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ARICE: Arctic Research Icebreaker Consortium:

A strategy for meeting the needs for marine-based research in the Arctic

Deliverable 1.5 Report on the global and future resources' investments in Arctic icebreaker capacity to research

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Contents

Abstract

Vessels operating in the Arctic region must comply with standards and regulations to cope with the rough ice conditions, which represent additional costs in construction and operation. The main drivers of cost for ice capable vessels is the vessel design for research capability, ice capability, endurance (remote operations), and extra fuel consumption (due to less efficient hull-shape for open water and resistance from ice). This report briefly presents some recent investments in the global Arctic icebreaking capacity for research summarizing the acquisition costs of new national polar research vessels in Europe, North America, and Asia made during the past ten years and by reviewing the operation costs of five of the ARICE transnational access vessels.

Only a few of the European countries own vessels that can operate in polar waters, marginal ice zones, and the central Arctic.

1. Introduction

1.1. Aims, methods and limitations of the study

The objective of this report is to map the potential global polar research vessel (PRV) fleet and its capability, as well as establishing relations with the operational and scientific management of the international PRV fleet.

The report reflects the status of the global and future resources' investments in Arctic icebreaker capacity to research as of April 2020. It is a desktop study and the materials that have been used in conducting the review are limited by the publicity of information, the availability of online sources, and the expertise and knowledge of the ARICE consortium and network. The chapters on polar regulations and on costs and economics associated with polar research vessels were co-created with practitioners from the maritime and shipping sectors. The deliverable has benefited from the contribution of Arctic Marine Solutions (AMS).

The report belongs to task 1.3 in ARICE Work Package 1, which aims to present a coherent global picture of the Arctic research icebreaker infrastructure and potential of enhanced collaboration between the fleet operators as a basis for the further multilateral cooperation.

1.2. Arctic conditions

The Arctic Ocean and its archipelagos are vast with varying conditions. The size of the frozen area varies between and within seasons. In the winter season, open water areas are surrounding the compact frozen areas in the centre of the ocean. In the summer season, the open water areas expand, while the ice pack gradually breaks up.

The Arctic Ocean can be divided into three basic ice regimes besides the year around open water areas:

- Central Arctic with dense pack ice year around
- Marginal-ice zone with broken-up ice
- Areas with first-year ice and land-fast ice.

The ice in the central Arctic is more complex than elsewhere on earth. This is because the ice that freezes over winter can reach up to 180 cm thickness according to the World Meteorological Organization (WMO No. 259). Some of the winter ice survives the summer and gets up to ten times harder next winter. This hard ice may endure several summers and grows thicker and up to 100 times harder. This fortification process is due to the brine (salt) being leached out of the ice and replaced by freshwater, effectively reinforcing the ice (like concrete).

Any ship that goes into the Arctic must be capable to withstand all these ice types, i.e., First-Year-Ice, Second-Year-Ice and Multi-Year-Ice (WMO No. 259).

When evaluating ice conditions, several factors need to be taken into consideration. For example, the ice coverage – i.e. how much of the sea surface that is covered with ice. At higher ice coverage, the space for the broken ice to be pushed aside to must also be considered as well as ice types; first or multiyear- ice. In addition, the time of the year must be considered since ice hardness increases at low temperatures. Moreover, wind drift can make the ice more compact and increase potential ice pressure. All these factors put various demands on a vessels capability to navigate the Arctic Ocean.

The ice closer to the coast may be first-year ice, land-fast ice, or ice drifting from the central Arctic. Hence all operations require thorough planning for the expected conditions and an appropriate vessel for these conditions before setting out to sea.

"Open water" exists in the Arctic but is defined as the WMO Ice Nomenclature as an area with less than 10% ice cover. If there is no ice, then the nomenclature term is "Ice Free". Open water operation normally enables the vessel to navigate around the ice floes, but if the vessel is inside an ice floe the local concentration can be 90-100% even though the larger area may have less than 10% ice cover. For scientific missions that are dependent on a fixed location this has a significant impact on the operation

1.3. Regulations, Polar Classes and Polar Categories

The Polar Code:

The International Code for Ships Operating in Polar Waters (Polar Code) was adopted by the International Maritime Organization's (IMO) in 2014 to improve safety in Arctic and Antarctic shipping.

The Polar Code is a regulatory framework of shipping-related matters relevant to safety, environment and navigation in waters surrounding the two poles. One of its central requirements is that ships intending to operate in these waters need to apply for a Polar Ship Certificate that requires an assessment that takes into account the anticipated range of operating conditions and hazards the vessel may encounter in polar waters (IMO 2020).

Since 2017 all polar vessel design has been required to adhere to the IMO Polar Code to ensure the safety of operations in the polar marine environment.

One of its central requirements is that ships intending to operate in polar marine waters need to apply for a *Polar Ship Certificate* that requires an assessment that takes into account the anticipated range of operating conditions and hazards the vessel may encounter in polar waters (IMO 2020). The *Polar Ship Certificate* replaced the earlier Arctic Pollution Prevention Certificate and added topics like voyage planning and crew training.

The focus of the IMO Polar Code is to assist merchant vessel traffic in Arctic areas who do not normally traffic these routes. The IMO Polar Code divides ships into three categories, A, B and C, according to their ice capability (Table 1). I.e. Category A is for ships operating in conditions from medium first-year-ice that may include multi-year-ice inclusions and worse. It should be noted that the definition of medium first-year-ice as per WMO Ice Nomenclature is 70-120 cm nominal thickness.

Despite of this classification, there is still no unified design criterion for icebreakers as it is expected that each operator knows what it needs and can agree on a classification with the selected classification society. In addition, the Polar Class assigned to a vessel still says little about its ability to efficiently progress/work in an ice-infested area, as the rules do not indicate the trafficability in ice (AMS, professional experience).

It can be noted that the Polar Code does not apply to state-owned vessels/operated vessels such as the navy, coastguard and similar.

The Unified Requirements for Polar Class Ships:

The Unified Requirements for Polar Class Ships is a system of ice classes (PC classes) assigned to ships for polar water operation that was established and is being maintained by the International Association of Classification Societies (IACS). This system classifies the polar vessels in 7 PC classes (PC1 to PC7) in function of design criteria (Table 1), whilst vessels are still being built according to the rules of a classification society[1].

Thus, the IACS Polar Class rules should not be confused with the International Code for Ships Operating in Polar Waters (Polar Code) by the International Maritime Organization (IMO).

Table 1. IMO Polar Code and IACS Polar Class as presented by Det Norske Veritas-Germanischer Lloyd (DNV-GL)[2].

The Polar Code divides ships into three categories: Category A, B or C.

		ICE CLASS	OPERATING CAPABILITY
A	**Category A** ship means a ship designed for operation in polar waters in at least medium first-year ice, which may include old ice inclusions. This corresponds to vessels built to the IACS Polar ice classes PC1 to PC5.	PC1	Year-round operation in all polar waters
		PC2	Year-round operation in moderate multi-year ice
		PC3	Year-round operation in second-year ice, which may include multi-year inclusions
		PC4	Year-round operation in thick first-year ice, which may include old ice inclusions
		PC5	Year-round operation in medium first-year ice, which may include old ice inclusions
B	**Category B** ship means a ship not included in Category A, designed for operation in polar waters in at least thin first-year ice, which may include old ice inclusions. This corresponds to vessels built to the IACS Polar ice classes PC6 and PC7.	PC6	Summer/autumn operation in medium first-year ice, which may include old ice inclusions
		PC7	Summer/autumn operation in thin first-year ice, which may include old ice inclusions
C	**Category C** ship means a ship designed to operate in open water or in ice conditions less severe than those included in Categories A and B. This corresponds to ships of any Baltic ice class or with no ice strengthening at all.	ICE-1A* / E4	First-year ice to 1.0 m
		ICE-1A / E3	First-year ice to 0.8 m
		ICE-1B / E2	First-year ice to 0.6 m
	Vessels with other ice class notations must be evaluated on a case-by-case basis to determine their equivalent polar ship category (for example, the legacy DNV icebreaker ice classes ICE-05, 10 or 15 and POLAR-10, 20 or 30).	ICE-1C / E1	First-year ice to 0.4 m
		ICE-C / E	Light ice conditions
		None	Ice-free/open water conditions

1 A classification society is a non-governmental organization that establishes and maintains technical standards for the construction and operation of ships and offshore structures. Classification societies certify that the construction of a vessel complies with relevant standards and carry out regular surveys in service to ensure continuing compliance with the standards.

2 WMO Ice Nomenclature: Medium first-year ice is 70-120 cm; Thin first-year ice is 30-70 cm; Open Water is an area with less than 10% ice cover and ice thickness shall be less than 30 cm.

In ARICE *Deliverable 1.2. Guidelines on the conditions to access European PRVs* (ARICE 2019, 4), we presented a list of European PRV fleet where we referred to two frameworks for the measurement of vessel capabilities in ice navigation: the IMO Polar Code ice-classification and International Association for Classification Societies (IACS) Unified Requirements for Polar Class Ships. To compare vessel capabilities and costs in this report, we use these two frameworks as part of the comparison also here. To further facilitate the contextualization of the new vessels with global capabilities, we have also added an updated, corrected and internationally expanded overview of the list of vessels in Annex A.

1.4. Equivalences of ice classes according to IMO Polar Code, IACS Polar Classes and national ice classes

In addition to the IMO Polar Code and IACS PC, there are national ice classes owned by flag states where Finnish-Swedish (SWE-FIN), Russian, and Canadian are the most prominent. These are all setting criteria for each class and relates them to operating conditions (in respective area).

All vessels when built must abide by the construction rules of a classification society. When a vessel is built for heavy ice conditions, requirements for the operation area are studied and construction design is managed to match. Vessels are often matched to the construction rules *of a classification society and national ice classes* to meet the conditions in the planned area of operation and hence is built to the rules matched to national ice classes. For example, in wintertime in the Baltic, the normally required Finnish-Swedish ice class is 1A, which refers to, typically, 0.8-meter-thick first year ice and the traffic is assisted by Swedish and Finnish icebreakers. In Figure 1, we present a comparison of ice classes according to IMO Polar Code, IACS PC and some national ice classes.

In order not to get lost in the compromises of the above rules, an easy way of categorizing tonnage for ice operations is dividing the vessels in three categories that outlines the intention of their ice capability:

1. Icebreakers: vessels constructed to protect and assist other vessels in the ice. The vessels are built for very aggressive operation in ice, (i.e. IB Oden and PRV Polarstern).
2. Icebreaking vessels: vessels that for its own progress may operate aggressively in ice. (i.e. icebreaking research vessels RV Akademik Fedorov, RV Sikuliaq and S.A. Agulhas II).
3. Ice classed vessels: vessels that are ice-strengthened and may follow icebreakers and even proceed on their own in lighter ice conditions, (e.g. RV Maria S Merian).

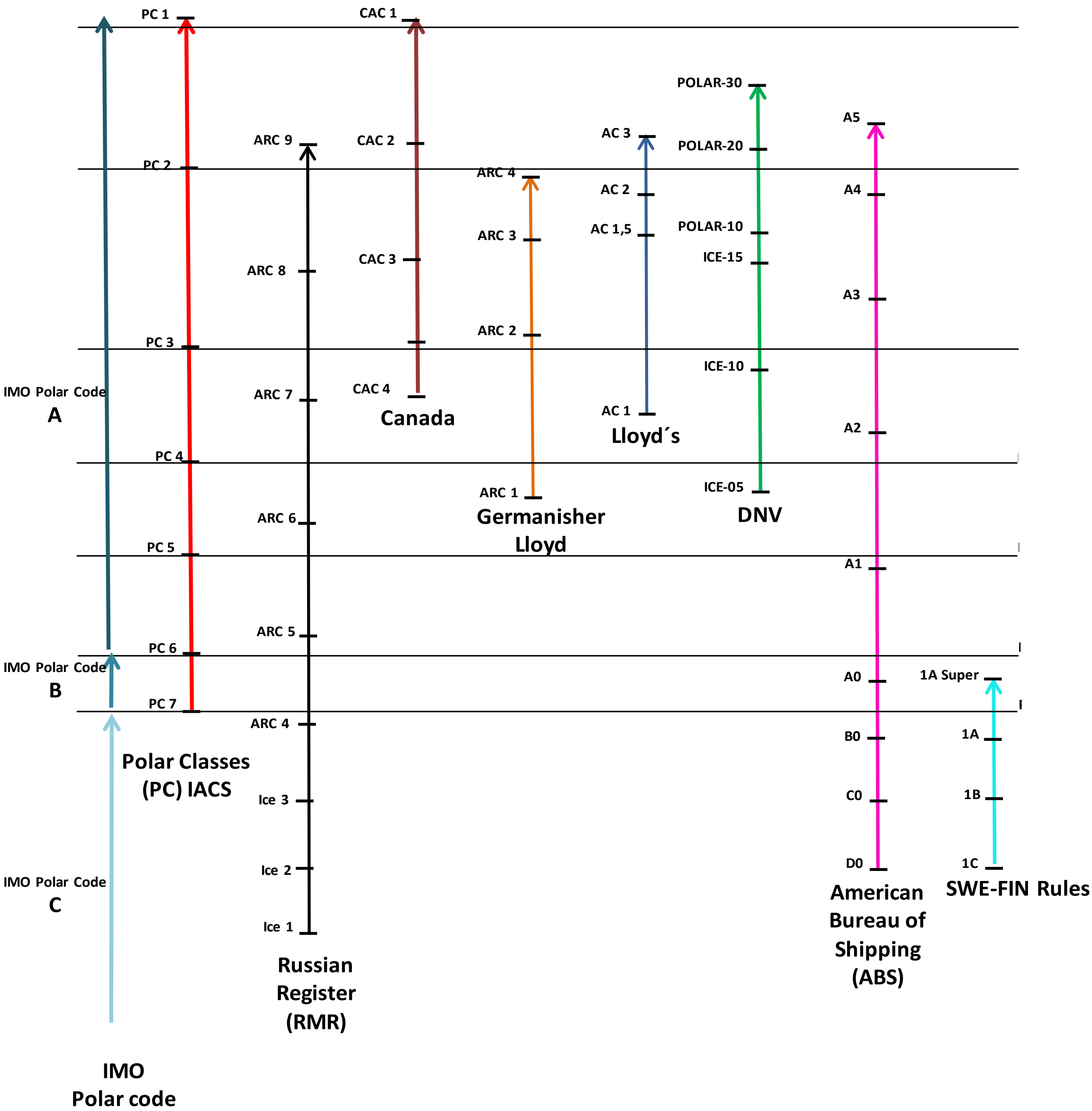

Figure 1. Comparison of ice classes according to regulating bodies IMO Polar Code, IACS PC, some national ice classes as well as to classification societies Germanischer Lloyd, Lloyd´s and Det Norske Veritas (DNV). The table was first drafted by Central Marine Research and Design Institute (CNIIMF) in Russia and has been modified by Arctic Marine Solutions AB, Sweden.

2. Costs and economics associated with Polar research vessels

Like other branches of global ocean science, Arctic marine research can be characterized as "big science" because it requires "numerous staff and large and costly equipment" (IOC-UNESCO 2017, 20). The natural geography and climatic conditions in the Arctic Ocean further add to the cost of conducting scientific research (The Aspen institute 2011, 28).

Vessels for Arctic expeditions also need an extraordinary endurance. Voyages can often be up to 90 days as transit to the area is long, places for refueling and crew change are very scarce and the cost of transit etc. pushes for extended work once in the operation area.

The costs and economics associated with Polar research vessels (PRVs) are complicated (Nieuwejaar et al. 2019, 10). These can vary significantly from season to season and vessel to vessel depending on the ownership, governance, icebreaking capabilities and performance of the vessels.

To compare costs of PRVs with other vessels, especially research vessels for open water, costs must be divided into cost categories.

1. Capital expenses (CAPEX), the cost of building the vessel
2. Operational expenses (OPEX), crew and maintenance, daily cost of operating the vessel.
3. Voyage expenses: fuel, harborage, pilot costs and direct costs for voyage.

2.1. Capital expenses of polar research vessels

The cost of constructing a polar research vessel is influenced by:

- The ice class of the vessel
- The vessel size (influencing number of on board participants and endurance)
- The vessel design (standard ship vs unique design)
- The scientific equipment included in the design
- -The shipbuilding market

The final cost of constructing a polar research vessel is the sum of costs which are influenced by the planning process before construction i.e. the size of the vessel, the design phase and the testing of ideas influencing the design plus the shipyard market price for ship construction at the point in time when the vessel was built. The cost usually is made up of the cost of the financing the funds paid to the shipyard during the construction phase and the inspection/oversight of the construction at the yard. Typically, the latter is an additional 5-10% of the actual contract price.

Ice class of the vessel:

A rough estimate, looking at ship design in the most effective way the cost for the “ice component” would add, around 10% for a PC-3 and 20% for a PC-1-2 compared to an open water vessel (AMS)

Vessel size and design:

The vessel design will define the ship size, endurance and will influence the running costs through fuel consumption among others (due to less efficient hull-shape for open water and resistance from ice).

The CAPEX cost can be very different if a standard vessel is built and then adapted to science, or if designing the science part first and then build a one-of a kind ship around the science. For example, an icebreaking research vessel with design optimized for ice capability and endurance and built in of some basic scientific systems like dynamic positioning (DP), moonpool, multibeam and sea water systems included in design from start but yet with space and possibility to fit further specialized scientific requirements after, will have a huge influence on price compared to designing and building the vessel around science already from the start.

This also explains some of the wide range in cost between research vessels we can see, again depending on ship size, endurance, ice capability and design process. For example, the future PRV Polarstern II that was planned at EUR €455M, is now approaching €650M fully equipped for science (Brockmann, 2020).

In Sweden, current discussions with an industry consortium in support of polar science estimates that the construction costs of a new Swedish icebreaking research vessel with PC-1, larger (140x30meter) and stronger (30MW) than IB Oden (see Annex A for description of IB Oden), is €150M. This estimated cost would include DPS and the minimum built-in scientific equipment (e.g. multibeam, winches for CTD and drilling, moonpool, sea water system, IT). This estimation is based on a potential contract with an international shipyard (AMS professional experience). The estimated price for this vessel is considerably lower than the estimated for the future PRV Polarsten II. One reason behind this is that Polarstern II is planned to be delivered already equipped with all the necessary scientific equipment, whereas the estimated costs from the Swedish industry consortium only includes the basic built-in scientific technique. This would allow that specific scientific equipment is added later on for future expeditions. Another difference lies in the estimated CAPEX which in turn is related to the complexity of the science design.

Scientific equipment included in the design:

The cost for scientific equipment does not vary between PRV and open water vessels but more from scientific ambition and degree of advanced approach and this must be considered when comparing research vessel building costs.

Shipbuilding market:

Another important factor for CAPEX is the ship building market. As research vessels are often one-of a kind, the price will be depending on the ship building market at the time. If yards are busy the vessel will be more expensive and if ship building is low the project will be very welcome. Cost of steel is not a major price driving factor.

National polar research vessels, compared to commercial vessels, are often built with other priorities than cost efficiency. The peculiarities of US shipbuilding; for instance, typically make building costs substantially higher than in any other place in the world and US contract prices must therefore not be compared to others.

It may be concluded that vessels for polar research are built, in most cases, as one-off a kind projects and this means that all design costs need to be carried by the one vessel built. Furthermore, the building yard cannot realize the substantial efficiency gains in productivity that comes from building a series of vessels. Multi or bi-lateral cooperation could reduce costs, provided national interests could be balanced.

Design optimization

The main purpose of a research vessel used in heavily ice infested waters is to safely take scientists to and back from interesting places for research which are out of reach for other vessels. This is a challenge for the vessel and its construction. Not only the ice but also the remote operation requires a very special vessel, not available “off the shelf”. The design must be optimized to its operation area and work task. For PRVs built for long expeditions in remote locations with severe ice, the design will have more focus on the vessel performance than for an open water research vessel.

Simply put, the design process of an ice capable vessel can start from the science and research visions or it can have its origin in the ship building tradition. In short, building a vessel around science or building science around a vessel.

Experience show that the latter is a way to keep the costs down. The reason for this is that an open process aiming to design the science on the ship will involve many special interests that must agree on a compromise. Once this is done the ship designers shall build the vessel around the scientific blueprint where all the science stations are laid out. This process often results in special solutions that are “one off a kind” and the vessel becomes expensive for the shipyard to design and build.

Going the other way, and thereby avoid "one of a kind" vessels. The designers can design an optimal vessel for its intended operation/science work area, including only functions that needs to be built into the ship from start as well as open space for future science installations. The facilities for science can significantly escalate the cost of building if not carefully managed

2.2 Operational expenses of polar research vessels

Operational expenses (OPEX), also known as "running costs" includes the following categories: crew wages and travel, management fees, insurance, maintenance and repairs, survey and certification, and drydocking. Running costs are calculated as a fixed daily cost. Running costs usually do not include fuel expenses.

Thus, it is not only vessel design and the remoteness that adds costs to the vessel-based Arctic research. The OPEX strongly depends on the size and complexity of the ship. These factors influence the number of crew members needed for technical- and science support, catering as well as the maintenance. The annual running costs for the vessels included in the ARICE consortium are presented in table 6. Part of the differences in running costs are due to the age of the ship and to the need with the age of more maintenance and renewal of equipment (for safety) and/or certifications.

2.3 Voyage expenses of polar research vessels

The long transit journeys to the research areas, the extra power needed for icebreaking and the less efficient hull shape of an icebreaking vessel increase voyage costs in terms of e.g. bunker consumption. The increased bunker cost over the last 20 years significantly changed the cost structure for marine based research and especially for operations in ice.

Because voyage costs depend strongly on the type of cruise and ice breaking activities, this cost is highly variable. The European Marine Board (EMP) estimates that only the fuel consumption of PRVs operating in polar waters can be up to 30% more than in other regions (Nieuwejaar et al. 2019, 10).

3. Recent investments into the acquisition of national PRV

In order to bring light to the investments made into polar marine research infrastructure, we review the costs associated with vessels that:

- Have been acquired (or being substantially retrofitted) during the past ten years or confirmed to be completed within the next five years.
- Operate or have plans to operate in the Arctic, which means vessels that have only dedicated operations in Antarctica are not included here.
- Are officially dedicated to research at least part of the year. This distinction leaves i.e. the Russian Project 222200- LC60YA for the acquisition of a new fleet of five nuclear icebreakers outside the scope of this study (Nilsen 2019).

For single vessel operations (i.e. not assisted) in ice covered waters and contributing to *Arctic icebreaker capacity to research,* only vessels grouped in PC class above 3 have the full capacity to work in the southern parts of the Arctic Ocean/MIZ or higher latitudes.

To exemplify the highest ice classes:

PC -1 Single vessel, year around operation in any ice

PC -2 Single vessel, summer and fall operation in any ice and year around operation in any ice if assisted by a PC1 vessel.

PC-3 summer operations in broken pack ice and year around operations in any ice if assisted by a PC1 (winter) or PC-2 (summer) vessel.

PC-4 is below the requirement as MYI is outside the capacity and MYI can be met in all Arctic even if in places rare.

PRVs are expensive national assets. During the past ten years only four new vessels with capability for research in the Arctic have been built in the world. The rough average acquisition cost of the vessels in this class is €200M, but the capabilities of vessels in this category vary significantly and none of the four recently acquired vessels are, for example, equivalent to IACS PC2 like the German PRV Polarstern or the Swedish IB Oden that were built already in 1982 and 1989, respectively, and will come soon to the end of their service life.

In order to illustrate the differences in acquisition cost and capabilities of vessels in different ice classes, we have not only reviewed the acquisition cost of high ice capacity vessels but also those in categories A, B and C, which includes ice-strengthened vessels but that are below the requirements.

Next to the plans that have been executed, there are planned and pending global investments in Arctic icebreaker capacity to research in different stages. We have referred to these estimated costs when appropriate.

3.1. European polar research vessels

A recent report from the European Marine Board (Nieuwejaar et al., 2019, 65 and references therein), reports that the total European PRV fleet in 2007, not including Russia, consisted of 13 ice-strengthened vessels out of which only two are ice-going or icebreaking vessels capable of year-round operations in high Arctic conditions i.e. PC 2 or above. Since then, investments in polar research capacity have been made in PC 3 vessels and below. Table 2 presents an overview of some recent European PRV investment together with their Polar Code category (for Polar Class see Annex A). However, as discussed in chapter 1, the classification of PRV is not a single representative measure on the resource investment in Arctic icebreaker capacity to research.

Table 2. Current resources investment in PRV to research in Europe

Country	Ship Name	Length (m)	Operator	Polar Code category	Acquisition budget (€)	Year built
Belgium	Belgica II	71	RBINS-OD Nature	C	54M	2020
Finland	Aranda	66.3	SYKE	B	15M	Retrofitted 2017 (built 1988)
Germany	Walter Herwig	85	BAW	C	85M	2020
Germany	Polarstern II		AWI	A	550-650	2027 tentatively
Greenland	Sanna	32	GINR	B	6,7M*	2012
Italy	Laura Bassi	80	OGS	A	12M in year 2019	1995 Retrofitted 2020

					(plus retroffitting costs)	
Norway	Kronprins Haakon	100	IMR	A	175M*	2018
Sweden	Svea	69	SLU	C	44,5M*	2019
Sweden	Skagerak	49	UoG	C	15M*	2017
UK	Sir David Attenborough	129	BAS	A	228M*	2018
UK	RSS Discovery	99	NOC NERC	C	84M	2013

* Indicates a converted currency. In the case of Sweden, Greenland, and the United Kingdom the sums have been converted from national currencies with the average rate for the currencies as reported by the European Central Bank Statistics (ECB). The acquisition costs in the local currencies were as follows: FF Kronprins Haakon NOK1,4B; RSS Sir David Attenborough £200M; Sanna DKK50M; Svea SEK445M; Skagerak SEK 150M.

A handful of recently purchased European research vessels fall under IMO category C (Table 2). This means that they do not qualify for IACS ice class but have some ice strengthening that qualifies them to operate in ice-prone areas such as the Baltic Sea (EMP 2019, 72). Of these vessels:

- The new Walter Herwig will be focused on fisheries research in Baltic, North Sea and North Atlantic (Thünen institute 2020; Todd 2017).
- R/V Svea is regularly used for environmental monitoring of Swedish seas by Swedish Meteorological Institute, Swedish Institute for Marine and Water Management, and the vessel operator Swedish University for Agricultural Sciences, (SLU 2020), but is also open for other projects (Naturvårdsverket 2018; SLU 2020).
- R/V Belgica II is a multidisciplinary vessel that is planned to operate in the North Sea, Atlantic Ocean, Mediterranean Sea and Arctic region (Naval Technology 2020).
- R/V Skagerak will be operated and used by University of Gothenburg for marine research in Swedish waters (Vive 2020). RSS Discovery is a global ocean research ship that has conducted marine research in the Arctic during the summer season.

As they are only ice-strengthened rather than ice-classed, none of these vessels can operate in the high Arctic or in conditions required for PC7.

Recent investments: IMO Category A and B vessels

Finland

The Finnish research vessel Aranda (built in 1988) was retrofitted in year 2017 and made 7 meters longer and is therefore included in this review (Table 2). The budget for the renovations that even extend the service life of the vessel until the 2030s was €15M (Hallamaa 2018; Finnish Environment Institute 2018).

Germany

There is one pending process for acquisition of a heavy icebreaking PRV, Polarstern II, ongoing in Germany. The estimated cost for the vessel was €455M in 2012. The tender invitation was issued in 2015. In 2018 the cost estimation for the new vessel had risen to €550-650M. In February 2020, the Berlin Research Ministry (BMBF) cancelled the five-year-old tender invitation and promised a new award procedure in the future leading to a more modern ship. The original plan was that the new PRV would be ready to replace the old Polarstern already in 2020. The cost of maintenance, repair, and technical upgrades of the old Polarstern now total a reported €10M a year (Todd 2018; 2020). It is currently unclear when a new ship can be ready but most likely a vessel could be ready 2027 if the project can be restarted.

Greenland

The newest acquisition of a category B class ship in Europe is R/V Sanna operated and owned by the Greenland Institute of Natural Resources (GINR). The vessel, launched in 2012, was built in Karstensens shipyard in Skagen and mainly use by GINR for fisheries and marine environment research in coastal waters of Greenland (GINR 2020).

The vessel's scientific equipment includes pelagic and demersal trawling to 1000 m, Fishery acoustic surveys, Hydrographic surveys, Mooring deployments, and Benthic surveys (Eurofleets+ 2020). It can even be engaged prospecting for oil and minerals (GINR 2020).

Italy

Since May 2019, the previous BAS vessel, RRS Ernest Shackleton, has been the property of Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) in Italy. The management of the ship is entrusted to a public consortium which includes OGS, CNR and ENEA, these two latter agencies in charge of supervising, planning and carrying out the Antarctic Research Program (PNRA).

The vessel, which was renamed N/R Laura Bassi for OGS after the sale, was originally built in 1995 by Kvaerner Leirvik A/S Norway for Rieber Shipping, as the MV Polar Queen. She was later acquired by BAS that has used it primarily as a logistics vessel to transport cargo, fuel, and passengers from 1999 (BAS 2020a).

N/R Laura Bassi has a basic scientific capability and is the only Italian vessel in polar class. The purchase price in 2019 was €12M (OGS 2020). Scientific capabilities of the ship regarding morphobathymetry, oceanography, scientific fishery, water and sea-floor acoustics, sediment sampling, atmospheric observations will be improved thanks to a contribution of 5 M€ from CNR and xx?? M€ from OGS. Certification for Polar code and operational conditions until -30°C will be also made. Its yearly operational costs are between €400-600 000 with an additional cost of about €300 000 for maintenance of the two motors (Alberizia 2019).

Norway

The Norwegian government decided about the acquisition of a new national ice-going research vessel in October 2012 with an allocated budget of 1.4 billion NOK (~€175M). The new vessel in category A was to replace several older vessels with lower ice class. It was designed by Rolls-Royce in Norway and built in Italy by the shipping yard consortium Fincantieri. The initial delivery was planned for 2015 but was delayed until 2018 (Stensvold 2017; Kirstofferssen 2014; Hellesund 2018; Havforskningsinstituttet 2020).

In terms of operating cost and environmental concerns, the vessel, which was named FF Kronprins Haakon constitutes an innovative PRV project with a liquefied natural gas generator for ice station and a low underwater noise radiation following ICES-209 (Dañobeitia et al. 2014, 14).

The vessel has a gross tonnage of around 9,000, is 100 meters long and 21 meters wide, and can accommodate 55 people - scientists, students and crew - in 38 cabins. The hangar in the bow has space for two helicopters and is equipped with complex instruments for studying the marine ecology, morphology and geology of the sea floor. Designed by Rolls-Royce, the ship have a cruising speed of 15 knots and be capable of breaking through ice up to one meter thick (IMR 2020).

United Kingdom

In April 2014, the British Government agreed on the investment into a new £200 million PRV. The category A vessel, which was eventually named RSS Sir David Attenborough was commissioned by the Natural Environment Research Council (NERC), procured by UK Shared Business Services (UKSBS), built by Cammell Laird and will be operated by the British Antarctic Survey (BAS) (BAS 2020b).

Like FF Kronprins Haakon, RSS Sir David Attenborough is designed to include a set of new innovations and investments in cutting edge environmentally and fuel-efficient technologies.

With greater fuel efficiency and its ability to deploy remotely operated and robotic technologies, the ship is expected to reduce the environmental impact of ship-borne science and save (estimated £100mil.)* in operating costs over its 25-year lifespan (BAS 2016).

RSS Sir David Attenborough was launched on schedule in 2018. It was planned to commence operations in 2019. The start has, however, been delayed and is now scheduled to commence in 2023.

Commercial initiatives

Next to these public investments Norwegian Kjell Inge Rokke's foundation invested $350M in the acquisition of a PC 6 PRV in 2017 (Dixon 2018). The 182.9 m long vessel REV is planned to be launched in 2020 (Boat International 2018; REV Ocean 2020). Her use will span from private to scientific purposes, or mixed (tourism and science). Not included in table 2.

As another commercial comparison, Ponant, the French luxury owned cruise operator, ordered a PC 2 vessel with a reported contract price of approximately $324M in 2017 (Flanagan 2018; Mathisen 2017). The tourist vessel, which is expected to begin operation in 2021, will host a laboratory for research on board (Bureau Veritas 2020; Lonsdale 2019). Not included in table 2.

3.2. Non-European polar research vessels

Russia

Today the Russian Federation possesses the largest research fleet designed to work in the Arctic. It consists of 29 ships, which exceeds the total number of similar vessels of the United States, Canada, Norway, Sweden, Denmark, Finland, Germany, the UK, China, Japan and the Republic of Korea.

Most of the Russian ships belong to ice class Arc 4 or Arc 5 (Figure 1). They are regularly used in a relatively favorable ice conditions (thin, residual or young ice) in the summer and autumn navigation. The vessels "Akademik Fedorov", "Akademik Treshnikov" and "Mikhail Somov" can navigate in difficult ice conditions (ice class Arc 7 — independent navigation throughout the waters of the Northern Sea Route with all types of ice conditions in summer-autumn navigation or with icebreakers in the winter-spring navigation in the thick annual ice with thickness up to 1.8 m).

Among 29 Russian vessels, 26 were exclusively designed for research; the three other vessels ("Akademik Treshnikov", "Akademik Fedorov" and "Mikhail Somov") belong to the class of scientific and expedition ships, adapted for transportation of goods. This allows using them to supply the remote areas and polar stations (Kudrayashova et al 2017).

Russia has only one modern scientific and expedition vessel "Akademik Treshnikov" capable of research, icebreaker assistance, rescue work, and freight.

According to Kudrayashova et al (2017) the renewal of the Arctic and Antarctic research fleet is reflected in the state program "Development of shipbuilding and equipment for offshore fields development in 2015–2030". The document secures the priority of the state policy in the shipbuilding, the creation of a competitive specialized marine equipment, ships and vessels for the development of

* Specification from BAS 2020b.

the continental shelf and the Northern Sea Route, the creation of high-tech medium-tonnage transport and support vessels, high-tech fishing vessels, marine and inland research and scientific expedition vessels.

The Sub-program “Expeditions in the World Ocean” of the Federal target program “World Ocean” for 2018–2023 involves the construction of the research expedition vessel of the Arc 7 ice class to replace the R/V “Mikhail Somov” and to study the Arctic and Antarctic seas and to maintain the remote polar stations. However, the Government of the Russian Federation has not approved the Federal target program by now.

The Russian Navy plans construction of the research vessels. By 2024, it plans to introduce two ocean-going research vessels with ice class. The main task of these vessels will be carrying out a wide range of scientific studies in the Arctic (Kudrayashova et al 2017).

Table 3. Current resources investment in PRV to research in Russia since 2012

Ship Name	Length (m)	Operator	Polar Code category	Acquisition budget (€)	Year built
Akademik Alexandrov	96	Russian Navy	B	N/A	2018
Akademik Tryeshnikov	134	AARI	A	N/A	2012
Viktor Chernomyrdin	142	Rosmorport	A	N/A	2020
Serverniy Polyos	83	Roshydromet/AARI	A	122M	2022

A number of the modern Russian icebreakers are potentially workable for science duties as they have the required ice capability, but they are not dedicated to science. Of the modern Russian icebreakers, the Viktor Chernomyrdin (24 MW, built 2020) has 300 m2 space reserved for science laboratories, Dynamic Positioning, large bed capacity, significant helicopter capability, and would thus has significant science potential if used in this way.

As significant new research vessel capability, when delivered, will be the Serverniy Polyos (North Pole) that is a vessel designed as a drifting station in the high Arctic. The vessel will be operated by Roshydromet/AARI and shall be able to have an endurance of up to 2 years. It will have a crew of 14 and capacity of 34 scientists. The vessel is self-propelled (3.6 MW) and shall be able to navigate independently in light ice conditions. The vessel is currently being built at the Admirality Shipyard. Delivery was scheduled for 2020, but delivery is now expected 2022/2023. Original contract price in 2018 was RUB 6.97 billion (€90M) but as of June 2020 this has been increased by RUB 2.5 billion (€32M) to RUB 9.47 billion (€122M) (Staalesen A. 2020, AMS personal communication).

In 1997, Russia issued a presidential decree on expanding of Russia's activities in the Arctic, Antarctic, and World Oceans (Russian Federation 1997). The construction of the research expedition vessel Akademik Treshnikov was the first step in the implementation of the presidential decree (JSC Admiralteyskie Verfi 2012). According to the shipyard, the ship combines functions of icebreaker, dry cargo ship, passenger liner, and scientific research station; she has strengthened ice-class hull and is equipped with up-to-date navigation facilities, two heliports, special laboratories capable to process results of oceanographic researches, atmospheric soundings, and other scientific experiments (JSC Admiralteyskie Verfi 2012).

Akademik Aleksandrov is a multipurpose oceanographic research vessel that is built under Project 20183 – the Russian Navy's new generation special-purpose ships made for search and rescue operations and transportation of big-dimension maritime, military, and special equipment. According to shipyard Zvezdochka, which has built the vessel, it has equipment which enables it to conduct research activities on the Arctic shelf and take part in rescue operations in Arctic waters. The vessel has Russian ice classification Arc5, which allows it to operate in medium first year ice conditions without assistance of an icebreaker (Staalesen 2017; Baird Maritime 2019).

North America

Table 4. National investments in the acquisition of PRV in North America since 2011.

Country	Ship Name	Length (m)	Operator	Polar Code category	Acquisition budget ($)[4]	Year built
USA	TBA	x	USCG	A	746M	2024
USA	Sikuliaq	79.6	UAF	A	200M	2014
Canada	TBA	87.9	CCGS	B	249M [5]*	2024
Canada	Sir John Franklin	63	CCGS	B	Part of NSS 3 ship total 529M*	2017
Canada	Capt. Jacques Cartier	63	CCGS	B	Part of NSS 3 ship total 529M*	2019
Canada	John Cabot	63	CCGS	B	Part of NSS 3 ship total 529M*	2020
Canada	Nuliajuk	19.5	Government of Nunavut	C	2.32M*	2011
USA	Sally Ride	72.5	Scripps Institution of Oceanography	C	Total with RV Neil Armstrong 145M	2014
USA	Neil Armstrong	72.5	Woods Hole Oceanographic Institution	C	Total with Sally Ride 145M	2015

Both the American and the Canadian governments have announced plans to update their national icebreaking fleets. Canada has planned to procure six new program icebreakers to replace the Canadian Coast Guard's heavy and medium icebreakers that operate in Atlantic Canada and the St.

[4] Acquisition costs in Table 4 are presented in USD ($). The figures in table 4 have been converted from CAD to USD by using the annual average rates of Bank of Canada.

[5] * The original cost for the Canadian unnamed vessel was CAD 331M; the total for three ships CAD 687M; and for Nuliajuk CAD 3.2M.

Lawrence waterways in the winter and in the high Arctic during the summer (Vavasseur 2019).The order for a Polar icebreaker was cancelled, only smaller Coast guard vessels remain in the program.

The United States Coast Guard (USGC) Polar Security Cutter (PSC) program aims to acquire three new heavy polar icebreakers, to be followed by the acquisition of up to three new medium polar icebreakers (O'Rourke 2018).

None of the twelve vessels are dedicated solely to scientific research, but the roles of the new U.S. polar icebreakers, of which icebreaker number 3 is not yet ordered, specifically include conducting and supporting scientific research in the Arctic and Antarctic (O'Rourke 2018, 1). As such the recent acquisitions in Arctic icebreaker capacity to research in North America include; in category A, the 2014 built RV Sikuliaq and the 2019 tenured first USGC vessel that is pending building and delivery; in category B, three new Offshore Fisheries Science Vessels (OFSV), non-Arctic, in PC 7 and one offshore oceanographic science vessel in PC 6 that are built for the Canadian Coast Guard (CCGS) under the National Shipbuilding Strategy (NSS); and in category C, the Canadian MV Nuliajuk.

USA

In April 2019, the contract for the first of three new heavy icebreakers for the US was signed and valued at nearly USD746 million. The vessel will be constructed by VT Halter Marine Inc., Pascagoula, Mississippi, and is scheduled for delivery in 2024 (U.S. Dept. of Defence 2019). The contract includes options for building the second and third vessel. If these options are exercised, the total value of the contract would increase to USD1,942.8M (CRS 2020).

The figures of USD745.9M and USD1,942.8M cover only the shipbuilder's costs and do not include the cost of the equipment for the ships that the government purchases and then provides to the shipbuilder for incorporation into the ship, or government program-management costs. When these costs are included, the total estimated procurement cost of the first vessel is between USD925 million and USD940M, and the total estimated procurement cost of the three-ship PSC program is about USD2.95B (CRS 2020).

In terms of capacity, the USGC has only one heavy polar icebreaker in operation – Polar Star, which is at the end of its service life. The investigations for the cost of the work needed for the limited service life extension is to be conducted by June 2020. If the costs are higher than expected, the United States faces a potential gap in icebreaking capabilities of three years before the new vessel is planned to enter service (Figure 2).

Two Armstrong-Class Auxiliary General Oceanographic Research (AGOR) vessels were built by Dakota Creek Industries (DCI) for the US Navy's Office of Naval Research (ONR) between 2012 and 2014. The first vessel, R/V Niels Armstrong, is operated by the world's largest private, non-profit oceanographic research institution Massachusetts-based Woods Hole Oceanographic Institution (WHOI).

The pivotal role that the North Atlantic and Arctic Oceans play in Earth's climate has resulted in an increase in efforts to observe these areas, as well new efforts to study North Atlantic ecosystems and their sustainability. R/V *Neil Armstrong* will be uniquely equipped and positioned to enable scientists from around the world to reveal new details about this critical part of the global ocean (WHOI 2020).

The second AGOR vessel, R/V Sally Ride, is operated by the University of California, San Diego, Scripps Institution of Oceanography (SIO) (Verdict Media 2020).

R/V Sally Ride is an Ocean Class Auxiliary General Oceanographic Research (AGOR) vessel designed to perform multidisciplinary oceanographic research worldwide, from littoral environments to the deepest ocean, from the tropics into first-year sea ice (Scripps Institution of Oceanography 2018).

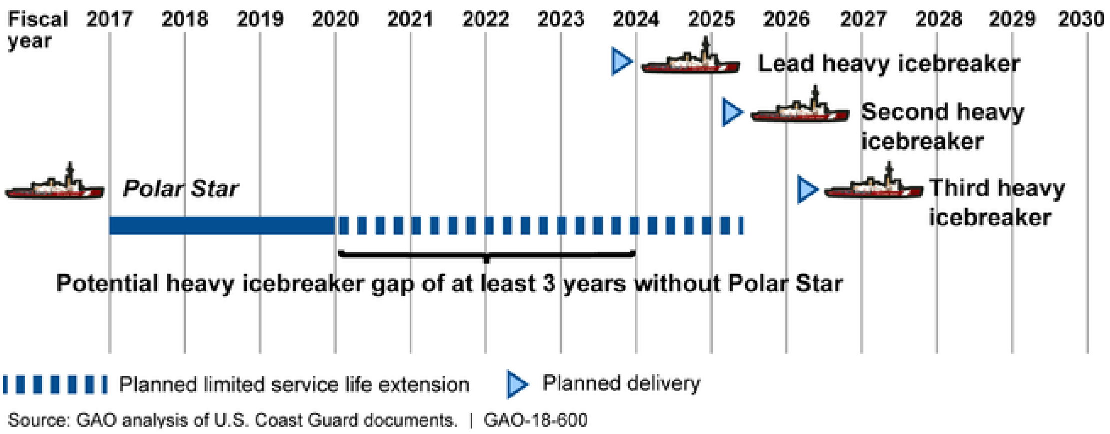

Figure 2. Potential gap in USGC icebreaking capabilities (US-GAO 2018).

Next to the USGC vessels, the United States has one category A class PRV, the 2014 built Sikuliaq owned by the National Science Foundation and operated by the College of Fisheries and Ocean Sciences at the University of Alaska Fairbanks (UAF), as part of the U.S. academic research fleet.

The acquisition of Sikuliaq was a long process. The need for a vessel that was able to operate in the coastal and open ocean waters of the Alaska region was first recognized by American marine scientists in 1973. It was only in 2001 that Congress appropriated USD1 million for a design study. Construction began in December 2009 (UAF 2020).

The vessel was designed by The Glosten Associates, a marine architecture and engineering firm in Seattle. Sufficient ice strengthening allows Sikuliaq to work safely in moderate seasonal ice, operating over a longer period than formerly possible in the North Pacific Ocean, Gulf of Alaska, and the Bering, Chukchi, and Beaufort Seas (UAF 2020)

Canada

Three new Offshore Fisheries Science Vessels (OFSV) in PC 7 are built under the National Shipbuilding Strategy (NSS) in Canada. The first vessel, Sir. John Franklin was launched in 2017 and the second Jacques Cartier in 2019. The third one, John Cabot, is planned to be launched in 2020. All three category B vessels are to be built by Seaspan's Vancouver Shipyards with a total budget of CAD687M (Withers 2020; PSP Canada 2019a). In terms of their operation area:

A 63m Canadian Coast Guard (CCG) fisheries research vessel, the OFSV will be deployed on Canada's east and west coasts. These ships will allow for a better understanding of the health of fish stocks and their ocean environment (Seaspan ULC 2020).

The first OFSV was launched on December 8, 2017. The second and third ships are currently under construction at Vancouver Shipyards (Seaspan ULC 2020).

In November 2015, Canada awarded the initial construction engineering contract for an Oceanographic Research Vessel (OOSV) to Seaspan's Vancouver Shipyards. It is anticipated that the start of production of the 86m OOSV that will be deployed on Canada's east coast will begin in winter 2021, with delivery scheduled for 2024. (PCP Canada 2019b). "Once in service, the OOSV will develop hydrographic charts and bolster our understanding of the ocean's physical environment." (Seaspan ULC 2020).

The Government of Nunavut in Canada purchased a category C fisheries research vessel, MV Nuliajuk in 2011. The vessel, equipped with specialized gear, which includes long lines, otter trawls and gill nets, supports science-based conservation and the sustainable development of Nunavut fisheries by understanding biological and environmental factors that influence fish stock health and productivity

(Nunavut department of Environment 2020). MV Nuliajuk has an operating and maintenance budget of CAD400 000 and can accommodate eight researchers plus captain and crew (Rogers, 2011).

Asia

Asian countries' steadily growing political interest towards the Arctic is mirrored in recent investments in icebreaker capacity to research. South Korea acquired the category A class PRV Araon in 2009. India has since 2010 planned to acquire a new PRV. In 2014, the budget was set at USD 171M (Offshore Energy 2014). The progress of the process has not been updated since the publication of a tender by National Centre for Antarctic & Ocean Research (NCAOR) in 2017 (NCAOR 2017). Chinese Xue Long II is, hence, the only new national PRV that has been built for an Asian country in the past decade, Table 5.

Table 5. Resent resources investments in Arctic icebreaker capacity to Research in Asia

Country	**Ship Name**	**Length**	**Operator**	**Polar Code Category**	**Acquisition budget ($)**	**Year built**
China	Xue Long II	122.5	Polar Research Institute China (PRIC)	A	613M*	2018

China

China launched plans to build a new research icebreaker in 2011. The vessel was designed by Aker Arctic in Finland with a design cost that exceeded €5M (The Marine Executive 2012; Qian 2014). After the delivery of the vessel design, she was built in China's Jiangnan Shipyard (Si 2019). The operator of the vessel is Polar Research Institute in China. In terms of the capabilities of the vessel:

Before the acquisition of Xue Long II, China had spent USD17.5M on the acquisition and USD3M on the refits of Xue Long I, a 1993 built vessel in category A (for Polar Class see Annex A) that it acquired from Ukraine in 2007 (Brady 2017, 165).

In June 2018 China National Nuclear Corporation (CNNC) issued a tender to build a nuclear-powered icebreaker. Shanghai Jiaotong University won the contract. (Eiterjord 2019). According to the tender this vessel will be 152 meters long by 30 meters wide, with a maximum draft of 18 meters and displace 30,069 tons, placing it among the largest icebreakers ever constructed (Humpert 2019). Delivery, building and further details about the new vessel are pending.

4. Operational costs of ARICE transnational access vessels

As mentioned before, the calculation of the average operational costs of PRVs is challenging as they can be significantly different from season to season and from expedition to expedition. Personnel costs vary, for example, depending on whether they are employed by the operator full-time or hired in seasonally on needs basis. Some PRVs are also owned by different national institutions than the ones that operate or use them for research. The time charters and expected costs are negotiated yearly. Another fluctuating variable in cost evaluations is fuel cost that varies based on coordinates for research and oil's market price. To give an indication of the estimated operational costs of PRVs, we have compiled data of the average costs of five of the six ARICE transnational access vessels under the heading of each vessel in Table 6. As sea trials of RV Sir David Attenborough will start in October 2020

6 *Acquisition costs in Table 5 are presented in USD ($).

and the vessel has not been running yet, a full overview of the running costs for this vessel is not available.

A description of the vessels with their main characteristics and operational costs breakdown when available is provided in Table 6 below.

Table 6. Operating costs of the ARICE Transnational Access Vessels. Cost of fuel is included in the annual operating costs, unless indicated.

Country	Ship Name	Length (m)	Operating area	Operator	Polar Code category	Year built	Construction costs	Annual operating costs
Germany	PRV Polarstern	118	Arctic and Antarctica	AWI	A	1982	€100M	€22M
Sweden	IB Oden	108	Arctic	SMA	A	1988	€34M	€6.5M excluding fuel
Norway	Kronprins Haakon	100	Arctic &Antarctica	IMR	A	2018	€175M	€7.88M
Canada	CCGS Amundsen	98	Arctic	CCG	A	1978 (retrofitted in 2003)	*see below	€9.6M
United States	RV Sikuliaq	79.6	Arctic	UAF	A	2014	$200M	$10M

* The CCGS Amundsen was made possible after a consortium of 15 Canadian universities and research centres, in partnership with the federal government, received funding from the CFI for the retrofit of the decommissioned Canadian Coast Guard Icebreaker Sir John Franklin as an Arctic Ocean research vessel through a contribution of $27.5 million from the CFI International Joint Venture Fund (IJVF).

PRV Polarstern

The Research Vessel Polarstern is based in Bremerhaven and operated by the Alfred-Wegener-Institute, Helmholtz Centre for Polar and Marine Research. Since its commission in December 1982, she has logged 2.7 million kilometres (as of 2014). Still today she is one of the worlds most advanced and versatile polar research ships.

With a maximum capacity of 124 persons, among them a crew of 44 members, the Polarstern operates an average of 310 days a year, typically cruising in the Antarctic from November to March and pursuing research in the Arctic during the northern hemisphere summer months. In the process, she covers ca. 50 000 nautical miles every year – the equivalent of two trips around the Equator. The Polarstern can even operate in the pack ice zone: a double-walled steel hull and 20 000 horsepower allow her to easily break through 1.5-metre-thick ice; thicker ice can be overcome by ramming. Further, the Polarstern is equipped for sustained operations at temperatures down to -50 degrees Celsius, and can even overwinter in the ice of the polar seas.

The averaging costs of operating such an infrastructure amount to 71.532€ per day, which is 1490€ per scientific berth and day (as of 2017/2018). Operating an average of 310 days a year, the annual budget for operating such an infrastructure is ca 22M€ per year, including cost of fuel on a full costs basis. Fuel usage varies strongly by the operations with breaking ice and transiting. The vessel is not available for commercial charter.

During the current operation of Polarstern in the frame of the MOSAiC Expedition, operating costs of MOSAiC alone are roughly €200 000 per day (not including the costs for the instruments or researchers). The total budget of the expedition amounts roughly €140M, of which about 70% is covered by the BMBF which provides the platform and significant parts of logistical support free of charge.

IB Oden

An example of a cost efficient and flexible vessel is the icebreaker ODEN, that today is a highly regarded polar research vessel, but that was not built with science in mind.

IB Oden is owned and operated by the Swedish Maritime Agency (SMA) and the approximate yearly operating cost is about €6.5M for both icebreaking missions for shipping in the Baltic wintertime and Arctic science expeditions during summer season, excluding fuel. Fuel consumption for science expedition depending on expedition route and ice conditions fuel can cost € 20K per day (500$/m3) The Swedish Polar Research Secretariat (SPRS) has a long-term time-charter agreement with SMA and covers the operating costs during the charter time plus the costs for science infrastructure and science support personnel. On science expeditions, IB Oden has a crew of 23 and SPRS science support crew of approximately 10, including meteorologists, medical doctor, technicians, helicopter pilots etc. Since IB Oden is classified as a special purpose ship, she can carry up to 40 additional science personnel. In summary, the expedition costs for IB Oden should cover the expedition preparations, transits, expedition day rates, Oden fuel, helicopter day rates and fuel, extra personnel etc. The actual cost for an Oden expedition is updated and negotiated prior to each expedition due to the special adaptations needed, estimations on routes and fuel consumptions and other parameters. From a practical standpoint ODEN can operate in 2 m respectively 3 m thick ice making progress.

ODEN's science capability is fundamentally coming from the vessels ability to bring the scientists "where they want to go for science". It is estimated that the gradual cost of adaption of the ODEN for science has been in the region of €10M spread over the last 30 years. (Source: SPRS)

Icebreaker ODEN was constructed for Arctic Icebreaking and Ice Management as opposed to POLARSTERN that was designed for polar research

Kronprins Haakon

The average operating costs of FF Kronprins Haakon, which is owned by the Norwegian Polar Institute, but operated within the fleet of Norwegian research vessels by the IMR and is based in Tromsø, is around NOK 80M (€7.88M) per year – including cost of fuel. This is, however, a very crude calculation.

The big uncertainty in operating costs is fuel consumption, which varies depending on whether the vessel is operating in ice or not. Research projects that plan operations in thick ice must calculate that the cost of fuel will be high. Fuel consumption can vary from 16m^3 to 80m^3 per day, which is the difference between minimum and maximum consumption. Individual research projects cover the actual fuel costs and research personnel's costs; thus, the price is not fixed beforehand.

CCGS Amundsen

The CCGS *Amundsen* is a Canadian Arctic Class 3 icebreaker (equivalent to Polar Class 4) from the Canadian Coast Guard (CCG) built in 1979 and refitted for science in 2002-03 following substantial investments from the Canada Foundation for Innovation (CFI) and Fisheries and Oceans Canada (DFO).

The scientific mandate of the vessel is managed by the not-for-profit Amundsen Science corporation (www.amundsen.ulaval.ca) according to a signed cost sharing agreement between the CCG/DFO and Université Laval (Québec, Canada). The agreement implies that up to 152 days per year could be dedicated to science operations from May to November, including mobilisation and demobilisation. The remaining of the year (from approximately December to April) is devoted to icebreaking and escort in the St. Lawrence estuary during the harsh Canadian winter. However, the vessel has so far supported two overwintering expeditions of more than 300 days in the Canadian Arctic (CASES 2003-04 and IPY-CFL 2007-08); and since 2018, opportunistic winter missions on-board the vessel in the St. Lawrence River are also conducted. Owing to her age, the CCGS *Amundsen* will undergo an extensive vessel life extension (VLE) refit over 2020-22 that should add an additional 10-15 years to her current life span, while new Canadian icebreakers are expected to being built within the country. The VLE scope of work will include a complete refit of the propeller, propulsion and dynamic positioning systems. New more powerful cranes will also be installed. Note that the VLE refit will be conducted during winter, implying that a full time window for arctic science will remain open during the summer months. With additional support of the CFI, the vessel is also being adapted for cutting-edge oceanographic technologies such as a Hugin 1000 AUV (2019), EK80 echosounder (2020), work-class ROV (new FTE Comanche ROV in 2021), EM304 multibeam upgrade (2021-22), and Calypso-type geological coring (2022).

Running costs for the *Amundsen* as of 2018-19 (Table 7) include transit time to position the vessel from/to the Canadian Arctic, expedition days, support costs (food/accommodations, helicopter, zodiac/barge, etc.), scientific equipment/vessel repairs and maintenance (prorated to the duration of the science mission), mobilization/demobilization costs, and personnel costs (crew, technical and logistic). Note that fuel costs may vary from year to year and according to the nature of the program (frequent icebreaking, ROV operations, etc.). The current approach is to provide to users a mean daily cost for the ship for planning purposes. However, these costs have to be modulated depending on needs and requirements. Further information on costs for any given program can be obtained by contacting info@as.ulaval.ca.

Table 7: Cost estimates for an average *Amundsen* annual expedition of 152 days including mob/demob (based on 2018-2019 costs).

Cost category	**Daily rate (€)***	**No of days (example)**	**Estimated cost (€)***
Transit days (Quebec City to/from Baffin Bay)	33,793.10	14	473,103.45
Arctic expedition days	43,448.28	118	5,126,896.55
Mobilisation/Demobilisation days	17,241.38	20	344,827.59
Support costs (food, helicopter, zodiac, etc.)	594,482.76	-	594,482.76
Scientific equipment/vessel repairs and maintenance	1,605,103.45	-	1,605,103.45
Personnel costs (crew, technical, logistic)	1,507,160.68	-	1,507,160.68
Total €			9,651,574.48

* Costs not included in the table include charter/commercial flights to board the vessel in the Canadian Arctic, helicopter fuel for dedicated science operations (e.g. glacier surveys), and additional technical/logistical support for special projects (e.g. AUV, ROV, moorings). Note that additional investments towards the VLE refit are not included.

RV Sikuliaq

R/V Sikuliaq [pronounced: see-KOO-lee-auk] is a 261-foot oceanographic research vessel capable of breaking ice up to 0.9 meter thick. *Sikuliaq's* homeport is located at the University of Alaska Fairbanks (UAF) Seward Marine Center (SMC) in Seward, Alaska.

The vessel is owned by the National Science Foundation and operated by the UAF College of Fisheries and Ocean Sciences (CFOS), as part of the U.S. academic research fleet. *Sikuliaq* is used by scientists in the U.S. and by the international oceanographic community through the University-National Oceanographic Laboratory System (UNOLS).

The average operating costs of Sikuliaq are around USD10M, including fuel, crew salaries and benefits, and parts and supplies. Fuel usage varies by the operations with breaking ice and transiting using the most fuel (about 24.6 m^3 per day) to on-station operations (about 6.8m^3 per day).

5. Conclusions

Arctic Ocean science is "big science" that requires big investments. Calculating the average costs for these investments is difficult due to changing fuel prices and consumption and the different organizational and operational structures. In general, better ice navigation and research capabilities result in higher acquisition costs and the capacity results in longer expeditions further away, and hence higher operational costs.

In estimations of costs for the acquisition of new PRVs in IACS Polar Class 4 and budgets for recent builds in IACS Polar Class 1-2, the difference for the ice component is approximately 10-20%. Even though their acquisition costs of new vessels are high, newer vessels can ease operation and maintenance costs through technological innovation.

The main drivers of cost for ice capable vessels is the vessel design for research capability, ice capability, endurance (remote operations), and extra fuel consumption (due to less efficient hull-shape for open water and resistance from ice).

Vessels for polar research are in most cases built as one-off a kind projects and this means that all design costs need to be attributed to the one vessel built. Multi or bi-lateral cooperation could reduce costs, provided national interests could be balanced.

Even when political decisions for investment in the acquisition of new PRVs have been made, the timespan from governmental decision to tenure, build and delivery is long, ca. five years in average. Due to the old age of the current global PRV fleet and the dual-duties of most of the new category A PRVs (Arctic research and supplying national Antarctic research bases), the risk for significant gaps in capability for research in the Arctic Ocean is high.

Only few of European countries own vessels that can operate in high Arctic and marginal ice zone. This is mainly due to the fact that the commitment of owning and operating a PRV does not end with the construction of the vessel. The operation and maintenance of those costly infrastructures represents a very big budget that must be sustained by national and institutional dedicated allocations. As seen in this report, only the operation of European icebreakers for research in the Arctic (PRV Polarstern, IB Oden and RV Kronprins Haakon) is in the order of €40M per year, for a total of 650 operational days.

European nations with strong polar programmes and no dedicated infrastructures could strongly benefit from sustained mechanisms (and/or bilateral agreements) to ease Trans-National access while sharing operational costs.

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Annex A. List of polar research vessels

Category		
	ib	Icebreaker
	ibV	Icebreaking Vessel
	ic	Ice-classed Vessel

Cat	Name	Year	IMO number	Type	Owner/Operator	Length (m)	Beam (m)	Draft (m)	Shaft power (MW)	Machinery	Propulsion	Bollard Pull (tons)	Ice class	Class	Comment	Icebreaking capability level ice at 2 knots (m)	Country
ib	Almirante Irizar	1978	7533628	Research	Argentine Navy	121,3	25,2	9,5	11,9	Diesel-electric shaftlines	2 x FPP	122	(n/a)		Refit 2008-2016	1,0	ARG
ibV	Aurora Australis	1990	8717283	Research	P&O Maritime Services	94,9	20,3	7,9	10,0	Diesel-mechanical shaftline	1 x CPP		1A Super	LR		1,3	AUS
ibV	Nuyina	2021*	9797060	Research	Australian Antarctic Division	156,0	25,6	9,6	26,6	Diesel Direct Hybrid	2 x CPP		PC3	LR		1,75	AUS
ic	Belgica	2020*	(n/a)	Research		71,4	16,8	4,8			2 x Pod		1C	DNV	Research ship		BEL
ic	Ary Rongel - H44 (ex old Polar	1981	7922142	Research	Brazilian Navy	75,3	13,0	6,0	3,3	Diesel-mechanical shaftline	1 x CPPn						BRZ
ib	Amundsen ex Franklin	1979	7510846	Icebreaker	Candian Coast Guard	98,3	19,5	7,2	11,0	Diesel-electric shaftlines	2 x FPP		Arctic class 3		R-class icebreaker	1,15	CDN
ibV	Antártica1	2023*	9843948	Research	Chilean Navy	109,8	21,0	7,2	9,0	Diesel-electric shaftlines	2 x FPP		PC 5	LR	Under construction	1,2	CHI
ib	Polarstern	1982	8013132	Research	Alfred Wegener Institute	117,9	25,1	11,2	14,0	Diesel-mechanical shaftlines	2 x CPPn	209	ARC3	GL DNV		1,45	DE
ic	Maria S. Merian	2006	9274197	Research	Liebniz Insitute	94,8	19,2	6,5	4,1	Diesel-electric	1 x Pod		E3 (hull PC7)	GL	Research ship		DE
ic	Walter Herwig IV	2023*	(n/a)	Research	BAW	84,7	17,4	5,6	3,0	Diesel-electric	1 x		1C	GL DNV	Research ship		DE
ic	Hespérides - A33	1991	8803563	Research	Spanish Navy	82,5	14,3	4,5	2,8		1 x CPP		1C	LR	Additional ice strengthening		ESP
ic	Aranda	1989	8802076	Research	SYKE	66,3	13,8	4,6	2,9	Semi-diesel electric system	1 x CPPn		Ice 1A	DNV	Vessel lengthened and refurbished in 2018		FIN
ibV	L'Astrolabe	2017	9797539	Research / Supply	French Navy	72,0	16,0	5,3	6,4	Diesel-mechanical shaftlines	2 x CPP		PC5 + additional	BV			FR
ic	Sanna	2012	9606065	Research	GINR	32,3	10,0	4,9	0,8				(n/a)	DMA	Research ship		GRL
ic	Laura Bassi ex Shackleton, Polar Queen	1995	9114252	Research	OGS	80,0	17,0	7,4	5,1	Diesel-mechanical shaftline	1 x CPPn		DNV ICE05	RINA			IT
ib	Shirase (5003)	2009	(n/a)	Research	JMSDF	138,0	28,0	9,2	22,0	Diesel-electric shaftlines	2 x FPP		(n/a)				JAP
ibV	Araon	2009	9490935	Research	Korea Polar Research Institute	111,0	19,0	7,6	10,0	Diesel-electric azimuth thrusters	2 x FPP		PL10	KR		1,1	KOR
ib	Kronprins Haakon	2017	9739587	Research	Norwegian Polar Institute	100,0	21,0	8,0	10,0	Diesel-electric azimuth thrusters	2 x FPPn	158	POLAR-10 Icebreaker / PC3	DNV			NOR

ic	Lance	1978	7638351	Research	Northshore AS	60,8	12,6	5,5	2,3		1 x CPP		1A		Research ship		NOR
ic	Carrasco	2017	9770464	Research	Peruvian Navy	95,3	18,0	6,5	3,0		2 x Pod		PC7	DNV	Research ship		PER
ib	Xue Long II	2019	9829241	Research	Polar Research Institute of China	122,5	22,3	7,9	15,0	Diesel-electric Azipod thrusters	2 x FPP		Polar Class 3	CCS		1,6	PRC
ibV	Xue Long	1993	8877899	Research	Polar Research Institute of China	167,0	22,6	8,7	13,2	Diesel-mechanical shaftline	1 x CPPn		B1* (RMRS UL as	CCS		1,0	PRC
ibV	Akademik Fedorov	1987	8519837	Research	AARI	141,2	23,5	8,5	12,0	Diesel-electric shaftline	1 x FPP		ULA	RMRS			RUS
ibV	Academic Treshnikov	2012	9548536	Research	AARI	133,5	23,0	8,5	14,0	Diesel-electric shaftlines	2 x FPP		Arc7	RMRS		1,1	RUS
ibV	Severny Polyus (North Pole)	2022*		Research		83,1	22,5	8,6	3,5		1 x		Arc5 (hull Arc8)	RMRS	Ice resistant platform		RUS
ibV	S. A. Agulhas II	2012	9577135	Research	Department of Environmental Affairs	134,2	21,7	7,7	9,0	Diesel-electric shaftlines	2 x CPP		PC 5	DNV			SA
ib	Oden	1989	8700876	Icebreaker Research	Sjöfartsverket	107,8	29,4	9,0	18,0	Diesel-mechanical shaftlines	2 x CPPn	240	POLAR-20 Icebreaker	GL DNV		2,0	SWE
ic	Svea	2019	9829332	Research	SGU	69,5	15,8	5,4	2,0	Diesel-electric	1 x FPP		1B	DNV	Research ship		SWE
ic	Skagerak	2021*	9776963	Research	GU	49,0	11,0	3,9	1,2		1 x CPPn		1B	BV	Research ship		SWE
ibV	RRS Sir David Attenborough	2020*	9798222	Research	British Antarctic Survey	129,6	24,0	7,5	11,0	Diesel-electric shaftlines	2 x CPP		Polar Class 4	LR		1,2	UK
ib	Healy	1999	9083380	Icebreaker	United States Coast Guard	128,0	24,9	8,5	22,4	Diesel-electric shaftlines	2 x FPP	200	(n/a)			1,5	USA
ib	Polar Security Cutter	2024*	(n/a)	Icebreaker	United States Coast Guard	140,0	26,8		33,0	Diesel-electric hybrid	1 x FPP 2 x FFP				3 vessel to be built	2,4	USA
ibV	Sikuliaq	2014	9578945	Research	UAF	78,7	15,9	5,7	4,4	Diesel-electric azimuth thrusters	2 x FPP		PC5	ABS		0,9	USA
ibV	Nathaniel B. Palmer	1992	9007257	Research	Chouest	94,0	18,3	6,6	9,3	Diesel-mechanical shaftline	2 x CPPn		A2	ABS	Research vessel		USA
ibV	Laurence M. Gould	1997	9137337	Research	Chouest	70,1	14,0	6,0	5,5	Diesel-mechanical shaftline	2 x FP		A1	ABS	Research vessel		USA
Icebreakers that may be available for research																	
ib	Viktor Chernomyrdin	2020	9658630	Icebreaker	Rosmorport	146,8	28,5	9,7	25,0	Diesel-electric hybrid	1 x FPP 2 x FFP		Icebreaker8	RMRS	LK-25, Project 22600		RUS
ib	Vladivostok	2015	9658654	Icebreaker	Rosmorport	119,8	27,5	8,5	17,4	Diesel-electric azimuth thrusters	2 x FPP	180	Icebreaker6	RMRS	Class of 4 ibs, LK-16M		Rus