# ZERO CARBON FUELS ACCELERATION

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| **Project Number** | **Q020216** |
| **Document Number** | **RD19-003074-4** |
| **Date** | **7 October 2019** |
| **Clients** | **BIMCO, CLIA, INTERCARGO, INTERFERRY, INTERTANKO, International Chamber of Shipping, IPTA and World Shipping Council** |
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# STUDY BOUNDARY CONDITIONS & DISCLAIMER

**Study boundary conditions:**

- Ricardo has prepared this concise report, within a 3 week time window, using their existing technical, environmental and market knowledge. No further quantitative analysis or predictions (either technical or financial) have been undertaken for this report beyond Ricardo's existing knowledge. Consequently, the forward-looking statements in this report are informed hypotheses and not expectations based on detailed forecasts or modelling.
- The report only considers technology aspects, not political aspects.

# EXECUTIVE SUMMARY

It is understood that the proposed ‘International Maritime Research and Development Board’ (IMRB) and its associated fund would collect Research and Development (R&D) contributions from shipowners globally and distribute the monies collected to activities which will meaningly contribute towards the development and deployment of zero carbon vessel power systems on board commercial ships**. A number of international shipowner associations have jointly commissioned this document as an initial independent high-level review covering only the technological aspects of the proposed fund.** This includes how the envisaged income, of around US$500 million per annum over a 10 to 12 year period, could hypothetically be utilised to accelerate the application of zero carbon technologies, consistent with the Initial IMO GHG Strategy, and what the potential benefits could be. It focuses on transoceanic shipping which presents the greatest challenge.

This document introduces some of the technical issues associated with the move to zero carbon considering battery and hybrid, hydrogen and ammonia technology. It explains the typical R&D process including Technology Readiness Levels (TRLs), provides example R&D case studies of projects which could be required, and it illustrates the breadth of projects the fund could support. Finally, the implications for vessel owners and operators are discussed.

The key technical issues with the three technologies are discussed:

- Battery hybrid systems suitable for transoceanic marine vessels are not yet commercially produced, so a significant number of R&D projects would be required to accelerate their development.
- The big challenges associated with hydrogen are around the safety of the fuel and the systems to store it on vessels. Further engine and fuel cell development would be required too.
- Ammonia has issues around its toxicity and emissions, whether used in reciprocating internal combustion engines or solid oxide fuel cells. Work is required to develop these technologies for ammonia and marine use respectively.

The potential to reduce $CO_2$ emissions is believed to be greatest for the transoceanic vessel sectors emitting the largest proportion of $CO_2$: the container, bulk carrier and liquid bulk tanker sectors. While much of the R&D is expected to be applicable across many sectors, there are expected to be some different solutions for each sector. These differences include vessel layouts to accommodate the zero carbon technologies, vessel sizes as well as different voyage power requirements.

It is hypothesised that the IMRB fund could support the development of approximately 200 technology and vessel sector combinations, which would be expected to reduce to approximately 20 on vessel demonstration projects as the technologies advance into the systems which are the most suitable solutions.

The IMRB fund benefits for vessel owner and operators would lie in the reduced risk of zero carbon technology adoption and accelerated pathways to commercial implementation. Similarly, ensuring that the solutions with good technical merit prevail, which should minimise future fuel or energy and maintenance costs.

This document suggests how the proposed fund could make a significant contribution towards accelerating the deployment of zero carbon propulsion systems and the achievement of GHG reduction targets for 2050 set by IMO.

  

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## 1 INTRODUCTION

The proposed 'International Maritime Research and Development Board' (IMRB) and its associated fund is intended to collect funds and distribute these to activities which will contribute towards the development and deployment of zero carbon vessel power systems. This document discusses how the fund could be utilised to overcome the many vessel challenges associated with the deployment of zero carbon fuels for transoceanic shipping.

The IMO has set forward an ambition to reduce total annual GHG emissions by at least 50% by 2050 compared to 2008. To achieve this, given typical transoceanic vessel and power system lifetimes together with an anticipated continued growth in transoceanic shipping demand, will require the mainstream commercial deployment of zero carbon vessel power systems by around 2035. As such, the proposed fund would consider projects to be undertaken in the timeframe 2023 to 2035, which would then become available for mainstream deployment from around 2035.

It is understood that the fund would consider R&D of relevance to the application of new power system technologies to transoceanic ships. It would not consider funding of port bunkering infrastructure or any form of carbon offsetting. The development of new energy storage methods such as fundamental fuels or battery cell chemistry are not expected to be a focus for the fund so are not discussed in this report. The total fund is expected to be approximately US$5bn, generated by total contributions from shipowners of approximately US$500m per year.

**A number of international shipowner associations have jointly commissioned this document as an initial independent high-level review covering only the technological aspects of the fund, including how the fund could hypothetically be spent on transoceanic shipping and what the potential benefits could be.**

Ricardo is a global multi-industry and multi-discipline consultancy with over 100 years of experience in helping clients define the future. Its broad expertise includes developing power systems, environmental consulting and market and socioeconomic analysis.

## 2 VESSEL TECHNOLOGY AND TECHNOLOGY READINESS LEVELS

To develop zero or near zero carbon power systems for transoceanic shipping there are many possible technology pathways. These range from renewable fuels such as green hydrogen or ammonia through to alternative energy storage and power systems such as batteries, hybrid-electric and fuel cells provided they all utilise renewable energy. Fundamentally, for transoceanic shipping all these pathways require an energy dense method of storing renewable electricity. The alternative power systems either enable the use of these energy storage methods or the opportunity to improve power system efficiency. This document will focus on those solutions which are 'zero carbon' throughout their use and do not use carbon-based molecules as the fuel. Alternative carbon neutral technologies, such as Renewable Natural Gas (RNG) or methanol fuels that remove carbon from the atmosphere to manufacture fuels synthetically or from biomass sources, could also be capable of achieving the GHG reduction targets and might usefully also be the recipient of R&D Funds, but are not considered in this document. Similarly, the use of on-board Carbon Capture and Storage (CCS) using existing fossil fuels and power systems is not considered in this report.

  

Technology Readiness Levels (TRLs) are a standard method of estimating technology maturity, see Figure 2-1. TRL 1 is the initial scientific research, while TRL 9 is fully operational deployment of the technology on commercial shipping. The fund will concentrate on the development, demonstration and deployment phases (TRL 4 to TRL 8).

| TRL | Explanation |
|---|---|
| 1 | **Basic principles** of scientific research observed and reported |
| 2 | **Invention and research** of practical applications |
| 3 | **Proof of concept** with analytical and experimental studies to validate the critical principles of individual elements of the technology |
| 4 | Development and validation of component in a **laboratory** |
| 5 | **Pilot scale** testing of component in a simulated environment to demonstrate specific aspects of the design |
| 6 | **Prototype system** built and tested in a **simulated environment** |
| 7 | **Prototype system** built and validated in a **marine operational environment** |
| 8 | **Active commissioning** where the actual system is proven to work in its final form under expected marine operating conditions |
| 9 | **Operational application** of system on a commercial vessel |

Basic research, minor focus (TRL 1–3)
Development, major focus (TRL 4–6)
Demonstration, major focus (TRL 7)
Deployment, major focus (TRL 8–9)

**Figure 2-1: Technology Readiness Levels (TRLs)**

To develop a complete zero carbon vessel would require a significant number of new and adapted technologies, which are currently at different TRLs. Even technology used commercially in adjacent industries, such as electrical grid power generation, will have a low TRL for transoceanic shipping. As such development of multiple technologies would be required up to TRL 5, with some of these being combined into systems for TRL 6 and above. The complete zero carbon vessel will require many of these systems.

## 2.1 Battery and hybrid

Battery and hybrid vessels are already in commercial operation on some ferry routes (Ship Technology). The largest has a battery with a capacity of 5 MWh weighing 65 tonnes (Electrek, 2019) (Ulstein, 2019). However, transoceanic shipping's power requirements are vastly different.

A pure battery electric transoceanic ship would require an energy storage system of up to circa 15 Gigawatt hours (GWh) to complete a single transoceanic crossing depending on the vessel tonnage (Ricardo estimation). Using current battery cell technology this equates to a battery array of tens of thousands of tonnes, severely limiting the vessel's cargo carrying capacity. As of 2019, the largest battery array installation has an energy storage capacity of only 129 Megawatt hours (MWh), which is much less than 15 GWh, and is used to supplement an onshore wind farm (Hornsdale Power Reserve, 2019).

A hybrid vessel offers good fuel consumption improvement for applications with variable power demands. They can also offer the potential for zero non-carbon emissions from ship operation, which could be a legislative requirement in some ports by 2050. For transoceanic shipping a likely application would be entering and leaving ports.

Battery arrays are comprised of battery packs which are manufactured from modules containing individual cells. A battery management system would be required together with consideration of cell thermal management and ageing. While all these elements can be scaled, there will be considerable challenges developing a battery system of enough capacity to meet the requirements of a hybrid transoceanic vessel. A significant improvement in battery cell energy and power density would improve pure battery electric viability. This is an area of active research currently driven by the automotive industry.

  

The direct engine to propeller drive arrangement should be maintained with a hybrid system to preserve propeller and drive efficiency. This could require the development of low speed motors to match the speed of the two-stroke engines; technology could be used from the generators in direct drive wind turbines which are circa 10 MW (Siemens Gamesa, 2019).

Current TRLs for hybrid electric transoceanic shipping are estimated at between 4 to 6, although much of the technology is mature in other smaller applications. The vessel challenges are the scale of the electrical systems and the durability required. Additionally, the batteries must be mechanically robust in a harsh environment. TRLs are lower for alternative battery chemistry cells with improved energy density.

## 2.2 Hydrogen

Hydrogen produced using electrolysers powered by renewable electricity (as opposed to that derived from fossil fuels) or “green hydrogen” is considered zero-carbon. It can either be burnt in a reciprocating internal combustion engine or used in fuel cells. Spark ignited or dual fuel two stroke and medium speed engines are capable of operating on hydrogen with some modifications. There are several types of fuel cells which can operate using hydrogen, including proton exchange membrane fuel cells (PEMFCs) used in automotive applications and solid oxide fuel cells (SOFC) currently used for industrial stationary applications. Currently the largest have power outputs of a few MW (E4tech, 2018). Marine fuel cell systems are expected to involve hybrid designs to manage variations in load. Hydrogen ferries are currently under development using fuel cells and are expected to enter service in the early 2020s (DNV-GL, 2019).

Hydrogen can be transported as either a compressed gas or in liquid form. The former at pressures, typically in excess of 300 bar and the latter at cryogenic conditions (below -253 °C); both have a significant cost. Large scale storage of hydrogen on ships would require development of new vessel storage systems. The relatively low energy density of hydrogen compared to traditional fuel oils will make this more challenging.

Hydrogen safety poses significant vessel challenges where development and demonstration projects will be required. Other vessel challenges include determining which fuel cell type is most appropriate and scaling these to the transoceanic vessels’ power demands, together with changes to standard vessel configuration to allow the storage of hydrogen. Due to flammability characteristics and the explosive nature of hydrogen, additional safety measures in a vessel must be deployed. Measures include hydrogen sensors, additional ventilation and electrical equipment that does not arc when switched.

Current TRLs for using hydrogen fuel in transoceanic shipping are estimated at between 3 and 5 for the various new technologies. The deployment of hydrogen fuels in other industries is modest.

## 2.3 Ammonia

“Green ammonia”, which is produced using “green hydrogen”, can either be directly burnt in a reciprocating engine or used in SOFCs. Indirectly it can be cracked to hydrogen for use in any hydrogen fuel cell. Ammonia typically needs a supporting fuel for use in reciprocating engines due to its combustion instability and high ignition temperature. For compression ignition this would be a typical dual fuel arrangement similar to current dual fuel LNG engines (for example HFO or renewable synthetic diesel as the supporting fuel). For spark ignition a proportion of hydrogen is expected to be required, which could be cracked from the ammonia upstream of the engine (Ash & Scarbrough, 2019). Leading engine manufacturer MAN has stated that their dual fuel two-stroke engines will be able to operate using ammonia once they have completed the engine development work. In total up to 3000 existing engines could be converted. (MAN Energy Solutions, 2018)

  

Compared to hydrogen, ammonia can be stored more easily and with less energy as it liquifies at a pressure of only 10 bar or at a temperature of -33 °C at atmospheric pressure. Bulk transport of liquid ammonia is already established using transoceanic gas carriers. It does not pose the same flammability concerns as hydrogen, although it is toxic. The marine industry would need to address this major toxicity challenge using the knowledge and experience of the chemical industry.

Ammonia can also be used as a refrigerant, meaning a possible synergy for vessels refrigerating their cargos.

Current TRLs for ammonia fuel in transoceanic shipping are estimated to be between 2 and 5. The current large-scale shipping of liquid ammonia together with more favourable storage capability than hydrogen compensate for the engine or fuel cell development required, the toxicity of the fuel, and the lack of technology available from other industries.

# 3 VESSEL SECTORS

The latest available $CO_2$ emissions by ship sector produced by the IMO are for 2012 (IMO, 2015). Figure 3-1 shows the range of $CO_2$ emissions for each vessel sector. The relative proportion will have changed since 2012 due to the relative growth or decline in different vessel subsectors. However, they are an indication of current $CO_2$. These are for international shipping, but removing ship types which are not transoceanic, such as ferries and the smaller 'general cargo vessels' (below ~15,000 dwt) results in the estimated split shown in Figure 3-2. This is a representation of expected transoceanic $CO_2$ emissions. The relative financial contributions to the fund from different vessel sectors are expected to be similar to these $CO_2$ estimates.

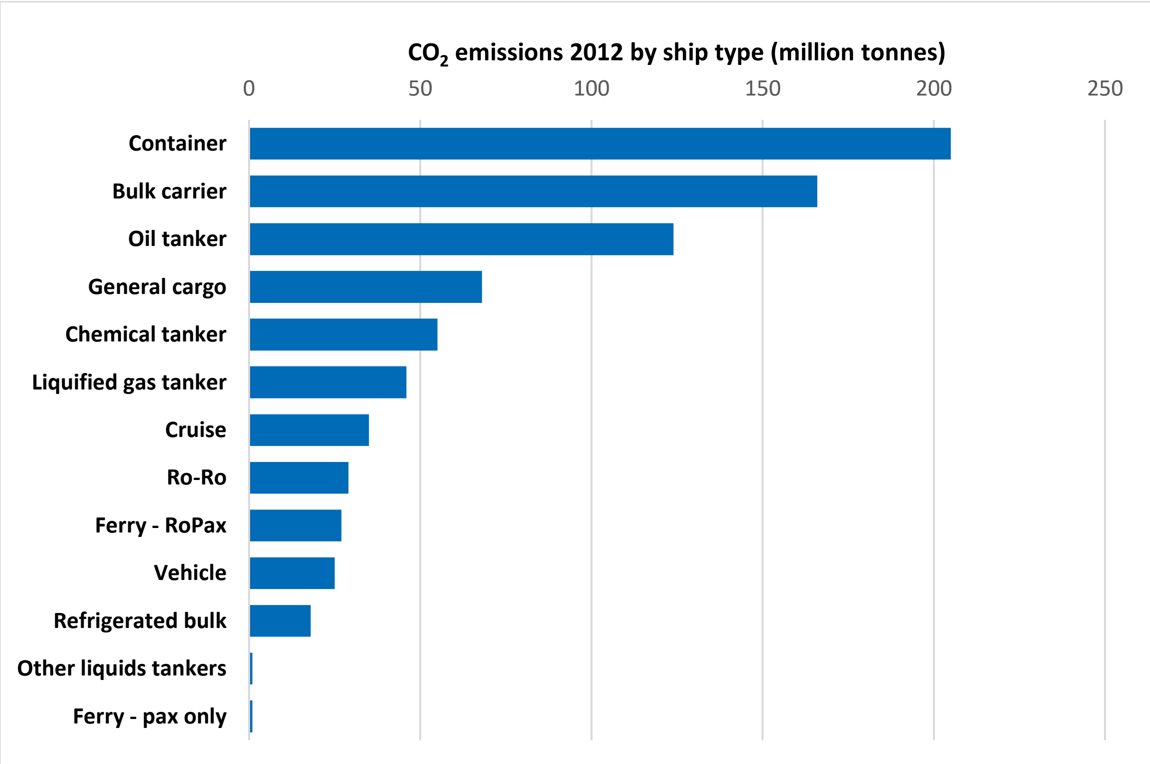


**Figure 3-1: Ship type $CO_2$ emissions 2012 (latest IMO data available) (IMO, 2015)**

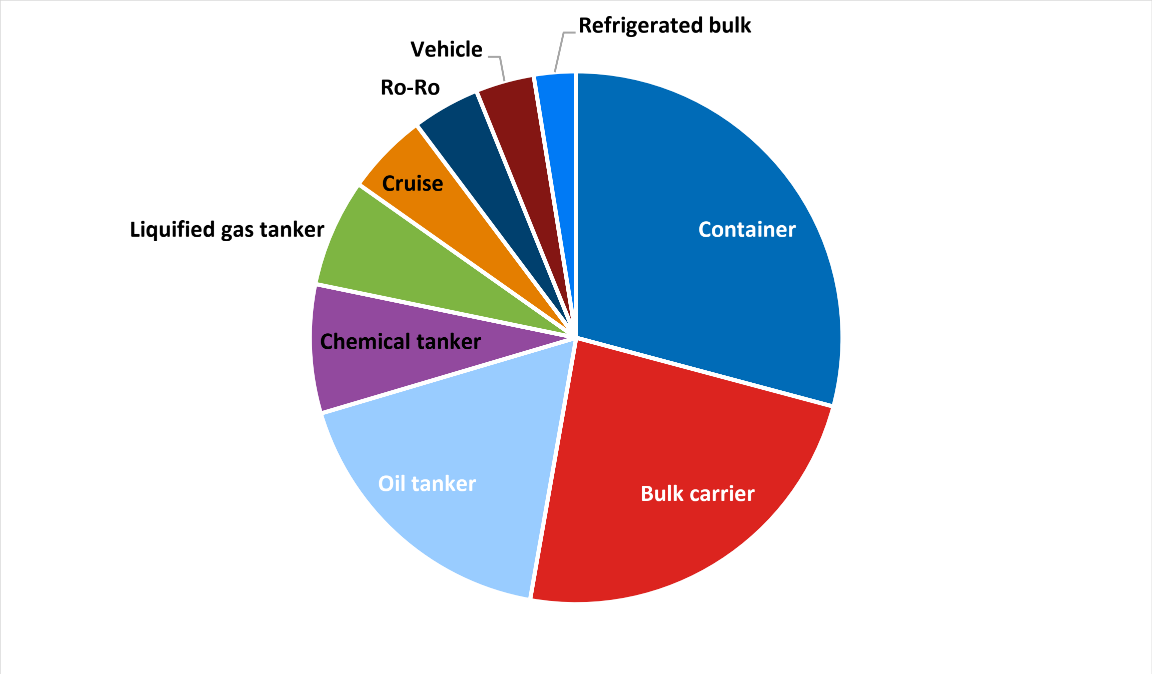


**Figure 3-2: Estimated distribution of transoceanic shipping $CO_2$ emission by ship type 2012**

The potential to reduce $CO_2$ emissions is greatest for the sectors emitting the greatest $CO_2$: the container, bulk carrier and liquid bulk tanker sectors.

Much of the R&D anticipated to be undertaken is expected to be applicable across these three sectors. Different solutions may be required for other sectors such as cruise, vehicle carriers and refrigerated bulk.

Differences between sectors are likely to be related to the vessel layout configuration to accommodate the zero carbon power and energy systems around the cargo types.

Variations within each sector, such as vessel sizes and operational routes, may cause variations in technological solutions, and therefore differences in R&D projects. Differences in operation, such as speed and routes, depend not only on the vessel type, but whether a vessel is engaged in the liner or tramp trade.

# 4 POTENTIAL R&D AND CASE STUDIES

To determine which technologies are most appropriate for different vessel types and operation, it is expected that it will be necessary to progress development with hybrid battery, hydrogen, and ammonia energy simultaneously. For each zero carbon energy storage method, a wide range of new vessel-based technologies and systems will be required. Each of these technologies and systems will require project(s) to progress their technology readiness. Some of these projects may be relatively small, especially at the mid TRLs of 4 and 5 where simulation tools can be used; a fund contribution of circa US$1m or less per project is likely to be appropriate. However, at later TRLs where full transoceanic demonstrators and full sea trials are required, a fund contribution in excess of US$20m per project is likely to be appropriate, considering only the cost of the new equipment and excluding the ship cost. It is assumed that the fund contributes between 30% to 50% of the R&D costs. Therefore, a project with a fund contribution of US$1m could have a total cost of US$2-3m and a fund contribution of US$20m could have a total cost of US$40-60m.

  

Where there are gaps in the technology required to enable a concept zero carbon energy storage system to safely and reliably function, low TRL research projects may be required which would be carried out as applied research typically by a university. These projects may not become apparent until sufficient development of other technologies.

It is anticipated that at least circa 200 projects would be required to enable widespread deployment of zero carbon transoceanic vessels (this is explained in Section 5). To illustrate, six case studies are presented covering possible example projects which could be funded. (The example case studies are provided for indication only and do not imply that these are viable or justifiable projects, without further detailed appraisal.) These cover projects with fund contributions of both circa US$1m and greater than US$20m for the three zero carbon energy solutions.

## 4.1 Case study 1: Maintenance of battery systems (circa US$1m)

Battery systems installed on transoceanic shipping are likely to require ongoing maintenance and replacement of battery modules to enable the full range to be utilised. This will include replacement when at sea by the ship's crew. The development of equipment and procedures are expected to be required to allow this to be carried out safely. While equipment to replace battery modules exists in other sectors, a different approach may be needed given the size of the battery installations.

| **Maintenance of battery systems** | |  |
|---|---|---|
| *Vessel system:* | Energy storage | *Project deliverables:* |
| *Vessel sector:* | All | Design and development of equipment for safe removal of battery modules at sea, including an on-ship battery systems workshop |
| *TRL estimate:* | 4 to 7 | |

## 4.2 Case study 2: Battery array design and analysis (greater than US$20m)

Battery systems require bespoke development for the specific application. This is needed to account for the expected power draw over the operational duty cycles and the battery state of charge, as well as other factors such as shock loading, vibration and cell temperature management. As part of the design and development, these factors will need to be modelled to ensure sufficient durability of the battery pack. Development of a single, large battery pack design is typically in the order of US$10m. While a modular approach is expected, there may need to be several different base battery pack designs to ensure maximum utilisation and durability of the battery array system.

The battery arrays will also need design and development to package within the vessel without compromising significant cargo capacity as well as further considerations including sufficient thermal management and design for maintenance.

Follow on projects will include the manufacture and testing of the battery pack, including a vessel demonstrator.

  

| **Battery array design and analysis** | | $$$$ |
|---|---|---|
| *Vessel system:* | Energy storage | *Project deliverables:* |
| *Vessel sector:* | Array specific to each vessel class<br><br>Pack applicable across classes | Design and analysis of a transoceanic battery array for a hybrid power system in a specific vessel class.<br><br>Design and analysis of modular base battery packs for transoceanic hybrid requirements |
| *TRL estimate:* | 5 to 6 | |

## 4.3 Case study 3: Safe engine room concept with hydrogen (circa US$1m)

Safe engine room (or 'fuel cell machinery' room), including fire suppression systems, will be needed throughout any vessel operating on hydrogen. These systems will need to be developed and proven by rig demonstration.

This project would consider methods for hydrogen detection and prevention of hydrogen build up by trialling different sensors and engine room designs through modelling. A scale model of the chosen design would be built to prove the concept. Further projects would be required to consider engine room fire suppression systems.

| **Safe engine room concept with hydrogen** | | $H_2$ $ |
|---|---|---|
| *Vessel system:* | Engine room | *Project deliverables:* |
| *Vessel sector:* | All | Proven guidelines to ensure safe ventilation of hydrogen with transoceanic shipping |
| *TRL estimate:* | 5 to 7 | |
| *Other:* | SOLAS | |

## 4.4 Case study 4: 50 MW hydrogen fuel cell system manufacture, testing and development (greater than US$20m)

Current fuel cell systems are available up to several MWs in power. These systems will need to be scaled up to provide the required power of a transoceanic ship. Whether the actual fuel cells are arranged as modules, or designed as fewer larger fuel cells, projects are required to manufacture and validate the full fuel cell system design through testing. The testing is likely to reveal areas which will require further development.

The system to be tested would likely include a fuel delivery system, heat transfer system, power electronics and control systems. If larger fuel cells are required for a modular array, significant work will also be required to test the fundamental fuel cell design.

Following iterations of development, further projects will be required to test these fuel cell systems on vessels.

| **50 MW hydrogen fuel cell system, testing, validation and development** | | $H_2$ $$$$ |
|---|---|---|
| *Vessel system:* | Power system | *Project deliverables:* |
| *Vessel sector:* | All | 50 MW fuel cell system manufactured and then tested on-shore over a range of different operating and ambient conditions |
| *TRL estimate:* | 4 to 7 | |

## 4.5 Case study 5: Ammonia cold start emissions strategy, (circa US$1m)

When starting the power system of an ammonia power system, the exhaust gas and aftertreatment system will start cold. During this phase conventional ammonia slip catalysts and selective catalytic reduction (SCR) systems will not be effective at reducing ammonia and $NO_x$ emissions to acceptable levels respectively. Therefore, a solution needs to be developed to prevent release of ammonia droplets into the air, which as toxic, could potentially harm anyone in the vicinity such as residents local to a port or any crew on deck. The solution could be an ammonia storage catalyst specifically designed for low temperatures.

This project is required to develop a control strategy and / or technology to reduce ammonia emissions to acceptable levels to meet various national emissions limits. Further projects are required to develop a demonstration of the strategy on board a vessel with emissions monitoring equipment.

This technology is applicable to both ammonia reciprocating internal combustion engines and ammonia SOFCs, the latter which typically emit some ammonia during the fuel conversion process.

| **Ammonia cold start emissions strategy** | | $NH_3$ $ |
|---|---|---|
| *Vessel system:* | Power system | *Project deliverables:* |
| *Vessel sector:* | All | Development of a strategy and technology system to prevent release of ammonia into the atmosphere |
| *TRL estimate:* | 4 to 5 | |
| *Other:* | Environmental | |

### 4.6 Case study 6: Waste heat recovery demonstration in vessel with ammonia fuel cell (greater than US$20m)

SOFCs (and to some extent internal combustion engines) using ammonia will have a different temperature grade of waste heat to that of current fuel oil or natural gas internal combustion engines. A system developed to optimise the waste heat recovery for ammonia will require testing on a transoceanic ship. This project is to verify the previous design, analysis and simulation projects to ensure that the system functions reliably and provides the required power and heat under commercial vessel operating conditions.

| **Ammonia cold start emissions strategy** | | $NH_3$ $$$$ | |
|---|---|---|---|
| *Vessel system:* | Power system | *Project deliverables:* | |
| *Vessel sector:* | All | On vessel demonstration system for use under commercial shipping activities | |
| *TRL estimate:* | 7 to 8 | | |

## 5 IMPACT OF THE R&D FUND

### 5.1 Potential for comprehensive R&D of multiple technology paths

Considering battery, hydrogen, and ammonia energy storage alone, this document has highlighted a number of possible projects and technologies. These are a small example of the overall number of projects required; Ricardo has identified over 50 different technologies, systems and problems requiring development to support the application of ammonia alone. Taking an ammonia powered reefer (refrigerated container vessel) as an example the following need to be considered, and each of these have many systems and sub-systems which will need to function reliably:

- Fuel storage
- On vessel fuel transportation
- Propulsion
- Auxiliary power
- Waste heat recovery
- Refrigeration
- Emissions
- Engine room safety
- Wider vessel safety
- Vessel configuration
- Voyage adjustments and more

Considering battery, hybrid and hydrogen as well as other possible zero carbon fuels across multiple vessel sectors, it could be plausible to investigate in excess of 200 different technologies.

Each of these technologies would need to be progressed to a level to determine whether they are applicable for transoceanic marine applications. Figure 5-1 illustrates the possible number of projects which the fund could support at each TRL. A typical project would be similar to those identified in the case studies in Section 4 and would advance the technology readiness. Figure 5-2 illustrates a possible fund contribution for each type of project; for simplicity these are the contributions assumed to progress a technology by one TRL. Combining the number of projects and the estimated project costs results in an estimated total fund contribution of approximately US$5bn plus administration costs. Development of each TRL would be expected to take between 6 months and 2 years, requiring the fund to operate for at least circa 12 years (to advance TRL 4 to 9). Therefore, a fund, with an income of circa US$500m per annum operating between approximately 2023 and 2035, could make a significant contribution towards accelerating the development and deployment of new zero carbon technologies.

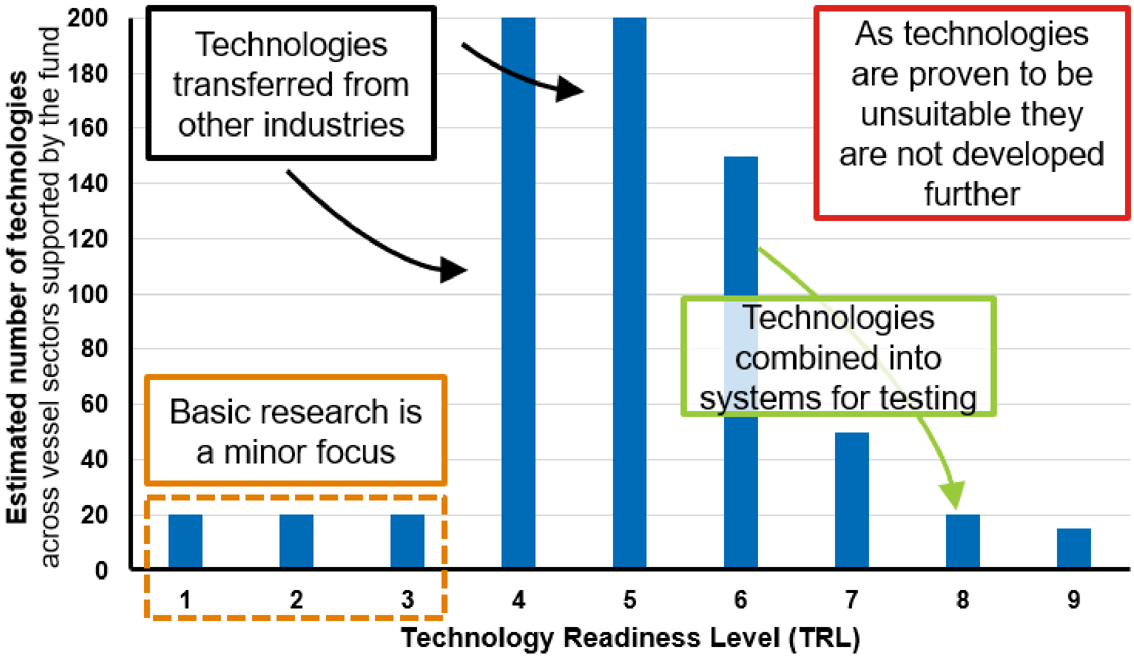


**Figure 5-1: An example of the estimated number of projects the fund could support as technologies develop through the TRLs (Ricardo)**

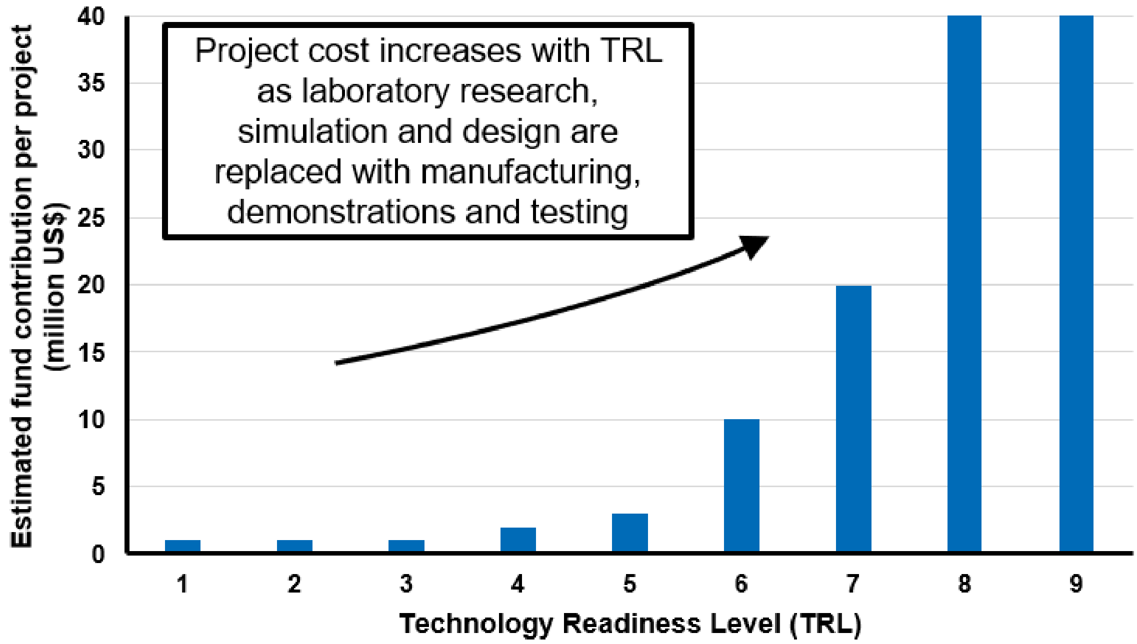


**Figure 5-2: Example of the estimated average fund contribution to projects (at 30% to 50% funding) to develop a technology through one TRL (Ricardo)**

## 5.2 Impacts on ship development

While the fund will only apply to vessel technology, it is expected that it will have a "pull" effect on investment in zero carbon technologies by other parties, multiplying its impact. One example being that fuel companies and engine manufacturers will often not seriously invest in developing fundamental novel technology until a demand exists. The shipping industry will often not develop vessels until the technology exists. Therefore, using the fund to develop demonstrator vessels should help overcome this impasse by creating a situation where zero carbon technologies are under development thereby expanding the level of activity and investment in maritime technologies.

## 5.3 Impacts on shipping companies

The fund would be expected to reduce the impact of the complex transoceanic transition to zero carbon fuels. While naval architects, ship yards and other manufacturing and research companies will benefit, there is expected to be a long-term benefit to the vessel owners and operators. These include:

- **Reducing the impact of the complex transition process:** Documented trials with the technologies should enable more of the issues to be fixed prior to commercial use, meaning more robust technology applied to commercial vessels.
- **Giving opportunities for the solutions with good technical merit to prevail:** The size of the fund means that a range of technologies can be properly assessed by ship owners and operators, so informed decisions can be made by the shipping industry and used as a market "pull".
- **Inclusion of owners and operators in R&D:** It is normal for projects supported by funds to require the inclusion of end users in the projects at later TRLs. This should allow the owners and operators an opportunity to influence the technology direction.
- **Whole ship optimisation:** R&D is split across engine OEMs, naval architects, ship builders, owners and operators. An R&D fund should respond to bids for the funding which are from integrated collaborations, so the marine industry should end up with more optimum ship-level zero carbon solutions.
- **Lower overall industry R&D costs:** Other industries are spending more on R&D. As an example, German automotive manufacturers collectively spent circa US$12bn on R&D for transitioning to zero carbon energy products in 2018 alone (Ricardo analysis, 2019). A marine R&D fund should also help avoid costly company competitive R&D replication, which in turn should help limit the R&D costs passed on to those purchasing zero carbon ships and in turn those chartering. Deciding on a technology path more quickly can also have the same impact.
- **Accelerated capital cost reduction:** The R&D acceleration provided by the fund should also accelerate the reduction in manufacturing costs, particularly for the relatively immature high power fuel cells and to some extent battery arrays too. This in turn should be reflected in the capital costs of technologies.
- **Quicker transition to zero carbon technology:** The fund should allow technology to be introduced into the fleet in a managed and structured way. This should reduce the risk of imposition of punitive measures for failing to meet targets as well as lowering the total $CO_2$ released into the atmosphere.
- **Quicker elimination of unsuitable technology:** The fund could accelerate a conclusive assessment of which fuels and energy storage are not suitable, and

  

therefore narrow the range of possible technologies for further development. This will help prevent uncertainty among shipping companies as to which technology to invest in. It will reduce the risk of adopting such a large step change in propulsion and energy storage technology.

# 6 CONCLUSIONS

The 'International Maritime Research and Development Board' (IMRB) and its associated fund could support the vessel development of a range of zero carbon fuels and energy storage such as ammonia, hydrogen, and batteries. It would help determine which methods are suitable for different vessel types, and which methods are unsuitable for any transoceanic vessel. This would narrow the range of possible technologies which should reduce the risk of investment in R&D for the industry towards 2035.

Each zero carbon fuel or energy storage method will require many different supporting on-vessel technologies. Battery and hybrid technologies are mature in other markets, but significant development is required to transfer these to marine applications. Ammonia and hydrogen are less mature and again significant marine development is required. The fund could support the development of new transoceanic technologies through TRL 4 to 9. Approximately 200 technologies could be supported through TRLs 4 and 5, which would be expected to reduce to approximately 20 on vessel demonstration projects as the technologies advance into systems in TRLs 8 and 9.

The fund's investments are expected to create a pull effect on investment in zero carbon technologies by other parties, multiplying its total impact to transoceanic shipping. It should give an opportunity for the energy and power systems solutions with good technical merit to prevail, while considering the whole vessel through structured collaboration.

The fund benefits for vessel owner and operators lie in this reduced risk of zero carbon technology adoption, which should limit the vessel purchase cost through reduced competitive R&D spend and accelerated manufacturing cost reductions. Similarly, ensuring that the solutions with good technical merit prevail should limit fuel or energy and maintenance costs.

A fund, with an income of circa US$500m per annum operating between approximately 2023 and 2035, could make a significant contribution towards accelerating the development and deployment of new zero carbon technologies for transoceanic vessels.

# 7 REFERENCES

Ash, N. & Scarbrough, T., 2019. *Sailing on solar: Could green ammonia decarbonise international shipping?',* London: Environmental Defense Fund.

DNV-GL, 2019. *Power ahead with hydrogen ferries.* [Online]
Available at: https://www.dnvgl.com/expert-story/maritime-impact/Power-ahead-with-hydrogen-ferries.html
[Accessed August 2019].

E4tech, 2018. *The Fuel Cell Industry Review,* s.l.: s.n.

Electrek, 2019. *World's largest plug-in hybrid ship hits water with equivalent of 50 Tesla battery packs.* [Online]
Available at: https://electrek.co/2019/08/02/world-largest-plug-in-hybrid-ship-tesla-battery-packs/
[Accessed August 2019].

Hornsdale Power Reserve, 2019. *Hornsdale Power Reserve.* [Online]
Available at: https://hornsdalepowerreserve.com.au/
[Accessed 2019].
IMO, 2015. *Third IMO Greenhouse Gas Study 2014,* s.l.: IMO.
MAN Energy Solutions, 2018. *Ship Operation Using LPG and Ammonia As Fuel on MAN B&W Dual Fuel ME-LGIP Engines.* s.l., AIChE.
Ricardo analysis, 2019. s.l.:s.n.
Ship Technology, . *Ampere Electric-Powered Ferry.* [Online]
Available at: https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/
[Accessed 2019].
Siemens Gamesa, 2019. *SG 10.0-193 DD Offshore wind turbine.* [Online]
Available at: https://www.siemensgamesa.com/en-int/products-and-services/offshore/wind-turbine-sg-10-0-193-dd
[Accessed August 2019].
Ulstein, 2019. *COLOR HYBRID.* [Online]
Available at: https://ulstein.com/color-hybrid
[Accessed August 2019].

  