Net Zero Oceanographic Capability - Scoping Study

WP5: Future Sensor Systems and Networks

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

This report covers the detailed findings of Work Package 5: Future Sensor Systems and Networks.

1 Introduction

Executive Summary

Observations

1) It has been apparent in this study that the community is biased towards science disciplines that are well served by research vessels, and by capability providers with a focus on ships. Thus scientists / stakeholders / users and capability providers for non-ship systems are underrepresented in community engagement activities.
2) Research vessels are extremely adaptable, capable and productive providing scientists with an immersive experience that is motivating and can lead to multidisciplinary cross working and productive serendipity. Replacing this beneficial characteristic with non-ship capability requires focus.
3) Future research vessels, if addressing the NZOC challenge will not be the same. For example, if ammonia fuel is used their fuel volume will increase from ~15% to > 45% of the ships available internal volume. This is a challenge to the status quo of the current multifunctional operations. Mitigations include: removing humans from the ship (in part or totally); developing automated measurement systems that require less volume on the vessel; developing offboard (non-ship) measurement systems.
4) The user community is rightly concerned that a transition from research ship based capability to non-ship capability (in full or in part) is not without risk. A pragmatic approach would be to overlap capability as non-ship system competence is developed and demonstrated. This would provide proof and confidence for future capability purchasing decisions.
5) If the UK could develop and drive the use of a non-ship or reduced ship capability it would lead the world in both technology and operations. It is currently a world leader in measurement systems.
6) Our analysis suggests that **research vessels currently address 55-60%** of the total requirements for oceanographic capability, whereas **current autonomy can at best address approximately 40%** (i.e. about 70% of ships capability). These numbers are largely unchanged when the amount of data needed for each requirement is considered.
7) If powered with rechargeable batteries autonomy and other small low carbon observing systems generate emissions *lower than research ships by three orders of magnitude* per km surveyed. However, because a research vessel can make many measurements in a single campaign, to achieve the comprehensive capability we foresee, non-ship solutions would generate 0.6% of the emissions of a research ship (neglecting emissions from logistics and staff travel). Using primary batteries is significantly inferior resulting in only a ~50% cut in emissions to deliver the capability. This is less than the saving predicted by switching ships to ammonia fuels (reduces emissions to ~35% of the status quo).

8) There is considerable room for improvement in emissions from logistics and staff travel, with the majority of emissions coming from staff travel. Indeed, current practices of flying multiple staff to site or ship for non-ship observing reduces the emissions cut to <80%, close to the cut achieved using ammonia fuelled ships (~70% cut). If staff flights were reduced (not eliminated) by utilising technical staff in existing field stations and in country institutions and greater use of virtual tools / support was made, then **a 97% cut in emissions remains feasible**.
9) The principal barrier to autonomy meeting stakeholders' requirements is the instrumentation and sampling systems carried by them. However, carrying additional sensors and instruments, and operating additional sampling equipment will also require adaptation of non-ship systems principally the ability to support larger size, weight and power requirements as well as enhanced interactivity (remote piloting) or artificial intelligence / enhanced autonomy for sampling or intervention experiments. Our carbon analysis also finds that the use of primary batteries must end in favour of rechargeable batteries or energy harvesting to enable autonomy to contribute to net zero.
10) Our analysis suggests with an approximately £50-120M technology development programme, a suite of instruments, sensors and samplers could be developed that would enable non-ship systems to address about 80% of stakeholder requirements (about 140 to 150% of current ship capability). However, selected disciplines would be supported by reduced capability even in this uplift scenario (see below).
11) Enhancement of autonomy capability as above would be in addition to this activity and is dealt with by WP3.
12) Such a large development programme requires considerable upscaling of research and development requiring induction of new personnel and resources to this task as well as improved coordination of existing R&D organisations and individuals.
13) The majority of the requirements met by ships look solvable with non-ship technology that is known or envisioned now. However, there are a number of requirements currently met by ships where this is not true. Further effort is required on those where a technological solution is not apparent.
14) We envisage that a move to non-ship capability without other mitigations or as yet unknown innovations would lead to a reduction in:
    a. On the fly and adaptable multidisciplinary capability
    b. Experimental and intervention capabilities
    c. The ability to exercise freedom of navigation
    d. Ability to characterise at sea (samples could be returned instead, with loss of some ephemeral and delicate signatures):
        i. particulate matter
        ii. pore waters
        iii. rock and sediment (including geological, biogeochemical, isotopic analysis and microfauna / fossils / paleo biology)

Recommendations

1) That a significant oceanographic measurement systems development programme is established to develop sensors, instruments samplers and intervention capability for non-ship and green ship / reduced crew systems.
2) That a reduction in research ship number and size is possible, together with up to a 97% cut in emissions and improved satisfaction of users' requirements by 2035 if there is sufficient priority and investment in the development and adoption of sensors, samplers, instruments and autonomous measurement capabilities
3) Without adoption and / or development of new measurement system capabilities, autonomy can only address 40% of stakeholders' requirements.
4) Measurement systems innovation will be required even if we maintain (green) research vessels to enable the same capability with reduced scientific volume (fuels take more space, and vessels may be smaller).
5) Whilst industry and other applications are developing technologies that will support a future Oceanography Capability less reliant on traditional research vessels (e.g. in acoustics and seismics) there remains significant gaps and challenges and these will need a focused and sustained programme to address. This will require enlargement of this area of research in the UK by one to two orders of magnitude.
6) We recommend the UK builds on its international leadership position in sensor, instruments and samplers and establishes a collaborative and inclusive network of research and development capability that is particularly well coordinated to enable efficiencies (e.g. avoiding duplication) and interoperability (e.g. with modularity and common interface standards).
7) To achieve efficient world class and coordinated R&D we recommend a hub and spoke model for the new measurement systems development programme. The hub should be a centre of excellence in measurement systems and autonomy, but should also support external (spoke) organisations by providing support from existing technological solutions (e.g. robust electronics, sensor components, data and software systems) to reduce development effort /accelerate delivery. The hub should also promote and develop the use of modularity, common interfaces and best practice in design, metrology and data system. Spokes should support innovation in the hub and will bring new ideas which should be aimed at capability gaps / requirements and should step through technology readiness levels to proof of concept (TRL 4) whence they should be inducted into the development roadmap. Spokes are likely to have different and complimentary skills to the hub and other spokes and the delivery of the technology development effort should be coordinated between hub and spokes to maximise delivery speed and quality.
8) Whilst autonomous systems (including moorings, observatories, landers as well as all types of drifter and vehicle) are capable now, and many systems are commercially available, the character of many current vehicles would have to change to meet all of the current

Oceanographic Capability requirements. This is because in many instances the measurement systems required could not be efficiently hosted by current designs e.g. because of data, size, weight and power requirements. This is especially true if multiple measurement systems are required to replace the multidisciplinary role played by research vessels.

9) That development efforts are prioritised in an ongoing process using the requirements (type and amount of measurement / capability) together with a rolling analysis of technological opportunities and hence projected carbon savings through the establishment of an Oceanographic Capability Roadmap.
10) That the gaps identified in this report are investigated in more detail by paper studies and where a prioritised requirement remains, development programmes are established.

1.1 Review Scope

This report forms part of outputs of the wider Net Zero Oceanography Capability (NZOC) project undertaken on behalf of NERC and examining the methods and impact for achieving a UK oceanographic capability with net zero emissions (see definition in §1.2). This report focuses on the sensors, instruments and sampler systems and how these could be used to enable emissions reductions.

The report examines what data the UK oceanographic and wider international user community currently acquires, using both ship-based methods and those not requiring ships. This builds on Work Package (hereafter WP) 1, as well as the Framework for Ocean Observing (FOO) Essential Ocean Variables (EOVs), and direct input from stakeholders as Workshop 4 within the NZOC project. It then examines how sensor, instrument and sampler systems could be used to reduce carbon as a contribution to achieving net zero, both now with existing technology, but also into the future. This includes a gap analysis, and recommendations on how these could be addressed (see §4.3). This includes a discussion of the extent of the work required and the skills needed.

Because of the carbon intensity of ship operations (see §7) vs other methods the focus has been on technology that could obviate the use of research ships, either fully or in part, without losing the extent, quality and flexibility of ship-based operations. This includes consideration of the serendipity and dynamic multidisciplinary often experienced in ship-based research and how this could be achieved in a different way. The report includes analysis of opportunities that are enabled when technologies replacing ship-based capabilities are used instead of or in addition to ship-based measurements such as increased temporal and spatial resolution, event detection and distributed synoptic measurements.

To calculate the carbon savings for each technological development and adoption the results from WP1 and further requirements capture were used to estimate the need (type and amount) of measurements / experiments required. An estimate of carbon utilisation to meet this requirement has been developed for each requirement for a low carbon delivery strategy and compared with the status quo (ship based with some operational efficiencies and resource / infrastructure sharing).

These results have been combined with cost, risk and timescale estimates for sensors, sampler and instrument technology developments to produce a prioritisation of technological developments and an estimate of the scale, cost and risk of concomitant carbon savings.

A first pass at this analysis is provided in this report, but we recommend refinement for greater accuracy and fidelity by wider peer review, engagement and repeat of this process at greater fidelity.

It is also acknowledged that this report would be improved by wider engagement and refinement both in terms of the definition of the requirements for the Oceanographic Capability *and* the technologies to deliver against this requirement. We recommend an ongoing dialogue to:

1. formalise the agreed requirements of the capability (type and amount of measurements and experiments required)
2. refine and agree a technology roadmap which encompasses adoption of existing technologies, those that are likely to result from other development programmes (such as the offshore industry) as well as those that should be developed to specifically address the requirement.
3. Enable focused effort (e.g. workshop or preferably establish an expert working group) on areas were the authors did not have deep technical knowledge:
    a. acoustic sensing technologies which would improve estimates for their role cutting carbon in mapping and biological observing in particular, as well as other applications.
    b. Seismic and sub-seabed imaging
    c. Large seabed sampling, drilling and coring technologies

However, the report does include input from domain experts in each of these categories not least through input at NZOC workshop 4. This has enabled some estimates of future trends and contributions to net zero for each of these technologies.

Annexes for this report include:

1. an excel file listing all requirements (variable or capability needed) gathered during assembly of this project together with an assessment of the current state of the art, remote sensing / satellite method (where appropriate), technology in development, state of the art for / using autonomy, ideas (with cost and time estimates), challenges / barriers (risks) and notes from the NZOC workshop 4
2. A summary of insights / inputs gained from NZOC workshop 4 by discipline / focus group.

This report also considers interactions with the outputs of other work packages notably:

1. WP4 (Autonomous Systems): if autonomy is to replace ship-based observation in full or in part, this will change the sensors, samplers and instruments it must carry and this has an impact on the design of autonomous systems. For example, they must be able to support a

multidisciplinary measurement package with increased data, size weight and power requirements compared to the state of the art; and must be able to operate in complex environments performing sophisticated sampling and intervention activities as well as more traditional measurements.

2. WP 2 (legal and regulatory): regulations both drive requirements and define constraints for operations. This includes the design of measurement systems. For example, radioisotopes are currently used in incubations and rate measurements onboard research ships but permitting this on autonomy under the current legal framework remains a challenge.
3. WP 6 (data): Autonomous instrumentation presents opportunities and challenges for communication and data systems. Whilst the data rate of many sensors is low (~80 bytes / hour for many chemical sensors) some generate enormous data sets (TB for some imaging and sonar systems). There are opportunities for data reduction with AI and ML and implications for application of best practice on the design and operation of the measurement systems.

1.2 Net Zero Definition

The IPCC / GHCP(Greenhouse Gas Protocol, 2021) establishes three scopes of emissions which are briefly:

1. Scope 1: direct GHG emissions produced during operations
2. Scope 2: energy input indirect emissions (e.g. from consumed electricity, heat or other external energy source)
3. Scope 3: other indirect emissions (e.g. embodied carbon from manufacture, transport and logistics)

Unlike other chapters in this report, this chapter considers (using published average emission rates and estimated activity), scope 1, scope 2 AND embodied carbon (part of scope 3) within its calculations and comparisons of contribution to Greenhouse Gas (GHG) emissions (see § 6) as this is instructive for comparing the true carbon impact of possible futures. It also considers logistics (crew and scientist flights, equipment shipping, mobilisation and demobilisation; part of Scope 3) carbon emissions with current practice but excludes these from all but overview comparison between ship and non-ship systems because of the scope for optimisation beyond current practice.

The economic case for achieving Net Zero through purchasing carbon offsets, which would in time stimulate external carbon negative activity (such as: reforestation; Carbon Utilisation; or Carbon Capture and Storage) is made and compared to payback periods for carbon cutting innovations at an assumed rate of £200/tCO2e based on projections to 2035 of the current EU ETS price and projections by the carbon trust.

"Analysis by the UK government's Department of Energy and Climate Change and the Carbon Trust estimates that in a scenario where warming is limited to less than 2 degrees, the global price of

carbon is expected to converge at $140 per tonne of CO_2 by 2030 and $400 by 2050. In a 1.5 degree scenario these costs would be considerably higher." (Carbon Trust, 2015)

Currently carbon trades at approximately €50/tCO_2e (EU ETS daily, July 2021) with the UK recently setting up its own ETS.

By estimating the comparative carbon impact of differing activities and technologies, and the cost savings vs purchase of carbon credits to achieve Net Zero, this report is able to identify a prioritised list of innovations that address the requirements of stakeholders and users.

1.3 Method

This report took as inputs the following

1. Requirements for oceanographic capability (now and to 2035): These have been established using the outputs of WP1, analysis of BODC cruise archives and data, by reference to the Framework of Ocean Observing / GOOS "Essential ocean variables" schema, the Marine Strategy Framework Directive (MSFD), OSPAR and by refinement with direct engagement of stakeholders (directly, and via NZOC workshop 4).
2. Current technologies and methods for delivering capability to meet these requirements (both ship-based and other) together with estimates of their ability to meet each requirement. These were gathered using the same data sources as above, with the addition of analysis of Ocean Best Practices, published information and domain experts in a range of technologies (directly and via NZOC workshop 4).
3. Technologies currently in development to address gaps in this need, their current maturity, the cost and time needed to develop them, and the extent to which they address requirements. Information was gathered as above
4. Ideas for technologies that could be developed to address remaining gaps if shipping availability were reduced together cost, development time, current maturity and ability to address requirements. Information was gathered as above
5. Estimates of carbon costs for construction and operation of different oceanographic capability (see §7)

This information is gathered in the excel file a copy of which was circulated before NZOC workshop 4 and was available on a google drive for edit. Subsequent to workshop 4 community input captured in the workshop notes was transferred to this file also. Additional findings from the workshop can also be found here. An explanation of how this model was constructed together with some plots of comparison of delivery mechanisms emissions can be found in §7.

2 Baseline Review 2020

We identified 68 distinct measurement requirement categories (see sheet "EOVs" in the excel file for detail), most with many subvariables (for example nutrients consists of 5 subvariables, Inorganic carbon has 4 major subvariables, MSFD/OSPAR pollutants number over 2700). Almost all of these requirements are addressed at least in part by current ship-based capability. In contrast current non-ship technologies do not address a number of requirements adequately, and in some cases at all. Considering the extent to which each requirement is met we estimate that current ship-based capability fulfils 61% of the required capability, whereas current non-ship based capability could fulfil approximately 42% of the requirement. Therefore, without mitigating actions, such as the development proposed by this report, the loss of research vessel support would have a significant detrimental effect to the UK oceanographic capability. It should also be noted that currently non-ship systems are not delivering 42% of the operational capability, this is instead the estimated maximum using current technologies. The reality is that a significantly lower amount of the capability is currently delivered without a ship. The reasons for this are numerous and include:

1) User satisfaction with ship-based approaches
2) Lack of confidence in the user community that sufficient measurement quality will be obtained
3) Lack of evidence (e.g. demonstration missions alongside tradition ship-based measurements) of the efficacy and quality of low carbon approaches
4) Lack of maturity (technology readiness level) of key technologies
5) A number of measurements are virtually impossible without a research vessel with current technologies.
6) Lack of a coordinated UK wide effort of significant scale dedicated to addressing a wide requirement base: current projects tend (with some notable exceptions; e.g. Oceanids sensors projects) to focus on the development of niche technologies, or support specific scientific disciplines.
7) Limited leverage of existing technologies for other requirements (e.g. coordinating machine learning and automated processing of images for both seabed mapping *and* pelagic species taxonomy and population studies).
8) Limited measurement system SWaP (Size Weight and Power) supported by existing autonomy and non-ship systems

Current technologies that are mature or approaching maturity but remain underutilised include:

- eDNA / particle samplers for a wide range of biological and particle rate studies
- Autonomous water samplers for a wide range of chemical and microbiological studies
- Time Resolved Fluorescence primary productivity measurements
- AI/ML assisted taxonomy (pelagic and benthic over wide size range) and benthic habitat characterisation using images
- Active and passive acoustic sensors for biology (e.g. fish, zooplankton)
- Acoustic and data tagging of marine species to examine populations, migrations, behaviour and physiology
- In situ cytometers / particle imaging systems for microbiology, zooplankton and particle studies

- GNSS and met system enabled surface autonomy for surface flux and sealevel studies
- In situ chemical analysers (nutrients, carbonate, metals) both surface and subsurface
- Autonomously deployable geophysics instruments including Ocean Bottom Seismometers, Marine Vibrator and Electromagnetic sources, and autonomy towed streamers / detector arrays (including coordinated arrays with multiple vehicles).

Wider optimisation and use of these existing technologies present an opportunity for the proposed programme (see §9)

3 Outputs from community engagement

A summary of the discussion and findings from the community engagement (mostly through NZOC workshop 4) can be found here. The principal findings /views of the community were:

1. The community is aware of the considerable gap between their requirements and the capability of measurement system enabled non-ship and low-carbon observing capability and is therefore aware of the development challenge and keen to maintain access to crewed multirole research vessels and the free at point of use model.
2. The science that can be done, and therefore oceanographers' career directions and methods are to some degree determined by the capabilities, strengths and weaknesses of current research ship dominated capability. This can provide a source of resistance and scepticism towards change.
3. There was enthusiasm for non-ship / low-emission systems to provide data with greater persistence and at higher temporal and spatial resolution than possible with ship-based capability.
4. There are a large number of technologies envisaged and in development that could fill gaps in measurement abilities in a low carbon capability. These have been recorded in the roadmap (§9) and excel file.
5. Identified gaps included metrology quality of autonomous measurements (e.g. addressing drift and in situ calibration of current conductivity sensors) as well as currently unaddressed requirements.
6. There remain concerns about reliability of autonomous and non-ship observing systems.
7. It was articulated that current funding for marine measurement technologies was insufficient and structured / reviewed in such a way that it was hard to compete with projects with more immediate scientific rather than operational impacts.
8. A number of hard to address requirements with low carbon capability were identified (see §9.4)
9. A growing challenge is the likely need to stop disposal at sea of instrumentation, e.g. the Argo Float array. This would suggest low-carbon recoverable systems are required and this has an impact measurement system design.
10. There are a number of excellent technologies, such as animal tags and some instruments, that are operated outside of the NERC oceanographic capability / national marine facilities.

These have been incorporated in the technology development roadmap and existing technology should be considered for inclusion in the new operational capability.

11. There remains a need to assemble expert user groups as well as technologists to: explore the development of measurement requirements; examine potential technological and operational solutions; and to work together to realise new low-emission technologies and capabilities that are fit for purpose. This incudes in areas where greater representation of particular disciplines within the NZOC project would have been beneficial.
12. Many stakeholders recommended that before ship-based capability is reduced lower emission technologies are used alongside traditional approaches to provide time for confidence building, performance assessment, continuity of datasets and where required design and operating procedure changes / optimisation.

4 Horizon Scan to 2020-2035

The requirements articulated by ocean capability users change relatively slowly with most measurement needs persisting over decades and in many cases centuries. Whilst new scientific ideas and disciplines do lead to change, technological opportunities are often the engines of change in requirements. These can enable new methods to improve delivery against existing measurement requirements (e.g. the advent of eddy covariance measurements for flux studies, cavity ringdown spectroscopy for gas composition including isotopes) as well as opening up new areas of study (e.g. biotechnology to examine the role of functional genes and diversity in the environment). To keep pace with these significant but modest changes in comparison to the existing requirement, there is a continuing need to innovate and accommodate new approaches. Tactics to enable this include the following, which have been included in our suggested roadmap:

1. The development and use of sampling and sample preservation technologies amenable to new sample analysis technologies and requirements
2. A programme of continual technology development
3. Marinization of technologies proven in terrestrial, aerospace or laboratory settings etc. so that they can be deployed in situ
4. The use of larger platforms, including low-emission surface vessels that present similar environmental and metrology challenges for measurement technologies to that of a research vessel. Hence minimising the impact on measurement system capability by a change in platform type.

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 approximately 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.

This is despite there being a wealth of measurement system research and development for other applications (see §5 and §6) this tends to be either at low technology readiness level (e.g. through EPSRC research) or when more mature directed at commercial or other scientific / healthcare applications. In both cases considerable R&D is required to apply these technologies to oceanographic problems and to achieve technological maturity so that operations are enabled. However, this adaptation and “marinization” of innovations made elsewhere has been a successful strategy and numerous projects are ongoing of this character. Examples include: Artificial Intelligence and Machine Learning (AI/ML) for image processing, classification and / or taxonomy; application of molecular assays such as PCR and genome sequencing.

Currently individual technologies are developed in isolation and with relatively small teams, the exception being coordinated efforts through European (e.g. Horizons 2020) funding, but even with these large projects genuine collaboration is limited as even in large consortia addressing multiple requirements each of the institutions can only participate in the development of relatively few technologies because of the relatively small scale and duration of the funding. This results in a typical advancement of technology readiness levels of 2-3 years per TRL at a cost of typically £300-500k per TRL. Whilst improved cost efficiency and progress is possible (see §9) similar progress is likely if the current R&D and operational status quo is maintained.

Whilst other sectors do make advances that have significant impact on marine science (see §5, for example the analytical chemistry and biochemistry industries) it is rare for those technologies to be immediately applicable to in situ marine measurement. For example, the biochemistry and biotech industries’ developments of molecular diagnostic assays, such as PCR and isothermal Nucleic Acid analysis assays, have widespread applications in biological and biogeochemical oceanography. Yet these industries do not have the business drivers to develop in situ systems that can acquire and preserve suitable samples of Nucleic Acid from seawater, nor is there a driver to develop technologies that can perform these analyses in situ. The dedicated environmental metrology sector servicing sectors that overlap the oceanographic requirement are relatively small, or do not have oceanography as their key driver but nonetheless will make a contribution to improved oceanographic capability to 2035. These contributions are included in this assessment.

Efforts could be made in the period 2020-2035 to improve uptake of existing technologies, and the incremental developments that occur. This should include confidence building with, and improved use of, current / existing sensor, sampler and instrumentation technologies in non-ship systems. To better use existing technologies a number of approaches could be applied including:

1) Systematic integration, trials and demonstration of new measurement systems in existing low carbon observing platforms (e.g. Autosub long range, Saildrone (all variants))
2) Improved engagement of the user communities in optimising and adopting new technologies, particularly in trials, performance evaluation, suggested improvements and best practices for operation to support appropriate disciplines.

3) Opportunities that support the use of reduced emission oceanographic capabilities alongside current benchmarks to verify performance and demonstrate advantages.
4) Increased opportunities for use of reduced emission oceanographic capabilities for operational data acquisition.
5) Greater use of larger low carbon platforms (e.g. Saildrone Surveyor, Hugin Superior) which can support measurement systems with greater SWaP (Size, Weight and Power) which translates into a greater number of deployable measurement systems within this relaxed constraint.
6) Other constraints / requirements that could be relaxed to enable greater use of existing low emission technologies and approaches include service intervals / deployment durations and environmental conditions. For example, systems unable to operate for multiple years in freezing conditions, the tropics or in storm conditions could nonetheless meet a great deal of the oceanographic requirement.

4.1 Data Requirements

As detailed in §2, we have assembled a list of 68 categories of measurements / oceanographic capability requirements, each typically containing a number of subvariables and often supported by other measurements. This extensive requirement is recorded in the sheet "EOVS" in the associated excel file.

Whilst not the focus of this work package, there are a number of data challenges associated with an expanded low-carbon observing system, that is likely to include an increased use of drifters, moorings /observatories, autonomy, animal tags, small vessels and ships of opportunity. These include:

1. Local storage, in situ processing / compression, transmission, FAIR curation, and interpretation / visualisation of very high data volume instrumentation including:
    a. Turbulence and microstructure measurement
    b. Images
    c. Sonar, seismic and acoustic sensors
    d. Nucleic Acid sequencing
2. A larger volume and more continuous supply of data matched with a requirement for users to have near real time access to raw and quality-controlled data
3. Re-tasking of autonomy, and particularly remote operation (e.g. of an ROV deployed from an Uncrewed Surface Vessel) will require low-latency communications for both returned data *and* control of assets.

Potential solutions identified during this project include:

1. The use of simple unique identifiers for instruments and platforms, together with shorebased storage and curation of metadata (e.g. calibrations, use histories, capabilities, service records) to enable low-bandwidth systems to associate data with its metadata. This

is in preference to local (on the instrument) storage and onward transmission of metadata which would lead to transmission and energy inefficiencies

2. The use of data compression, Artificial intelligence, Machine Learning and other in situ data processing to reduce the bandwidth required for information communication. E.g. AI / ML image and sonar feature extraction or taxonomy.
3. The use of automated ingestion and processing of data (utilising standard formats, translators, and the above metadata approaches).
4. High bandwidth links using existing technologies including: satellite communications; fibre optics (seabed and between vehicles); through water optical / EM comms; acoustic modems and data buoys.
5. The use of high-performance computing and advanced data visualisation tools / suites to enable improved observation and understanding of the data, as well as real-time control of oceanographic capability assets.

Further discussion of data aspects can be found in the summary and WP6 reports.

4.2 Interconnection of Different Technologies

Interconnections between measurement technologies, and between measurement, platform, modelling and data systems technologies and their adaptation to a low-emission capability include:

1. It is normal practice, and an increasing trend, that many measurement requirements are made simultaneously in multidisciplinary ship-based expeditions and experiments (see WP1). To replace this capability non-ship systems (moorings, landers, drifters, floats, autonomy) the non-ship systems would either need to carry significantly greater measurement systems payloads than the current NMEP MAS fleet, or multiple platforms would need to be coordinated to enable measurement and sampling of all the required variables.
2. Whilst a lower emission research vessel could carry larger payloads, especially if crew / scientist complement is reduced or eliminated using autonomy, its total payload will be smaller due to the lower energy density of ammonia, or deck / hull space required for renewables (sail, solar, wave). The resulting drop in capability could be offset by carrying more compact instruments, or developing lower footprint Launch And Recovery Systems (LARS, e.g. modular or with submerged platform) that could be used by multiple measurement / sampling systems (e.g. one LARS for ROV, Corer, AUV and Rockdrill capability). This would likely save operation and capital costs as well as enabling greater capability and should be considered for both crewed and uncrewed surface vessels.
3. Whilst there have been notable exceptions, e.g. the development of ISFET based pH sensors, and oxygen optode technologies (both produced outwith oceanographic technology development and then adapted to those requirements), miniature solid-state approaches for remaining variables remains a distant prospect which are unlikely to be achieved within the period to 2035. The technologies proposed (§9.3) would require significant

measurement system payload capabilities if used to address multiple requirements. This couples to the design and coordinated use of platforms.

4. Some of the technologies proposed (for example intervention / experiment technologies (e.g. for incubations) and targeted benthic sampling) require an element of intelligent control. This could either be achieved with improved telecommunications or with enhanced artificial intelligence, both feasible if challenging and outwith the WP5 remit. The development of such capability will need input from the instrumentation, platforms, communications and AI communities (as well as engagement of users and stakeholders).
5. Some systems (e.g. active and passive acoustics, benthic and pelagic imaging) produce large raw data sets (some are measured in TBytes) which need in situ processing / information extraction, and / or data compression, and or enhanced bandwidth telecommunication links. This collective need could enable some cost / resource / time efficiencies if development was coordinated and shared across the development of these technologies. See also §4.1

4.3 Gap Analysis

As described in §0, community engagement, literature survey and commissioned reports (see WP1) all contributed to a comprehensive review of requirements and current technological capabilities. This provided a framework to numerically assess the gaps between stated requirements and the ability of both current and future oceanographic technologies to address these. Table 1 lists requirements where there would be a capability gap. As discussed in §2 current utilisation of low-emission approaches is significantly lower than the potential and hence in reality the current gap of non-ship operations compared to mature and high-quality ship operations is considerably larger.

Table 1 List of requirements where non-ship systems currently have an inferior ability to address these. This is ordered by size of the capability gap.

Requirement	gap between current ship technology and low emissions approaches
Freedom of navigation demonstration	100%
rock and sediment samples / analysis	95%
other stable isotopes	90%
experimental and intervention capability	80%
pore water analysis	80%
Transient tracers	80%
Halocarbon / organic gas analysis	75%
Iron	70%
Rock or Sediment / core isotopic analysis	70%
Sediment / core fossil / paleo biological record	70%
Oxygen and nitrogen isotopes	65%
Viruses, symbionts and communities	65%
Particulate matter	60%
Rock or Sediment / core (bio)geochemical analysis	60%
activity of genes	55%

Description and molecular analysis of new species	55%
Biomolecular analysis and bioprospecting	50%
Microbe biomass and diversity (*emerging)	50%
multidisciplinary lab	50%
multidisciplinary long term datasets	45%
Nitrous oxide	45%
Aquaculture medications	40%
biological and biogeochemical rates	40%
Invertebrate abundance and distribution (*emerging)	40%
Biotoxins	35%
Pathogens	35%
ecosystems	35%
Benthic impact	30%
E.coli	30%
particle rates	30%
Stable carbon isotopes	30%
Fish abundance and distribution	25%
MSFD Physics / habitat	25%
surface and sediment fluxes	25%
Contaminants	25%
Dissolved organic carbon	20%
MSFD chemistry / pollutants	15%
Harmful Algal Blooms	15%
Phytoplankton biomass and diversity	15%
MSFD species	15%
Zooplankton biomass and diversity	15%
multidisciplinary command and control / community	10%

4.4 Known Unknowns

As noted above, this project has established a framework and first pass at the estimation of oceanographic capability requirements and technological response to achieve Net Zero emissions. A mechanism of updating and adding detail to both the requirements and technology roadmaps will be required if the proposed roadmap is undertaken in full or in part. These issues are addressed in further detail below. The response to these issues are listed in §9.7

4.4.1 Accurate estimation and forecasting of requirements

Whilst WP1, analysis of BODC holdings, published papers and cruise reports and peer review and input has enabled us to establish a comprehensive list of oceanographic and stakeholder requirements there are likely to be omitted requirements. In addition, we have attempted to estimate the amount of data required for each requirement by stating an equivalent annual cruise track (in km) for each requirement. This was particularly difficult to estimate with disparate and contradictory sources and opinions and therefore we expect this value to have the largest error in our analysis.

4.4.2 Accurate costs and duration for the development programme

Despite the engagement of many experts in the relevant fields, it has not been possible to definitively define the costs and durations of the technology development programme. This is perhaps not surprising given the extent of what is proposed. We recommend the wholesale adoption of current state of the art technologies, equating to at least 10 classes of currently under utilised technology (see §2) as well as the development of 60 less mature (average TRL 5.2) classes of measurement or sampling technologies (see Table 2). This task has been further complicated by activity in other sectors (see §5 & 6) as well as existing funding and likely future funding from other sources that offset the total cost. Further, accurate costing of technology development programmes is notoriously difficult (in all sectors, but including ocean technologies) especially when there are hard defined success criteria / outcomes such as is the case to achieve Net Zero *and* to match the capability of current ship-based provision. To account for this we report costs with an error margin of up to ~250% a value developed based on expert judgement / experience and peer review input.

The timescale and sequencing of development could not be accurately predicted within the time and resource constraints of this project. Instead the duration of each technology development was estimated assuming it was progressed in isolation and using expert judgement. This will require further refinement. In reality availability of resources including suitably qualified engineers and technology developers, and engaged users / stakeholders as well as risks and setbacks R&D will impact likely lead to longer durations than currently recorded. However, it should be noted that we estimate that most technologies would reach maturity within 5 years, and all within 7 years in an uplifted R&D programme, which matches well with a timeline of 14 years to predicted ship-replacement in 2035.

4.4.3 Appropriate use and development of some technologies

Further input from experts in Seismic / Geosciences, Acoustic and AI / ML technologies would improve the optimal deployment of these technologies to address requirements. Despite excellent engagement in the workshop from experts, the size of the challenge associated with use of large rock drills and corers with reduced research ship capability future suggest that this area would also benefit from further specific expert input.

4.4.4 Programme of platform development

The proposed roadmap has been developed in discussion with WP4 and with reference to existing and emerging solutions for low-emission platforms. However, the development of measurement systems and the platforms that carry them are intrinsically linked and will need to be co-developed. See §9.7 for details of further work to address this issue.

5 Review of Commercial Priorities and Opportunities for Collaboration

Opportunities for collaboration with, or benefitting from activity in the commercial sector are numerous. A full mapping of these opportunities should follow refinement of the requirements and technologies roadmap. However, a non-exhaustive list where there are activities in the community includes:

1. Development and commercial supply of oceanographic technologies in both the UK and beyond. There are opportunities to accelerate these development efforts in partnership as well as through direct purchase. These technologies include
    a. Fluorometers for both miniature platforms (e.g. Valeport Ltd) or for measurement of primary productivity (e.g. Chelsea Technologies Ltd).
    b. Sensor suites for the Bio-Argo programme including optical sensors for transmission, backscatter and nitrate as well as pH (currently electrochemical / ISFET sensor)
    c. Optodes including for profiling (e.g. Aanderaa Ltd.) for incubations (e.g. Presens GmbH) and benthic profiling (e.g. Pyroscience GmbH, Unisense A/S)
    d. Plankton imaging systems (e.g. Sequoia Scientific inc, Hydroptic SARL)
    e. Benthic imaging and image processing systems (e.g. Sonardyne International)
    f. Cytometers (e.g. Cytobuoy b.v., MacLane inc.)
    g. Sampling systems (e.g. MacLane inc.)
    h. Reagent based Chemical Analysers (e.g. Satlantic / Seabird Electronics LLC, Systea S.p.A., ClearWater Sensors Ltd.)
    i. Remote /autonomously deployed ROV and intervention technologies (e.g Armada, Ocean infinity) which may require adaptation to low-emission platforms (currently diesel electric but could be ammonia or renewable powered).
2. Development of technologies that could be adapted to oceanographic requirements
    a. Molecular and biotechnology technologies including
        i. Point of care diagnostic platforms (for molecular and whole cell targets) that could be converted / adapted to in situ or surface autonomy based measurement
        ii. Isothermal nucleic acid analysis (e.g. RPA or LAMP) assays that are potentially easier to apply in situ than higher temperature PCR
        iii. Recombinant antibodies, affimers or aptamers that can be used to recognise target chemicals such as biotoxins, pollutants
        iv. Sequencing technologies (e.g. Oxford Nanopore or Illumina) that could be adapted for remote or even in situ operation
    b. Current laboratory instrumentation with potential to be ruggedized and applied in the field or in situ (e.g. submersed)

i. Mass spectroscopy (in situ MIMS system already exist albeit with high SWaP and reduced functionality vs laboratory systems)
ii. Optical systems including Cavity Ringdown Spectroscopy, IR spectroscopy, Raman Spectroscopy and LIBS
iii. High Pressure Liquid Chromatography (HPLC), Ion Chromotography, Gas Chromatography and other separation sciences
iv. Numerous colorimetric, fluorescence and luminescence based analytical assays

3. Alignment of requirements in a variety of sectors that could enable co-funding or joint development programmes to offset resource impacts
    a. Aquaculture and fisheries industries for example with commercial drivers to measure and mitigate harmful algal blooms, parasites, pathogens, feed waste and environmental impacts which may feedback to permitted and optimal stocking / profit.
    b. Offshore industries including energy and Carbon Capture and Storage who require measurement technologies to monitor and locate operations.

6 Review of Other Stakeholder Priorities and Opportunities for Collaboration

Non-commercial actors in this space include

1. Regulators (UK and beyond) in aquaculture, fisheries and terrestrial water management for both research and compliance assessment with regulations (e.g. on nutrient or other chemical loading, benthic impacts, waste treatment efficacy). There are examples of existing collaborations
2. Funding agencies with overlapping remits (there are examples of previous partnership within this space for each) for example:
    a. EPSRC would be an appropriate partner *if* the R&D programme was at low (<TRL4 typically) *and* the technology had significant applications outside of environmental or natural science.
    b. BBSRC particularly in biotechnologies, pathogen and parasite detection or optimisation of water quality to promote sustainable food production.
    c. Innovate UK where there is engagement of industry (particularly but not only SMEs) or preferably industry leadership
    d. EU / Horizons Europe which already funds extensive oceanographic and aquaculture / fisheries and agricultural technology development particularly with the aim of reaching higher TRL and commercialisation
3. Charities, foundations and philanthropic organisations. E.g. Schmidt Ocean Institute

7 Carbon Calculation

Emission calculations included references for values used can be found in the associated excel file and in the tab "carbon calcs" and "flights and logistics" in particular. Broadly this uses published emission rates for energy, operations, logistics and manufacture together with estimates of platform operations to address scientific requirements to calculate and compare the carbon impact of different scenarios. The absolute numbers are not accurate, but do show clear trends, and are surprisingly close to published values in some instances as they have been developed bottom up, largely without calibration.

This report calculates the greenhouse gas emission impact of the oceanographic capability by computing the equivalent weight of CO_2 (i.e. CO_{2e}) under the following scenarios

1) Business as usual (Marin Gas Oil powered vessels providing the majority of the capability)
2) Business as usual but using ammonia as a fuel which has been generated using renewable energy. These figures are based on published scope 1 and 2 emissions for ammonia and best in class (offshore wind) renewable energy carbon costs.
3) Delivery of the capability using autonomy / without the use of ships using *primary* batteries
4) Delivery of the capability using autonomy / without the use of ships using *rechargeable* batteries recharged with renewable energy.

These estimates include both the scope 1 and scope 2 emissions as well as the embodied carbon for manufacture of both ships and autonomous systems (part but not all of scope 3). This includes calculation of the carbon cost of batteries (both primary, i.e. single use, and rechargeable batteries). These scope 1,2 and embodied carbon figures are used to calculate emissions per km surveyed (Figure 1) and to delivering the defined capability on an annual basis (Figure 2). It should be noted that travel and logistics for all options has been calculated, but is *excluded* from the calculation of emissions as above. This was excluded from the comparative analysis because there are significant opportunities to improve this element over current practice. A simple model based on emission average values for personnel flights and sea freight logistics results in an approximately equal impact per km of ocean surveyed for all platforms (~3kgCO2e/km for ships, ~2kgCO2e/km for autonomy). However, the impact of logistics is significant on the total emissions to achieve the capability as shown in Figure 3. All other remaining calculations and results do not include logistics.

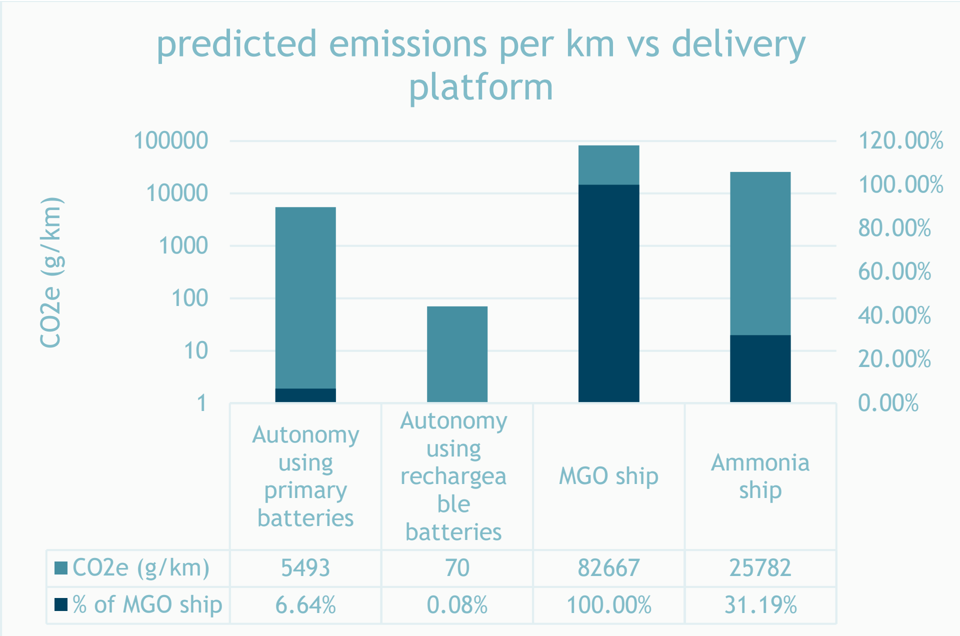


Figure 1 Bar graph and table of predicted emissions (per km) of different delivery platforms

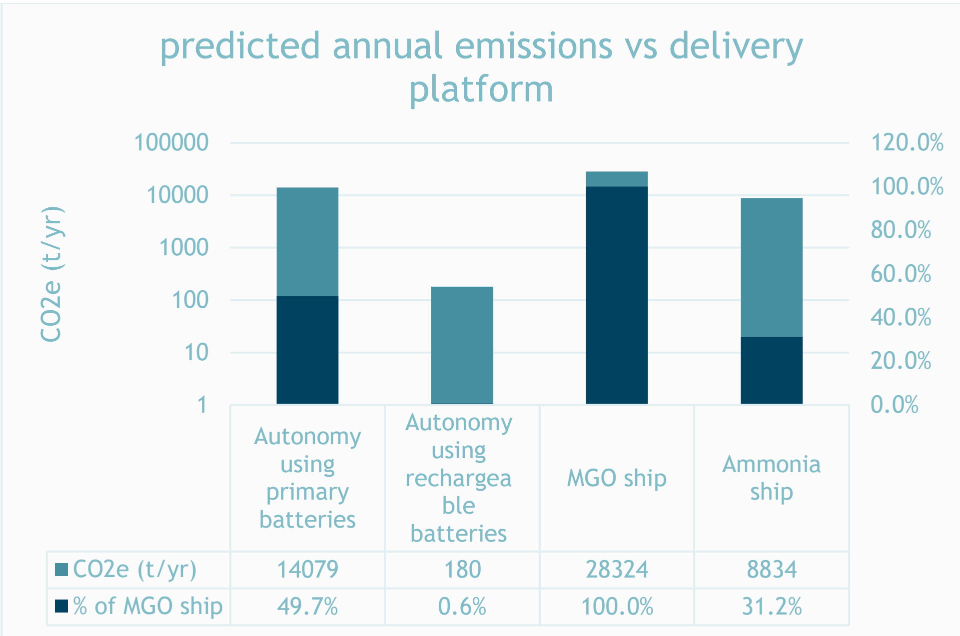
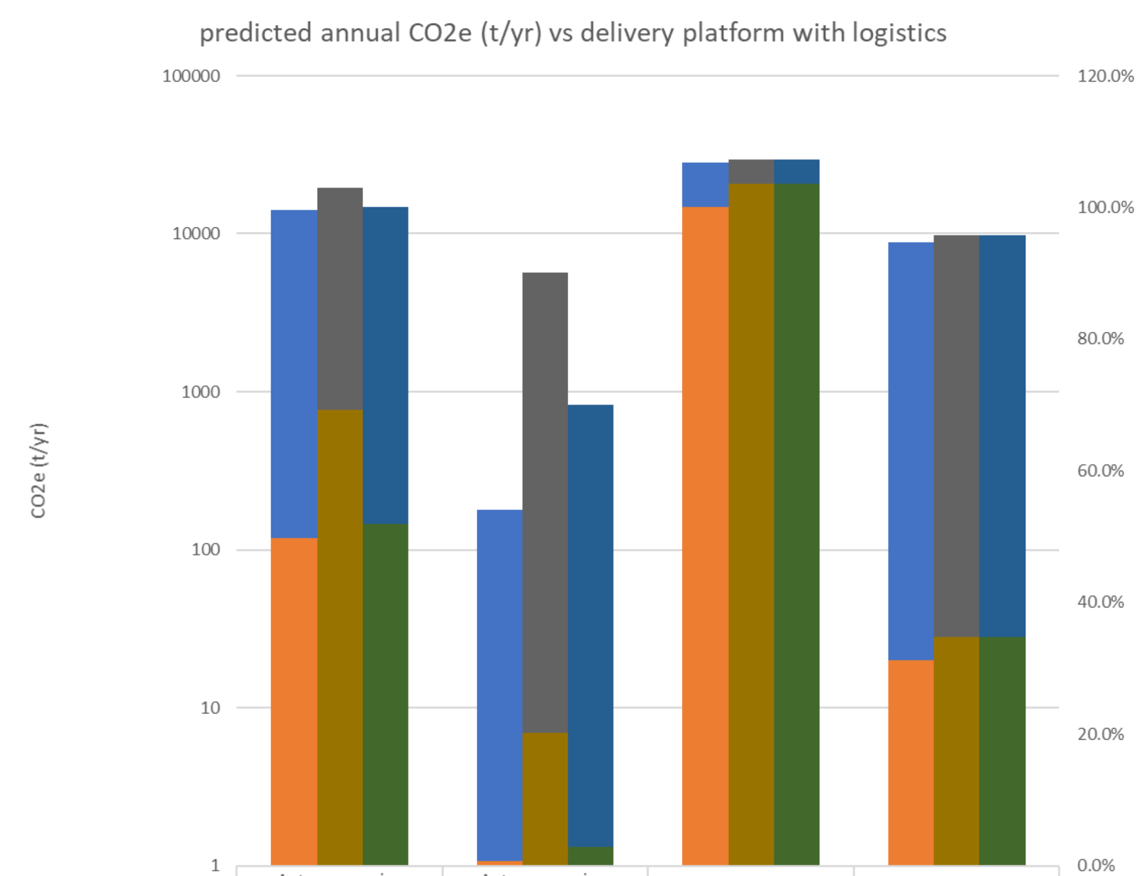


Figure 2 Bar graph and table of predicted emissions vs delivery platform per year of optimal operations



	Autonomy using primary batteries	Autonomy using rechargeable batteries	MGO ship	Ammonia ship
CO2e (t/yr) no logistics	14079	180	28324	8834
CO2e full logistics	19595	5696	29339	9849
CO2e remote ops	14722	823	29339	9849
% of MGO no logistics	49.7%	0.6%	100.0%	31.2%
% of MGO full logistics	69.2%	20.1%	103.6%	34.8%
% of MGO remote ops	52.0%	2.9%	103.6%	34.8%

Figure 3 Bar graph and table of predicted emissions (CO_2e t/yr) vs delivery platform per year of optimal operations considering three different logistics options: 1) No logistics (logistics for equipment and personnel are omitted from calculations), 2) Full logistics (estimated using current practice of shipping equipment and flying personnel to some ports to enable the programme), 3) Remote operations (autonomy is freighted in a more targeted way (e.g. to existing field stations) and flights for on-site technical staff reduced in favour of remote (telepresence / operations hub) and existing on-site support.

The emissions implications of each requirement, current practice, and future technology adoption are all calculated. The central method is to estimate the quantity of a requirement (e.g. the requirement to measure sea-surface salinity) in terms of the annual track length required for each measurement (in km). The emissions associated with meeting this requirement are multiplied by the fraction of the platform this measurement requires (i.e. a measure of how many other measurements the platform can make at the same time improving its productivity to emissions efficiency) as well as the calculated emissions rate (CO2e (g/km)). These calculations are performed in the sheet “EOVs” which lists all the requirements gathered from WP1, the literature, and peer / expert input. In particular see columns Y (% of ship, i.e. how much of a ship does meeting this requirement occupy), Z (% of autonomy, i.e. how much of an autonomous platform does meeting this requirement occupy), AC (annual UK km required, i.e. an estimate of the required track length for this parameter), and columns AE to AF (computed total carbon for each platform to deliver on this requirement in t/yr).

For all calculations regarding autonomy, the NOC Autosub Long Range (ALR) is taken as the reference platform and therefore column Z (% of autonomy) can have values larger than 100%. For example, for coring and drilling operations a larger platform than ALR would be required, with higher energy requirements and hence emissions: this is represented by a value higher than 100% in column Z. This simplification enables the comparison of multiple autonomy options but hinges on the correct estimation of “ALR equivalents” required to support the measurement.

The emissions per km surveyed for each platform are calculated in the sheets “carbon calcs” and “ammonia”. These use published values for shipping (fuel consumption and CO_2e typically per tonne of freight or weight of ship per km), construction (embodied emissions, part of scope 3), ammonia production (scope 1 and 2 only) as well as known values for ALR. Values for the NERC vessels were not available to the authors at time of writing and instead we have used industry averages and published values for freight and commercial shipping. This likely leads to an underestimate of true emissions, but nonetheless enables comparison of different capability delivery scenarios. Values were also unavailable for the batteries in ALR: instead we used published values for commercial batteries, in this instance the Nissan Leaf battery as values for embodied carbon are available for this. We also assumed that the embodied carbon in primary batteries is similar to this battery. This is likely an overestimate, but anecdotally (no references available) the embodied carbon in primary lithium batteries is similar to rechargeable batteries. The differences in the emissions produced by different delivery strategies are so large that targeting these inaccuracies, though worthy, were not the rate limiting step for this study.

Emissions associated with logistics were calculated using estimates of the amount of equipment, number of staff travelling, and transportation distances for field work as well as published emissions for shipped freight and personnel flights. This is done in the sheet “flights and logistics”.

To compare the impact of new technologies we also record (from peer input and expert judgement) how well current ship based (sheet “EOVs” column S) and non-ship (column R) meet the requirement of the community. The impact of the proposed sensor, sampler and instrument development programme is also calculated (see input for sheet “technologies”) and transferred to column T of the sheet “EOVs”. The technologies sheet records proposed sensor, sampler and instrument technology innovations together with how much they could address remaining requirements after current non-ship measurement capability is accounted for. For example, the EOV seastate is already well addressed by current non-ship measurement technology (e.g. waverider buoys) and therefore the “gap” is only 5% (the requirement is 95% addressed without ships) therefore new technologies need to add value over this existing capability and can only close a maximum gap of 5% of the requirement. In many instances, even with new technologies there is a residual gap and this is recorded in column N. However, it should be noted that this is the gap vs the requirement, and not the gap after replacing ship-based measurement: ship-based measurement may have a gap vs the requirement also and this may be larger than for non-ship solutions. It is the ability to close gaps that is used to rank technologies in terms of contributions to emission reductions. This is done by computing the “carbon opportunity” which is the emissions required to meet the requirement with current ship-based capability *minus* the emissions using non-ship solutions. This is recorded in comparison to an ammonia and MGO fuelled ship in column O and P respectively and can be thought of as the potential emissions saving. The contribution of the new technologies to achieving carbon saving vs ammonia and MGO ships is recorded in columns S and T and are the product of the *carbon opportunity* and the contribution of the technology to close remaining gaps (“% meet gap”, column R).

The current TRL together with time and costs associated with the proposed technologies are recorded in the sheet “lists”. This information is used to calculate total spend, spend profiles, spend efficiency and hence prioritisation of technology developments.

8 Regulation of autonomy and scientific data

Regulation impacts measurement system design in a number of ways including:

1. Control of substances used in measurement systems such as radiotracers / radioisotopes and hazardous materials. It is not clear that such materials will be permitted to be used on autonomous platforms, whereas they are currently permitted for use on crewed vessels. Clarification of this position and likely future regulatory environments is required.
2. Regulation of scientific instrumentation which will impact design particularly with regard to:
    a. Safety at sea which will affect the size and character of platforms
    b. Accidental or deliberate disposal at sea which will affect design, materials used, cost and reliability targets.

9 Proposed Roadmap

9.1 Long-term Vision – key recommendations

The proposed programme would enable a considerable reduction in research ship requirement and a comprehensive move to low-carbon non-ship systems. This could be achieved within 5-7 years if resources and R&D were not rate limiting, and perhaps 10-15 with realistic research capacity constraints. We predict that the resulting capability would meet a greater proportion (~80%) of the users’ requirements than current ship-based capability (~60%) and would uplift from current (~40%) and project (45-50%) capability which is limited predominantly because of the availability of sufficiently performing measurement technologies.

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 updating
- 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)
- Technology Readiness Level 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)

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 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 to reaching out to other hubs and spokes, e.g. to induct new sensor technologies into the animal tagging programme to address additional requirements (e.g. animal physiology, measurement of EOVs required for context).

9.2 Outputs from the model

Principal findings from the **model** are given here. Assuming the proposed technology development were complete (and there is both cost and risk in achieving this) then the following may occur.

1) An improvement in addressing the requirements of the user communities from 61% addressed using ships or 42% using current non-ship technologies to 84% using the new technologies.
2) A reduction in emissions (vs MGO ship) of up to 99.4% (neglecting logistics emissions, >97% considering logistics, see Figure 3) may be possible if non-ship delivery mechanisms were used. However, this would require current practices of using primary (not rechargeable) high capacity batteries to be replaced with the use of rechargeable batteries as well as stopping current practices of deploying from MGO powered ships, and flying staff to field sites. Modes of operation where this could be achieved have been identified.
3) The costs of this change will likely not be less than ~£50M (the model predicts £50.5M) and, with experience of delivery rather than cost bounded projects, may raise significantly to >£100M. An expected transition cost of £120M would be prudent for planning purposes.
4) The transition costs (above) would be in addition to the capital and operational costs of running the new capability, but whilst these were not estimated in detail, it is likely that they would be less than continuing with high emissions research vessels especially when carbon costs are included.
5) In comparison to the cost of achieving net zero by continuing with MGO ships and purchasing carbon credits or using and emission trading scheme, the development

programme would achieve financial break even[1], if only applied to the UK capability after approximately 38 years (assuming a £200/t CO2e emission offset cost). Many technologies have shorter payback periods. 8 technologies would have a payback of less than 15 years and would address more than half of the deficit in capability of current non-ship systems vs the status quo.

6) Consideration should be given for the potential for these developments to enable lower carbon observing worldwide. However, these non-UK emissions savings are not included in calculations.
7) The change and associated development programme could be achieved in seven years with the majority of technologies proposed needing a 3 to 5 year development programme. The model did not consider the capacity of the development community to develop all of these technologies in parallel, hence the discussion in this report about that potential problem (see §9.5.1)
8) Without change in operational practices (primary batteries, significant flying personnel to field sites) non-ship operations may have a worse impact (only a predicted 30% saving vs MGO) than an ammonia fuelled ship (predicted 65% emissions reduction vs MGO)
9) Some requirements would be difficult to address and the solutions presented are thought to lead to a reduction in capability unless further solutions are developed. These are discussed in more detail in §9.4:

9.3 Proposed technologies and development programme

We propose a comprehensive uplift in the development of technologies to meet the measurement challenge from low-carbon systems. The technologies proposed are shown in Table 2. The mapping between requirements and technologies is expanding in Table 3. We recommend that this list is refined and fidelity improved by engagement of both users and technology developers (see §**Error! Reference source not found.**). The table also lists the number of requirements that the technologies address, the current TRL, the estimated carbon saving directly attributable to this technology vs an MGO and ammonia ship and uses this to compute a directly attributable payback period compared to no development and purchase of ETS / carbon credits at the assumed rate of £200/t (see §1.2). Note the use of directly attributable carbon savings neglects the additional savings resulting from using existing low carbon approaches using existing measurement systems. A development programme unlocks these potential savings also, because it is likely that existing non-ship systems will only be widely applied if *ALL* of the requirements of a particular expedition, experiment or campaign can be met without the use of a ship. Otherwise a ship will have to be sent in addition to the low-carbon / non-ship systems. The total carbon saving from obviating extensive ship use is predicted to be a factor of ~4.2 (potential savings using non-ship (vs MGO)/directly

[1] This calculation looks at how long it would take for the costs of development to be recouped from reductions in carbon credit / ETS purchases only: capital and operational costs of ships and non-ships are excluded from the analysis. This is conservative as

attributable savings vs MGO) greater than that directly attributable to individual technologies. Therefore, the payback period for the proposed development programme vs purchasing ETS / carbon credits and continuing with MGO ship capability, once the overall reduction in ship support requirement is considered, is predicted to be less than 10 years. However, this payback period would be extended with any increase in transition budget and could be as much as 22 years, or longer if costs of transition of platforms (WP3) exceeds ship replacement costs.

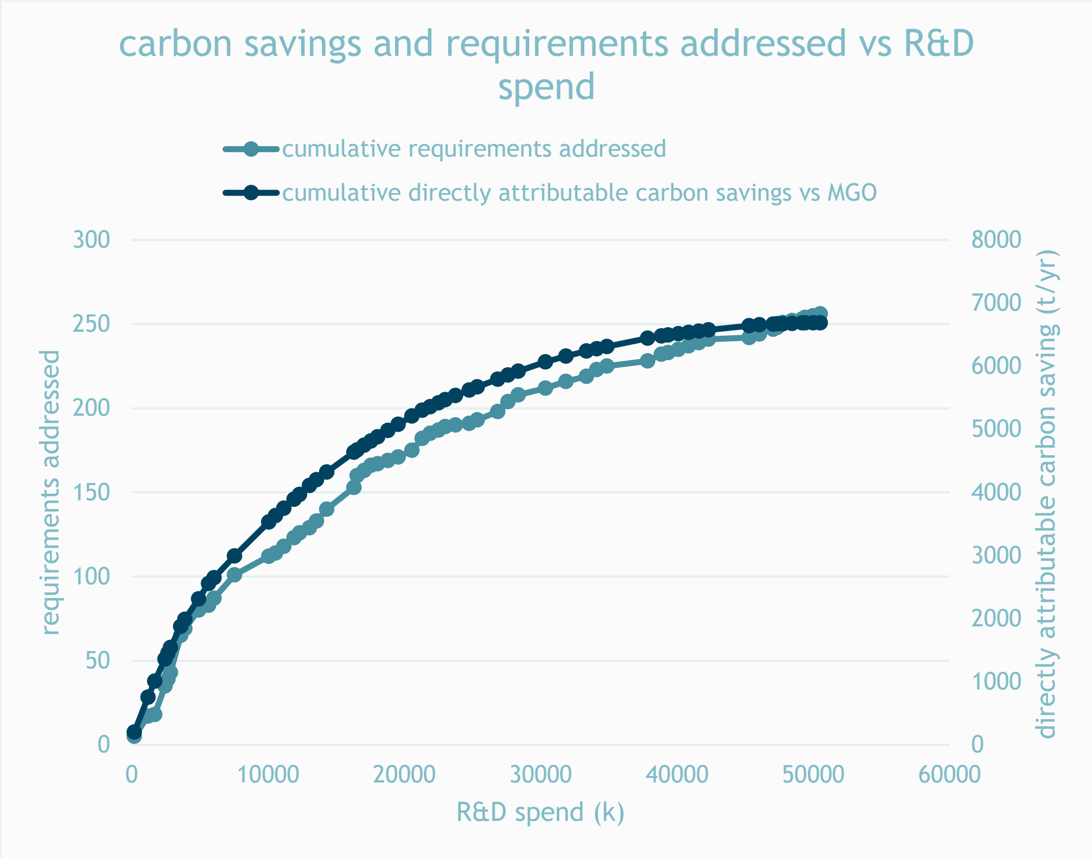


Figure 4 Graph of cumulative directly attributable carbon savings and requirements addressed vs R&D spend (proposed programme) assuming spend is prioritised by carbon saving.

The proposed technologies should be developed and used in addition to currently used and mature technologies as well as application of measurement technologies already sufficiently mature to begin integration in low-emission capability but which remain underutilised (see §2). For each requirement and technology we recommend a scoping exercise to add fidelity to cost, time, and achievable capability targets engaging both technology developers and users. The estimates below assume a level of existing funding (e.g. through EU, NERC National Capability and UKRI responsive mode) and have been adjusted to account for projects already funded or in progress.

There are a number of notable features in the list of proposed technologies when prioritised. This includes the prevalence of sampling technologies (water, particles, eDNA, sediment, rock) coupled with sample preservation. This tactic enables sample return to more capable terrestrial laboratories, or to onboard (crewed ship or advanced autonomy) sample analysis and therefore offsets the cost and risk associated with developing in situ sensor / analyser technologies to measure the same parameters. This presents some challenges in terms of feedback to assure that the correct sample or sample location was collected, and for preservation of short lived or delicate variables (e.g. oxidising organics, pressure sensitive biology or clathrates). These issues could be offset with in situ analysis where that is possible, analysis onboard autonomy and by ensuring preservation (chemical fixatives, antioxidants, freezing, maintained pressure etc.) is optimised for analytes of interest.

It is also notable, that some of the biggest emission saving opportunities are presented by technologies that can be applied to more than one requirement. This assumes that these technologies are developed in a coordinated manor to address a broad remit. This is not necessarily the case with current practice because of a lack of coordination. For example, AI /ML processing of images could address benthic species identification / taxonomy, pelagic macrofauna taxonomy, micro organism taxonomy over a wide range of scales, benthic habitat and condition mapping, litter / microplastic pollution etc. but currently is typically developed for each of these applications independently resulting in significant duplication of effort and missed opportunities for accelerated advancement.

It is also striking that the emission saving and payback period of proposed technologies is relatively uncoupled to the current TRL of the technology. For example, an autonomous intervention and sampling capability is only at TRL 3, yet could address multiple requirements leading to a significant (ranked 2) emission saving and relatively short payback period. This technology has not been explored in depth previously as ship-based capability currently addresses this requirement. This suggests that development across a range of TRLs is necessary and optimal and should be considered in the commissioning of the programme.

Not all of the suggested solutions are measurement technologies per se, for example a “virtual cabin” or virtual C2 (Command and Control) control room addresses the requirement of an immersive multidisciplinary research environment which is a particular benefit of confining a group of experts, operational technicians, ship’s crew and scientist aboard a research ship. Instead a virtual meeting place and information exchange system enables larger numbers of scientific, users and capability provider experts to view information and data with better presentation and processing typically performed at sea and to use latest collaboration tools to arrive at better operational decisions. This may be at the expense of the “hands on” experience, and the inevitable interruptions of life on land (though this could be mitigated by agreeing an interruptions policy, or housing groups in isolation in terrestrial locations). But other mitigating benefits include the ability to involve larger numbers of people, improving expert input and easing the impact of 24 hour operations / watches and exhaustion on productivity and decision making.

Table 2 proposed technologies to be developed, current TRL, costs, carbon saving and payback vs purchase of ETS / carbon credits

Technologies	Number of requirements addressed	Current TRL	Minimum cost (k)	Estimated carbon savings vs ammonia (t)	Estimated carbon savings vs MGO (t)	payback (yrs) vs ammonia	payback (yrs) vs MGO
Grand Total	**256**	**5.2 (average)**	**50500**	**2084.95**	**6685.17**	**121.11**	**37.77**
AI / ML of imagery	12	7	1000	172.18	552.06	29.04	9.06
intervention (inc. sampling) non ship (ROV, AUV, USV)	11	3	2500	168.63	540.69	74.13	23.12
particle sampler (filter) / eDNA sampler	17	6	750	108.45	347.74	34.58	10.78
in situ a priori genomics	14	5	1500	106.56	341.66	70.39	21.95
water sampler	22	5	750	104.29	334.38	35.96	11.21
in situ sample preservation	11	6	1000	101.51	325.48	49.26	15.36
in situ sequencing	13	3	2000	97.87	313.82	102.17	31.87
virtual cabin / C2 control rooms	1	6	500	78.97	253.21	31.66	9.87
AI / ML of acoustic data	3	5	750	75.98	243.61	49.36	15.39
active acoustics for biology on small autonomy / moorings	5	8	200	63.40	203.29	15.77	4.92
autonomous coring	4	5	2000	45.82	146.91	218.26	68.07
imaging microcytometer	5	5	750	44.47	142.60	84.32	26.30
In situ core XRF	3	3	750	43.85	140.59	85.52	26.67
autonomous drill	3	6	3000	41.78	133.95	359.05	111.98
in situ sediment processing	4	3	1000	40.99	131.42	121.99	38.05
microcytometer	7	5	750	39.02	125.12	96.10	29.97
In situ MS	5	7	1500	38.48	123.39	194.89	60.78

nano nutrients LOC	4	5	600	36.00	115.44	83.33	25.99
CarCASS (carbonate system analyser)	4	7	300	34.84	111.70	43.06	13.43
high resolution acoustics	2	7	500	31.41	100.71	79.59	24.82
in situ core microscopy	2	3	750	30.87	98.98	121.47	37.88
In situ rock / core element analyser: LIBS? Raman? MIR?	2	3	750	30.87	98.98	121.47	37.88
automated / no ship animal tagging	4	7	1500	28.82	92.40	260.26	81.17
added functionality tags (physio, behaviour, environment)	4	7	500	28.82	92.40	86.75	27.06
passive acoustics for biology	4	7	400	28.82	92.40	69.40	21.65
acoustic tag integration (OTN etc)	4	7	200	28.82	92.40	34.70	10.82
bate traps	4	2	200	28.82	92.40	34.70	10.82
modular multidisciplinary autonomy / non ship observing	1	3	1000	27.56	88.38	181.39	56.57
In situ CRD	7	6	750	27.37	87.77	136.99	42.73
in situ incubator / modular experimental platform	3	3	1500	25.70	82.39	291.88	91.03
FRRF	3	7	400	23.60	75.69	84.73	26.43
ammonia LOC	3	6	500	22.36	71.70	111.79	34.87
momentum and heat flux buoy / USV	3	6	500	21.68	69.52	115.30	35.96
autonomous mooring / observatory deployment system	1	7	3000	20.75	66.55	722.72	225.40
existing cable / infrastructure (DFOS acoustics)	1	6	750	20.75	66.55	180.68	56.35
virtual mooring	1	3	500	20.75	66.55	120.45	37.57
Biosensor	6	5	750	19.20	61.57	195.28	60.90

Gas extraction system for GC or MS including DIC to CO2	4	6	750	19.04	61.04	196.99	61.44
Organic nutrients analyser	3	6	600	18.71	59.98	160.37	50.02
delta O2 incubator	2	5	600	18.40	59.01	163.01	50.84
in situ Winkler	2	4	600	15.69	50.32	191.15	59.62
CaPASOS (robust miniature surface ΔpCO_2 analyser)	2	7	500	15.17	48.64	164.80	51.40
MIR analyser for Organics	4	4	750	11.42	36.61	328.48	102.44
Imaging UAV	7	8	250	11.33	36.34	110.29	34.40
in situ C calibration	2	4	750	10.71	34.34	350.11	109.19
in situ HPLC	4	3	1000	10.63	34.07	470.52	146.74
particle acid digestion and backscatter	2	4	750	6.32	20.25	593.71	185.16
Particle DON, DOP	2	4	750	6.32	20.25	593.71	185.16
Particle TOC / TIC	2	4	750	6.32	20.25	593.71	185.16
TOC analyser	2	5	700	5.63	18.05	621.77	193.92
benthic flux system (REA / EC / Gradient)	1	6	500	5.16	16.55	484.44	151.08
in situ GC with ECD	3	5	1000	4.17	13.39	1197.63	373.51
in situ radiation sensors	2	6	750	4.02	12.90	932.02	290.67
N2O supramolecular	1	5	750	1.61	5.17	2325.51	725.27
N2O IR	1	3	700	1.61	5.17	2170.48	676.92
spar buoy / wavewire	1	7	300	1.09	3.48	1381.73	430.93
Near surface SST / CTD	3	7	400	1.03	3.29	1950.02	608.16
flagged USV / autonomy and legal ruling	1	3	200	0.21	0.68	4683.18	1460.57
Skin temp thermometer	1	5	600	0.19	0.62	15394.99	4801.33

GNSS sea surface height (land, mooring and USV)	1	6	500	0.10	0.33	24307.87	7581.04

9.4 Stretch Targets

Whilst we propose a programme of work that would result in a low-carbon, and largely autonomous oceanographic capability that could address more of the users' requirements (~80%) than that achieved by research vessels (~60%), there remain a number of requirements where the capability would be inferior without additional efforts. These remain stretch targets for the measurement systems development effort and would require additional effort and resources over and above what has been proposed in the roadmap thus far. The areas of deficiency, and further work of particular concern are:

1) The ability to perform experiments and measurements that require direct intervention in the environment, such as sample acquisition in complex seabed and benthic experiments. However, this gap may be addressed if a remotely piloted low carbon "ROV" like capability were developed. Whilst an autonomously deployed ROV capability is envisaged by the commercial sector (see §5) the challenge would be for this to be delivered with low emissions. The current proposal to use relatively large MGO or ammonia powered USVs would still produce significant emissions and the emissions benefit over a crewed multirole ship are not clear at the time of writing.
2) The ability to exercise freedom of navigation to maintain access. However, this gap may be address through legal means (see WP2) for example if autonomous or remotely piloted surface vessels were deemed to fulfil the requirement. Or other flagged vessels could perform this role.
3) The ability to maintain a productive multidisciplinary laboratory and capability at sea. This could be mitigated using modular and reconfigurable non-ship systems or deployment of additional platforms in response to changing needs during an experiment, but this remains a challenge in terms of R&D, engineering design, and achieving low emissions.
4) The measurement of particulate matter: whilst the spatial and temporal resolution of particulate matter measurements could be dramatically improved, we cannot currently foresee a technological solution to the in situ analysis of some particle associated rates that may not be possible to sample and preserve for later analysis either. This needs further engagement with the user community to develop solutions but at time of writing, remains a challenge.
5) In situ or near real time analysis of porewater: whilst it may be possible to analyse some parameters (e.g. nutrients and carbonate system with lab on chip sensors coupled to in situ microfilters or micro-dialysis) and samplers with preservation may be technically feasible, it is unlikely that envisaged technologies will fully replace the excellent capability available on a dedicated crewed vessel without further innovations.

6) Despite being included in the roadmap and proposed technologies lists (see Table 2), low-carbon **coring and drilling** remain a significant challenge and the associated risk and potential cost inflation makes this a stretch target.
7) Rock and sediment sample analysis. Low-carbon sampling, sample preservation and limited in situ (e.g. XRF, extraction to gas and then CRD) could provide a wealth of information, but it is likely this would be a downgrade on current ship capability. Engagement with the expert user and technology communities to work on this problem is therefore suggested.
8) Rock and sediment biogeochemical analysis, particularly for parameters where there is no available in situ pelagic sensors, remain a challenge
9) Rock and sediment isotope analysis currently requires mass spectroscopy and extraction to gas and cavity ringdown spectroscopy. Replacing this capability with preservation or in situ instrumentation remains a challenge in some applications
10) Analysis of sediments paleo / fossil analysis could be achieved with retrieved samples but this reduces real-time feedback for users. In situ measurement requires sample processing, visualisation and analysis beyond what was envisaged by experts engaged with this project.

Whilst no measurement system challenges are predicted to result in a loss of capability to address requirements, realising low-carbon methods of deploying and retrieving moorings and landers remains a stretch target. This can in part be mitigated by the use of virtual moorings, i.e. holding vehicles on station. Alternatively, a low carbon launch and recovery system would be needed. There are opportunities for use of sail and electric propulsion and modular deployment systems to enable this but this is a platforms / robotics and autonomous systems challenge and hence in the remit of WP3 and WP4. A promising technology is the transport of equipment submerged or semi submerged which would ease both launch and recovery system complexity, load capacity requirements, cost and emissions impact. For example, UEA have demonstrated the launch of autonomous gliders from wave powered autonomous vehicles. This concept could be scaled to larger and static (e.g. mooring) payloads. Large low-emission surface vehicles (e.g. Autonaut, Saildrone) already exist and further work in this vein could be fruitful.

9.5 Key Challenges – Risk Management and Transition

9.5.1 Creating capacity

At present there is insufficient capacity in the ocean technology development community to undertake the required programme of work in the required timescale without significant risk. However, the skills required do exist in the UK workforce and also in potential international partner nations. Once commissioned the existence of the development programme will enable recruitment and retention of staff as well as purchase / commissioning of facilities and equipment. However, it will be challenging to attract sufficient staff because of the buoyant employment market for the necessary engineering, technical and scientific skills. Whilst the excitement of such an ambitious programme, interesting work, and a moral driver may well be effective recruitment tools, it may transpire that market forces require additional motivation including consideration of pay structures and other incentives. If this is indeed the case, an alternative would be to partner with existing academic and commercial organisations or second staff from these into the development programme. Partnership is likely to be an efficient method for capacity creation in many circumstances.

9.5.2 Programme and technical risks

As with any technology development programme, there are risks that commissioned technology does not meet the requirements within the specified timeframe and budget. This can be because of technical failure or programmatic failure such as poor estimation, or mistakes in programme management. There is a wealth of alternative practices to mitigate developmental, technological and programmatic risks and these should be employed during delivery of the programme. However, because we suggest existing, known or low risk developments of relatively high TRL (average 5.2) technologies for the majority of requirements, and many requirements are addressed by multiple technologies the overall technical and programmatic risk for the programme is reduced even before additional mitigation measures.

9.5.3 Community engagement and persuasion

Without effective engagement with user and stakeholder communities, there is a risk that the benefits of the technology development programme are not realised. Lack of sufficient engagement could lead to poor requirements specification and hence technology aiming for the wrong characteristics. Also, many of the more successful development programmes in the recent past have had engaged users within the development projects once initiated. This can lead to better technological solutions and pragmatic user orientated decision at key crisis or decision points. Without this some programmes have also seen a lack of faith in user communities that can lead to lobbying for funding to be withdrawn partway through the development cycle and before the benefits have been realised. A mechanism for including user communities in the development programme and its direction when underway, can prevent such a crisis being reached.

One of the suggestions emerging from NZOC workshops and community engagement activities (see §3) has been the use of a “tapered handover” between existing ship-based operations and new lower emissions technologies. An overlap would enable co-sampling and therefore comparison of the performance of ship and low-emission technologies. This would build confidence as well as giving technology developers and operators time to adjust their designs and procedures to maintain or offer improved delivery against users’ requirements.

9.6 Impact Upon Net Zero vs ‘Do Nothing’

As discussed above (particularly §7), we outline a shift to rechargeable battery and renewable energy powered observing capability that could reduce emissions by up to 97% using improved logistics and fieldwork procedures or by ~80% if current emission intensive logistics and fieldwork practices (e.g. flying multiple staff to site for autonomy deployments) were maintained (see Figure

3). This compares to a ~65% reduction if ship-based (crewed) operations were maintained but used ammonia manufactured with renewable energy inputs instead. However, it should be noted that this analysis of ammonia fuelled capability neglects embodied carbon in the ammonia supply chain *and* does not factor in the approximate 30% reduction in ships possible payload due to the increased fuel volume when using ammonia compared to MGO.

At the same time the new capability will enable approximately 80% of users' and stakeholders' requirements to be met: an uplift compared to 60% of requirements addressed by current ship-based operations. This latter figure relates to current ship-based practices with either MGO or ammonia as fuel, but with the caveat that the impact of increased fuel volume would reduce the ability to the ammonia fuelled vessel to deliver this capability without further reduction in crew and oceanographic staff complement or by increasing vessel size, which would impact the ability to make the above emissions savings.

9.7 Further Work

We recommend the following further work in addition to the commissioning of the significant and coordinated measurement technology development programme as above.

1. Ongoing refinement of the roadmap by peer review and expert input including
    a. Refinement and adaptation of requirements in collaboration with users and stakeholders
    b. Improved fidelity technology development programme including
        i. Technologies / technological opportunities
        ii. Review of technology roles to address identified requirements
        iii. Improved cost, time and risk estimates
        iv. Improved engagement with users and stakeholders to enhance alignment with their expectations and modes of operation
    c. Exploration of opportunities for collaboration with industry and other non-oceanographic stakeholders.
2. Establishment of a working group to scope the co-development of measurement system and platform technologies to maximise performance when integrated and realisation of opportunities for efficiency gains. Mechanisms to co-development should be integrated in the governance of the proposed development programme.
3. Clarification of the regulatory environment and its impacts on measurement systems including
    a. Control of hazardous substances including radioisotopes
    b. Safety and disposal at sea
4. The establishment of workshops and / or expert groups to address acknowledge weaknesses in the knowledge of the authors and in some cases workshop 4 participants including:
    a. Acoustic technologies, both passive and active for a range of requirements including mapping as well as location and identification of marine species.

   b. AI / ML and its application across a broad range of requirements
   c. Geoscience technologies including sources and detectors for subseabed imaging.
   d. Large samplers such as the BGS RD2 and corers
5. Further work and formation of teams to examine the hard to address requirements / stretch targets identified in §9.4
6. Examination and inaction of the state of the art in technological development risk and programme risk management techniques.
7. The development of a comprehensive user and stakeholder engagement plan such that requirements are accurate and updated, and that development programmes have the correct informed input at key decision points. The latter will require users and stakeholders to be embedded in the technology development programme.

10 Implications for E,D&I

The potential upsides for Equality Diversity and Inclusion include:

1. Engagement in knowledge intensive R&D for the technology development programme as well as development and optimisation of procedures using these.
2. Development of a wider range of career paths within oceanography including in robotics, artificial intelligence, analytical chemistry and biology, software, electronics and data sciences.
3. Disruptive change which can drive innovation and address inertia in achieving ED&I.
4. Development of a capability that enables operational oceanographic research success for those unable to pass current medical examinations / certification required to attend a ship, unable to work effectively at sea, or with responsibilities or other restrictions that mean they cannot be at sea for extended periods

Potential downsides include a possible reduction in the ability to recruit and retain early career scientists for whom seagoing aboard a research vessel is attractive and can provide a method to rapidly gain experience and skills.

11 Adaptation of Research Infrastructure

In addition to the effects of remodelling the oceanographic platform and data capabilities (see WPs 3,4 and 6) the development and widespread use of a new suite of measurement, sampling, preservation and collaboration technologies will require:

- A significant expansion in staff numbers dedicated to selection, integration, calibration, maintenance, preparation and demobilisation of measurement system technologies
- An increase in technical support for scientific instrumentation / disciplines that would previously have been expected of the seagoing scientist / oceanographer and their technicians. For example, analytical chemists, metrologists and biomolecular experts.

- Greater access to facilities for testing, calibration, preparation and refurbishment of measurement instruments and samplers. This will need to include some facilities at the capability providers facilities, but will include sourcing of facilities that can be rented and commissioned when needed from external suppliers.
- The development of a cohort of experts that can operate across the boundaries of: platforms (e.g. vehicles or moorings); measurement systems; data sciences; and oceanography / user applications.
- Access to improved legal and regulatory advice and if necessary, advocacy to enable operational changes (e.g. management of hazardous materials, disposal at sea etc.)
- Improved and more extensive collaborations and working practices with external providers of measurement systems. Most of the measurement systems should in time be produced and supported by industry / manufacturing companies. Maintaining technological capability in research institutions only can lead to sustainability and quality problems in the medium to long term.

12 Alignment with Broader UKRI and Government Policy

In addition to opportunities for alignment with regulators needs for capability and the objectives of UKRI (EPSRC, BBSRC and Innovate UK in particular) described in §6 the following alignment may be beneficial:

- Department of International Trade: the new capability including technologies developed in the UK as well as specialist know how in the integration and operation of the technologies provides an opportunity to support DIT's responsibility for promoting UK trade and attracting foreign investment. If successful this development programme would produce world leading technologies, knowledge and services with considerable export and investment value.
- Some technologies (e.g. pathogen detection and in situ sequencing in environmental and waste waters) would be beneficial for health protection (aligning with the Department of Health and Public Health England) and will have defence applications (aligning with the Ministry of Defence)
- The capability would deliver services, and demonstrate techniques that could be directly applied to government bodies with similar requirements including: The Environment Agency; DEFRA, Natural England, Natural Resource Wales and SEPA.
- The capability will deliver improved understanding of the marine environment as well as having spinout uses in measuring other natural systems aligning with UK environment and sustainability policy (DEFRA) and research beyond marine (other aspects of NERC)

13 References

Carbon Trust (2015). *Bringing externalities in-house: what is an internal carbon price and should my business be implementing one?* [Online]. Available: https://www.carbontrust.com/news-and-events/insights/bringing-externalities-in-house-what-is-an-internal-carbon-price-and [Accessed].

Greenhouse Gas Protocol (2021). *Greenhouse Gas Protocol* [Online]. Available: http://www.ghgprotocol.org/ [Accessed].

Table 3 Matrix of requirements and technologies recommended for development to address these

Requirement/technology	acoustic tag integration (OTN etc)	active acoustics for biology on small autonomy / moorings	added functionally tags (physio, behaviour, environment)	AI / ML of acoustic data	AI / ML of imagery	ammonia LOC	automated / no ship animal tagging	autonomous coring	autonomous drill	autonomous mooring / observatory deployment system	bate traps	benthic flux system (REA / EC / Gradient)	Biosensor	CaPASOS	CarCASS	delta O2 incubator	existing cable / infrastructure (DFOS acoustics)	flagged USV / autonomy and legal ruling	FRRF	Gas extraction system for GC or MS including DIC to CO2
Grand Total	**4**	**5**	**4**	**3**	**12**	**3**	**4**	**4**	**3**	**1**	**4**	**1**	**6**	**2**	**4**	**2**	**1**	**1**	**3**	**4**
Biogeochemistry						**1**							**1**	**1**	**1**					**1**
Dissolved organic carbon													1							
Inorganic carbon														1	1					
Nitrous oxide																				
Nutrients						1														
Oxygen																				
Particulate matter																				
Stable carbon isotopes																				1
Transient tracers																				
Biology and Ecosystems	**2**	**2**	**2**	**1**	**4**		**2**				**2**					**2**			**1**	
Fish abundance and distribution	1	1	1		1		1				1									
Hard coral cover and composition																				
Invertebrate abundance and distribution (*emerging)					1															
Macroalgal canopy cover and composition																				
Mangrove cover and composition																				
Marine turtles, birds, mammals abundance and distribution	1	1	1	1	1		1				1									
Microbe biomass and diversity (*emerging)																1				
Phytoplankton biomass and diversity																1			1	
Seagrass cover and composition																				
Zooplankton biomass and diversity					1															
Cross disciplinary				**1**															**1**	
Ocean colour																			1	
Ocean Sound				1																

Requirement/technology	GNSS sea surface height (land, mooring and USV)	high resolution acoustics	imaging microcytometer	imaging UAV	in situ a priori genomics	in situ C calibration	in situ core microscopy	in situ core XRF	in situ CRD	in situ GC with ECD	in situ HPLC	in situ incubator / modular experimental platform	in situ MS	in situ radiation sensors	in situ rock / core element analyser: LIBS? Raman? MIR?	in situ sample preservation	in situ sediment processing	in situ sequencing	in situ winkler	intervention (inc. sampling) non ship (ROV, AUV, USV)
Grand Total	**1**	**2**	**5**	**7**	**14**	**2**	**2**	**3**	**7**	**3**	**4**	**3**	**5**	**2**	**2**	**11**	**4**	**13**	**2**	**11**
Biogeochemistry									**2**	**2**	**1**								**1**	
Dissolved organic carbon											1									
Inorganic carbon																				
Nitrous oxide										1										
Nutrients																				
Oxygen																			1	
Particulate matter																				
Stable carbon isotopes									1											
Transient tracers									1	1										
Biology and Ecosystems		**1**	**2**	**6**	**6**							**1**					**1**	**6**		**5**
Fish abundance and distribution				1	1													1		
Hard coral cover and composition				1																1
Invertebrate abundance and distribution (*emerging)		1			1												1	1		1
Macroalgal canopy cover and composition				1																1
Mangrove cover and composition				1																1
Marine turtles, birds, mammals abundance and distribution				1	1													1		
Microbe biomass and diversity (*emerging)					1							1						1		
Phytoplankton biomass and diversity			1		1													1		
Seagrass cover and composition				1																1
Zooplankton biomass and diversity			1		1													1		
Cross disciplinary																				
Ocean colour																				
Ocean Sound																				

Requirement/technology	microcytometer	MIR analyser for Organics	modular multidisciplinary autonomy / non ship observing	momentum and heat flux buoy / USV	N2O IR	N2O supramolecular	nano nutrients LOC	Near surface SST / CTD	Organic nutrients analyser	particle acid digestion and backscatter	Particle DON, DOP	particle sampler (filter) / eDNA sampler	Particle TOC / TIC	passive acoustics for biology	Skin temp thermometer	spar buoy / wavewire	TOC analyser	virtual cabin / C2 control rooms	virtual mooring	water sampler	Grand Total
Grand Total	**7**	**4**	**1**	**3**	**1**	**1**	**4**	**3**	**3**	**2**	**2**	**17**	**2**	**4**	**1**	**1**	**2**	**1**	**1**	**22**	**256**
Biogeochemistry		**1**			**1**	**1**	**1**		**1**	**1**	**1**	**2**	**1**				**1**			**8**	**30**
Dissolved organic carbon		1							1								1			1	6
Inorganic carbon																				1	3
Nitrous oxide					1	1														1	4
Nutrients							1													1	3
Oxygen																				1	2
Particulate matter										1	1	1	1							1	5
Stable carbon isotopes												1								1	4
Transient tracers																				1	3
Biology and Ecosystems	**2**											**3**		**2**						**3**	**56**
Fish abundance and distribution														1							10
Hard coral cover and composition																					2
Invertebrate abundance and distribution (*emerging)																					6
Macroalgal canopy cover and composition																					2
Mangrove cover and composition																					2
Marine turtles, birds, mammals abundance and distribution														1							11
Microbe biomass and diversity (*emerging)	1											1								1	7
Phytoplankton biomass and diversity	1											1								1	8
Seagrass cover and composition																					2
Zooplankton biomass and diversity												1								1	6
Cross disciplinary																					**2**
Ocean colour																					1
Ocean Sound																					1

GO-ship https://www.go-ship.org/DatReq.html																					**1**									**1**				**1**																											**1**	**4**
Oxygen and nitrogen isotopes																					1									1				1																											1	4
MSFD	**2**	**3**	**2**		**4**		**2**					**2**		**1**														**2**											**1**				**2**		**3**	**1**	**1**										**1**		**2**						**1**	**30**
chemistry / pollutants													1																																															1	2
ecosystems	1	1	1		1		1				1														1												1		1														1							10
litter					1																																					1	1										1									4
Physics																																		1																										1
Physics / habitat		1			1																																			1																						3
species	1	1	1		1		1				1														1												1		1														1							10
physics																					**1**			**1**		**2**																					**3**				**3**											**1**	**1**				**1**	**13**
Ocean surface heat flux																																												1																	1
Ocean surface stress																																												1																	1
Sea ice																								1																																					1
Sea state																																												1													1					2
Sea surface height																					1																																							1
Sea surface salinity																										1																						1													1	3
Sea surface temperature																																																1								1						2
Subsurface salinity																										1																																			1
Subsurface temperature																																																1														1
Political driver																		**1**																																												**1**
Freedom of navigation demonstration																		1																																												1
Regulatory					**1**								**3**										**1**		**3**						**3**		**2**	**1**				**1**				**2**	**1**										**4**								**4**	**26**
Aquaculture medications													1																	1		1										1																		1	5
Benthic impact					1																			1												1																							3
Biotoxins													1																	1																					1								1	4
Contaminants													1																	1		1	1																		1								1	6
E.coli																									1															1										1									3
Harmful Algal Blooms																							1		1															1										1								1	5
Uk science										**1**							**1**																																										**1**		**3**
multidisciplinary long term datasets										1							1																																										1		3
UK Science drivers																																																										**1**			**1**
multidisciplinary command and control / community																																																										1			1
UK Science drivers, Biology / biochemistry					**2**	**2**		**3**	**2**			**1**	**1**	**1**	**3**				**1**	**2**			**2**		**3**		**1**	**2**	**4**	**1**		**2**	**1**		**1**	**11**	**2**	**4**	**1**	**2**	**2**	**1**	**1**				**3**		**2**	**1**	**1**	**7**	**1**				**1**			**4**	**79**
activity of genes																									1										1															1									3
biological and biogeochemical rates					1										1				1				1										1				1			1								1		1			1								1	11
Biomolecular analysis and bioprospecting																																				1		1													1									3
Description and molecular analysis of new species																																				1		1		1												1									4
experimental and intervention capability																																								1																				1
Halocarbon / organic gas analysis																													1	1																														1	3
Iron																																															1													1	2
multidisciplinary lab																																											1																			1
particle rates					1																		1									1										1								1	1	1	1	1				1			1	11
Pathogens													1											1										1		1			1										1									6
pore water analysis						1								1					1									1							1	1												1															7

Rock or Sediment / core (bio)geochemical analysis								1	1																			1								2																									5
Rock or Sediment / core isotopic analysis								1	1											1									1				1			1																									6
Sediment / core fossil / paleo biological record								1																			1	1							1	1	1					1																			7
surface and sediment fluxes						1						1		1	1														1																																	5
Viruses, symbionts and communities																									1											1		1																1									4
UK Science drivers, Geophysics				**1**	**1**			**1**	**1**													**1**					**1**	**1**					**1**		**1**		**1**			**1**																					**11**
Bathymetry																						1																																							1
rock and sediment samples / analysis								1	1																		1	1					1		1		1																								7
subseabed imaging				1	1																																			1																					3
Grand Total	**4**	**5**	**4**	**3**	**12**	**3**	**4**	**4**	**3**	**1**	**4**	**1**	**6**	**2**	**4**	**2**	**1**	**1**	**3**	**4**	**1**	**2**	**5**	**7**	**14**	**2**	**2**	**3**	**7**	**3**	**4**	**3**	**5**	**2**	**2**	**11**	**4**	**13**	**2**	**11**	**7**	**4**	**1**	**3**	**1**	**1**	**4**	**3**	**3**	**2**	**2**	**17**	**2**	**4**	**1**	**1**	**2**	**1**	**1**	**22**	**256**