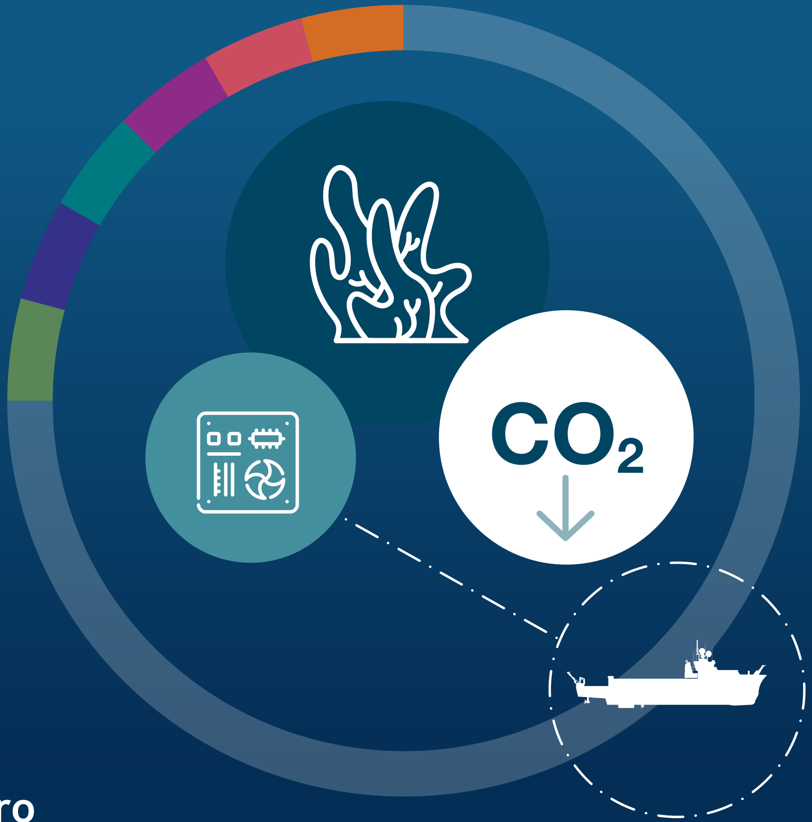
Met Office

University of BRISTOL

UNIVERSITY OF PORTSMOUTH

ROYAL HOLLOWAY UNIVERSITY OF LONDON

National Oceanography Centre



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