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Maria A. Pitukhina ✉ [a)], *Oleg V. Tolstoguzov* [b)], *Anastasia D. Belykh* [c)]
[a, b, c)] Petrozavodsk state University, Petrozavodsk, Russian Federation

Key Hubs of the Polar Silk Road: Sustainable Arctic Routes[1]

Abstract. Murmansk and Arkhangelsk ports have significant potential and are well-positioned to accommodate the growing traffic of the Northern Sea Route (NSR). It is projected that by 2030 the cargo turnover of both ports will increase, which underscores the importance of ensuring sustainable navigation along this route. Such sustainability depends heavily on accurate ice forecasting and the optimization of operational windows. Against this backdrop, this study examines the capacities of three key Polar Silk Road hubs — Murmansk, Arkhangelsk, and Qingdao, focusing on their roles in supporting NSR development. Accurate forecasting of ice conditions in the NSR water area is a critical prerequisite for the reliable planning of shipping operations. Although all three ports contribute to Polar Silk Road connectivity, they differ substantially in cargo volumes and structures, as well as in the types of vessels they service. Using 2022 annual reports from Murmansk, Arkhangelsk, and Qingdao, we analysed a set of comparable indicators, including cargo turnover, waste utilization, and emissions of harmful substances from vessels. To complement this, we also examined Chinese models for port infrastructure development and for integrating ice forecasting with navigation window optimization along the NSR. The comparative analysis reveals that rising port productivity, when accompanied by increased environmental protection expenditures, substantially reduces waste flows but does not necessarily result in lower harmful emissions. This finding points to differentiated strategic priorities: for Arkhangelsk, enhancing waste utilization capacity; for Qingdao, increasing environmental protection investment and achieving CO_2 emissions neutrality; and for Murmansk, accelerating the implementation of AI-driven solutions.

Keywords: Polar Silk Road, port capacity, Hydrogen 5G Model, NSR navigation window, Northern Sea Route, environmental protection

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ИССЛЕДОВАТЕЛЬСКАЯ СТАТЬЯ

М.А. Питухина ✉ [а], **О.В. Толстогузов** [б], **А.Д. Белых** [в]
[а, б, в] Петрозаводский государственный университет, г. Петрозаводск, Российская Федерация

Ключевые транспортные узлы полярного Шелкового пути: надежные и экологически безопасные арктические маршруты

Аннотация: Порты Мурманска и Архангельска обладают значительным потенциалом и выгодным географическим положением для обслуживания растущих объёмов перевозок по Северному морскому пути (СМП). Ожидается, что их грузооборот вырастет к 2030 г., что повышает значение бесперебойного и экологически безопасного судоходства на этом направлении. Достижение этой цели во многом зависит от точного прогнозирования ледовой обстановки и оптимизации навигационных окон. В настоящем исследовании анализируются мощности трёх ключевых узлов Полярного шелкового пути — Мурманска, Архангельска и Циндао, с акцентом на их роль в развитии СМП. Несмотря на общий вклад этих портов в формирование транспортной связности, они заметно различаются по объёмам и структуре грузов, а также по типам обслуживаемых судов. Анализ годовых отчётов за 2022 г. охватывал такие показатели, как грузооборот, уровень утилизации отходов и объём выбросов вредных веществ от судов. Дополнительно рассмотрены китайские модели развития портовой инфраструктуры и возможность совмещения прогнозирования ледовой обстановки с оптимизацией навигационных окон вдоль СМП. Сравнительный анализ показал, что рост производительности портов при увеличении затрат на охрану окружающей среды позволяет значительно снизить объём отходов, однако не всегда приводит к уменьшению выбросов вредных веществ. Это определяет различия в стратегических приоритетах: для Архангельска первостепенное значение имеет наращивание мощностей по утилизации отходов, для Циндао — увеличение инвестиций в экологические мероприятия и достижение углеродной нейтральности, а для Мурманска — ускоренное внедрение решений на основе искусственного интеллекта.

Ключевые слова: Полярный шелковый путь, портовые мощности, модель Hydrogen 5G, навигационное окно СМП, Северный морской путь, охрана окружающей среды

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Introduction

The concept of the Polar Silk Road was first introduced by Russia, when it was presented at the II International Forum "The Arctic: Territory of Dialogue" in 2011 (Qin, 2022). China welcomed the idea, later incorporating it into its 2018 Arctic Strategy outlined in the official White Paper[1].

The Polar Silk Road serves as the Arctic extension of China's "One Belt, One Road" Initiative, launched by Xi Jinping in 2013 to promote East–West trade along routes modelled on the historic Silk Road[2].

In 2022, the Russian government approved a plan for the development of the NSR until 2035[3]. It includes 155 measures focused on expanding cargo capacity, upgrading port infrastructure, building an icebreaker fleet, and advancing scientific research. By 2030, seaport capacity along the NSR is expected to reach 127.5 million tonnes annually—nearly 2.7 times the 2024 level. The plan also aims to generate over 20 trillion rubles in tax revenue by 2035, create jobs, boost Arctic economic growth, strengthen national security, and support international research cooperation.

The ports of Murmansk and Arkhangelsk play a key role in this strategy. Both seek to position themselves as major NSR hubs by attracting more cargo and vessels and offering competitive conditions to shipowners. However, achieving this requires substantial investment to modernize

[1] Full text: China's Arctic Policy (2018). The State Council of the PRC. http://english.www.gov.cn/archive/white_paper/2018/01/26/content_281476026660336.htm (Date of access: 17.10.2024).

[2] About China's "One Belt, One Road" initiative (2021). Ministry of Foreign Affairs of the Russian Federation. https://www.mid.ru/ru/activity/coordinating_and_advisory_body/head_of_subjects_council/materialy-o-vypolnenii-rekomendacij-zasedanij-sgs/xxxvi-zasedanie-sgs/1767163/ (date of access: 08.09.2024).

[3] Order No. 2115-r of August 1, 2022 (2022). Russian Government. http://static.government.ru/media/files/StA6ySKbBceANLRA6V2sF6wbOKSyxNzw.pdf (Date of access: 08.09.2024).

infrastructure, increase throughput, and improve service quality.

Research on the Polar Silk Road and the NSR generally falls into three main categories: 1) reviews of academic studies, particularly Chinese models for ice forecasting and navigation timing; 2) assessments of the NSR as an alternative to the Suez Canal; and 3) analyses of climate change and its impact on Arctic navigation windows.

Data and Methods

Researchers from the University of the Chinese Academy of Sciences have proposed launching a seasonal (irregular) container shipping service via the Northern Sea Route (NSR), operating only in September (Wu, 2022). This service would use ice-free vessels with a capacity of 10,000 tonnes. According to estimates, transportation costs along this route could be 3–5 % lower than those via the Suez Canal. A combined container service that includes both the NSR and the Suez Canal is also under consideration. In this case, ice-class vessels would be used, provided that the cost of icebreaker assistance along the NSR remains below 80 % of the Suez Canal transit fee (Yue et al., 2023; Dou et al., 2019).

Chinese scientists have also introduced RouteView, an intelligent, interactive route planning system (Wu, 2022). Designed to improve the efficiency and accuracy of Arctic navigation, RouteView enables automatic collection and analysis of navigational data along the NSR. As emphasized by Chinese researchers, for the NSR to be a viable alternative to the Suez Canal, the cost of icebreaker assistance must remain below 80 % of the Suez Canal transit fee (Wu, 2022).

China has developed numerous sea ice forecasting models, some of which have been in use for forecasting ice conditions and navigation windows in the Barents and Kara Seas. Notable examples include the AMSR model (Dong et al., 2022), the NESM model (Cao et al., 2015), and the ArcIOPS model (Liang et al., 2024), among others (Yu et al., 2022; Lin et al., 2024).

The most widely used model is the CMPI, developed by Shanghai Ocean University and the Guangdong Key Laboratory of Science and Technology. CMPI's core parameters include sea ice area, sea ice density, and sea ice thickness, with its latest version known as CMPI6. Among these variables, sea ice area is the easiest to model, while sea ice drift remains the most difficult and least accurate due to limited research and data. Forecasting sea ice density tends to be more accurate than drift predictions. Short-term forecast errors are typically linked to sea ice characteristics, atmospheric influences, and thermodynamic variability.

Only a few Chinese models are capable of medium – and long-term forecasting. These forecasts reveal regional differences: thinner ice tends to form on the Atlantic side, while thicker ice appears in the Beaufort Sea region. However, simulations of ice drift velocity remain extremely limited for medium – and long-term periods.

Currently, there is still insufficient data to validate the accuracy of short-, medium-, and long-term sea ice forecasts. Chinese researchers stress the need to improve the timeliness and quantity of field observations to enhance the reliability of these models. They also emphasize that a fully coupled ocean–sea ice–atmosphere model represents the most effective approach for predicting sea ice dynamics.

A separate body of literature focuses on the NSR's potential as an alternative international transport corridor to the Suez Canal (Schøyen & Bråthen, 2011; Zhang et al., 2016; Sibul & Jin, 2021; Xu & Yu, 2022). For instance, Blunden (2012) explores the increasing strategic importance of the NSR for Russia and the geopolitical implications of its development. Initially valued for defence purposes, the NSR is now primarily used for the export of raw materials and is viewed as a major project for increasing cargo traffic. Blunden argues that the NSR has the potential to serve as a viable alternative to the Suez Canal, which runs through a politically unstable region. Interest in the NSR is not limited to Arctic states like Russia and Canada, which seek to maintain exclusive jurisdiction, but also includes non-Arctic countries such as Germany and China, which aim to expand their influence in the region.

Gunnarsson and Moe (2021) analyse the development of international shipping along the NSR over the past decade. They highlight significant fluctuations in the volume and composition of maritime traffic since the NSR was opened to international use in 2010. While Russia expects international transit along the NSR to increase, the authors stress that its scale cannot be determined by Russia alone. Instead, the international shipping industry must independently evaluate Arctic routes in terms of safety, efficiency, reliability, environmental sustainability, and economic feasibility.

Hermann et al. (2022) examine the role of Arctic ports as transshipment hubs in NSR development. The authors note that current research has largely overlooked the importance of ports in this capacity. Drawing on a systematic review of 47 peer-reviewed studies, they identify four key policy areas: the operational and design characteristics of transshipment terminals; geopolitical and managerial requirements for developing deep-water facilities; financing options; and the potential impact of Arctic hubs on other polar shipping routes. The article underscores the influence of geopolitical factors, particularly sanctions against Russian Arctic gas projects, on the short – and medium-term prospects for transshipment hub development.

Faury et al. (2019) investigate Murmansk's evolving role as an Arctic maritime hub. Using Automatic Identification System (AIS) data and vessel movement analysis since 2010, the authors trace the port's shift from a coal-exporting facility to a key node for handling oil and liquefied natural gas (LNG) from Arctic fields. However, they also note growing competition from Arkhangelsk and Kirkenes, which, although currently offering more limited services, may become viable alternatives. In particular, Arkhangelsk's location on a popular transport route could make it increasingly attractive for Arctic resource exports.

Stepanov (2019) explores the historical development and contemporary economic potential of Arkhangelsk Oblast, which, being the largest region in European Russia, is rich in natural resources. However, the author argues for the need to transition away from a raw materials-based economy toward value-added processing industries. Arkhangelsk's geographic position is seen as a strategic advantage, making it a key port for Arctic development and NSR operations. Stepanov (2019) emphasizes that the NSR should become a central transport corridor for the Russian Far North, unlocking new opportunities for the region within the international division of labour.

Climate change and global warming remain central themes in discussions of the NSR's navigation window. These issues are addressed by international researchers such as Gustafson (2021), Chen et al. (2024), Wu et al. (2021), and Mahmoud et al. (2024).

Russian climatologists and environmental scientists, such as Semenov (2021), Bogoyavlensky et al. (2021), and Petrov & Volkov (2021), have contributed to studies on sea ice dynamics (Romanenko & Semenov, 2024; Cherenkova & Semenov, 2024), gas-saturated formations and degassing risks (Bogoyavlensky et al., 2024; Bogoyavlensky & Kishankov, 2024), and radioactive waste in the northern territories (Abramov et al., 2024; Petrov & Yudintsev, 2023).

Long-term temperature observations across the Arctic have made it possible to model sea ice conditions in NSR waters through the end of the 21st century. According to projections by Semenov, the NSR navigation window is expected to extend from June through January by the year 2100, lasting just over eight months (Khon et al., 2017) (see Fig. 1).

The aim of this study is to identify and analyse the capacities of key hubs along the Polar Silk Road (Murmansk, Arkhangelsk, and Qingdao) that contribute to navigation safety and the sustainable development of Arctic shipping routes. Our main focus is on assessing the potential of the Russian ports of Murmansk and Arkhangelsk to efficiently handle the increasing volume of traffic along the NSR, particularly in the context of implementing "smart" and "green" technologies. The advanced infrastructure of the Chinese port of Qingdao in Shandong Province serves as a comparative example.

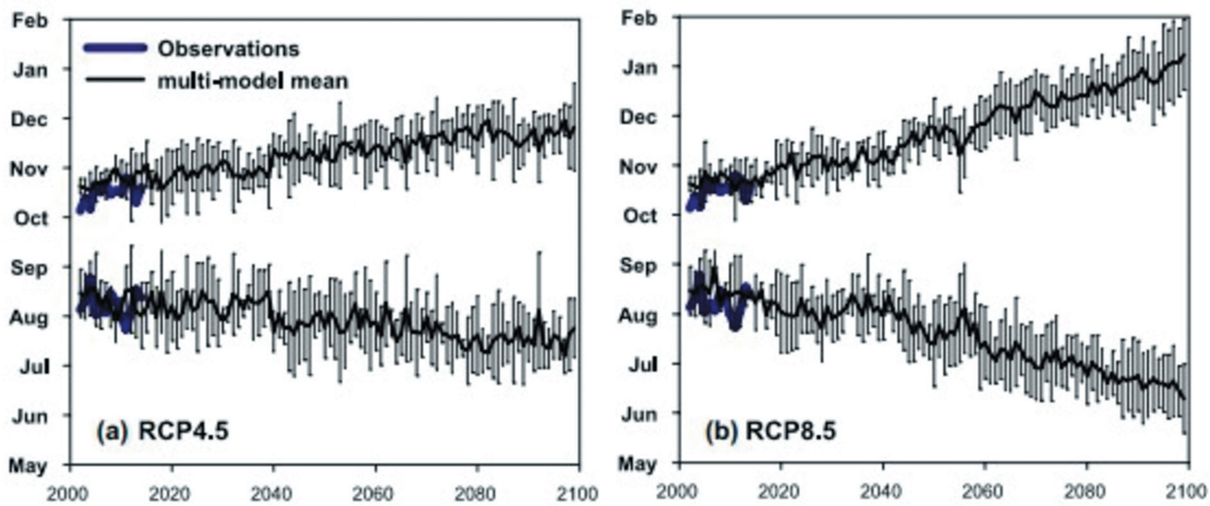

Fig. 1. *Navigation window along the NSR by 2100*

Source: Khon, V.C., Mokhov, I.I. & Semenov, V.A. (2017). Transit navigation through Northern Sea Route from satellite data and CMIP5 simulations. Environmental Research Letters, 12

Table 1

Comparison of Port Indicators: Murmansk, Arkhangelsk, and Qingdao, 2021–2023

Port	Emissions of harmful (pollutant) substances, tons per 1 million ton of cargo turnover	Waste utilization, tons per 1 million tons of cargo turnover	Port cargo turnover, thousand tons per person.	Expenses on environmental protection, thousand dollars per 1 ton of emissions	Expenses on environmental protection, thousand dollars per 1 ton of waste	Expenses on environmental protection, thousand dollars per 1 ton of cargo turnover	Emissions of harmful substances, tons per 1 thousand tons of cargo turnover and 1 person
Murmansk*	0,21	8,28	33,59	28,81	0,73	6,05	0,12
Arkhangelsk**	1,29	53,62	8,03	59,34	1,43	76,60	2,06
Qingdao***	415,19	10,66	179,89	0,09	3,41	36,13	43,94

Source: completed by the authors based on ports' annual data reports.

* Rosmorport data for Murmansk https://www.rosmorport.ru/filials/mur_ecology/?ysclid=m6ryiycjiw372893699 (Date of access: 05.02.2025)

** Rosmorport data for Archangelsk https://www.rosmorport.ru/filials/arf_ecology/?ysclid=m6ryi4t752447167499 (Date of access: 05.02.2025)

*** Sustainability report of Qingdao 2021, 2022, 2023 chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www1.hkexnews.hk/listedco/listconews/sehk/2024/0425/2024042500984.pdf (Date of access: 05.02.2025)

The study analyses recent trends in port development to identify key risks and opportunities related to modernization and sustainable technologies.

An additional research method included fieldwork conducted during a visit to the Ocean University of China in October 2024, which included an on-site study of Qingdao port infrastructure.

The research algorithm consists of the following steps: first, we developed a methodological framework, including the selection of data collection and analysis methods; second, we assessed the port capacities of Murmansk and Arkhangelsk—the main Russian hubs along the NSR—along with conducting an analysis of NSR shipping traffic; next, we examined the Chinese approach to ice forecasting along the NSR and Qingdao's implementation of the Hydrogen + 5G port model; and, finally, we formulated recommendations for port development in the Russian Arctic, with a focus on infrastructure optimization and the integration of "smart" and "green" technologies.

Results

The ports of Murmansk, Arkhangelsk, and Qingdao differ not only in cargo volumes but also, importantly, in cargo structure and the types of vessels they handle. Based on the 2022 annual reports of these ports, we analysed key indicators such as cargo turnover, waste utilization, and emissions of harmful substances produced by vessels[1].

Table 2 presents these data normalized per 1 ton of cargo turnover per employee. According to these metrics, Qingdao port's performance surpasses that of the two Russian Arctic ports.

Increasing port productivity, alongside rising environmental protection costs, helps reduce waste levels but does not lower emissions of harmful pollutants; in fact, it significantly increases their volume (Fig. 2).

Chinese researchers have identified six main sources of PM2.5 pollution in Qingdao: coal combustion, industrial emissions and mineral dust, marine vessel emissions, secondary aerosols and biomass burning, sea salt and crustal emissions, and vehicle exhaust (Wu et al., 2017). Among these, marine vessel emissions were the largest contributor, accounting for 25.05 % of PM2.5 during the sampling periods. In other words, the primary source of emissions is not the port itself, but the ships arriving at Qingdao.

These data challenge the perception of Qingdao port as a "green" facility, despite its implementation of the "Hydrogen + 5G" model.

If cargo turnover at the two Russian Arctic ports—Murmansk and Arkhangelsk—increases significantly, it will become imperative to address environmental issues, which will require substantial investments in environmental protection. In addition, it will be essential to

[1] Qingdao Port Sustainability Report 2022 https://sustainabilityreports.com/reports/qingdao-port-international-co-ltd-2022-sustainability-report-pdf/ ; Rosmorport data for Archangelsk https://www.rosmorport.ru/filials/arf_ecology/?ysclid=m6ryi4t752447167499; Rosmorport data for Murmansk https://www.rosmorport.ru/filials/mur_ecology/?ysclid=m6ryiycjiw372893699 (Date of access: 05.02.2025)

Table 2

Ports capacities comparison of Murmansk and Arkhangelsk

Criteria	Murmansk	Arkhangelsk
Largest hub	Barents Sea	White Sea
Traits	has a more developed infrastructure and a more advantageous geographical location (closer to Western markets)	has a rich historical heritage and potential for developing a tourist destination (closer to Asian markets)
Ship call in 2023	3 727 vessels	2 748 vessels
Cargo turnover in 2023	60 097 765 tonnes	5 035 591 tonnes
Ports of interaction with China	Dalian, Qingdao	Tianjin, Shanghai
Key Chinese projects in the region	Supply of modules and turbines for Artic-LNG 2	Construction of a plant for the production of MDF panels in Plesetsk Oblast, furniture export to China, opening of a Chinese medical center, export of peat
Navigation	All-year round	All-year round
Depth at the berth	Draft 17 м.	Draft 9,2 м
Port water area	53 699 square km	1 120 square km
Development plans	Murmansk transportation hub	Arkhangelsk transportation hub
Investments in logistics	Creation of a universal port in Murmansk will cost 20 billion rubles*	Construction of a new deep-water port in Arkhangelsk estimated at 300 billion rubles**
Inclusion in mega projects	Murmansk is a part of Eurasian Container Transit project***	Arkhangelsk is a part of: 1. Arctic express route (Shanghai - Arkhangelsk - Moscow railway****) 2. "Belkomur" route (White Sea, Komi, Urals), also known as the "Polar Trans-Siberian Railway"*****

Source: compiled by the authors.

* Creation of a universal port in Murmansk will cost 20 bln rubles (2024). RBC. https://murmansk.rbc.ru/murmansk/13/02/2024/65cb741c9a7947cba23b8880 (Date of access: 17.10.2024). ** Construction of a new deep-water port in Arkhangelsk estimated at 300 bln rubles (2024). Vedomosti. https://spb.vedomosti.ru/technology/articles/2024/08/09/1054914-stroitelstvo-novogo-glubokovodnogo-porta-v-arhangelske-otsenili-v-300-mlrd-rub (Date of access: 17.10.2024). *** Development of the Murmansk port (2023). Murmansk Region Development Corporation. https://invest.nashsever51.ru/public/uploads/mediastore/Media/%D0%98%D0%BD%D0%B2%D0%B5%D1%81%D1%82%D0%BD%D0%B8%D1%88%D0%B0_%D0%9F%D0%BE%D1%80%D1%82_%D0%9C%D1%83%D1%80%D0%BC%D0%B0%D0%BD%D1%81%D0%BA.pdf?_t=1703495759 (Date of access: 17.10.2024). **** Arctic Express No. 1 (2024). Arkhangelsk Commercial Seaport. https://www.ascp.ru/news/arkticheskiy-ekspress-1/ (Date of access: 08.09.2024). ***** Railway to the White Sea https://dzen.ru/a/ZYlyw6qN-jZtWOHY (Date of access: 08.09.2024).

develop new vessels, including nuclear-powered ships, that comply with current environmental standards.

Considering these climatic and environmental factors, a significant rise in cargo through Arctic ports along the NSR would inevitably lead to increased emissions of harmful substances such as CO_2, NO_x, SO_2, and particulate matter. Despite China's advanced "green" and AI technologies applied at Qingdao port, such as the Hydrogen + 5G model, these solutions mainly address waste management and do not sufficiently reduce CO_2 emissions.

For Qingdao, Murmansk, and Arkhangelsk, it is crucial to build new ships that meet contemporary environmental standards, including those established by the International Maritime Organization (IMO). This involves adopting liquefied natural gas (LNG) as a fuel instead of traditional fuels, installing gas cleaning systems (scrubbers), and incorporating alternative energy sources.

Based on the study's findings, recommendations for the three ports can be outlined as follows: first, Arkhangelsk should prioritize minimizing waste and improving waste utilization; second, Qingdao should focus on increasing investment in environmental protection; and, finally, Murmansk should emphasize the implementation of AI technologies.

It is also important to note that Chinese partners are interested not only in navigation along the NSR but also in railway infrastructure projects, such as the Arctic Express. This initiative, a collaboration between Chinese company NewNewShipping, Rosatom, Russian Railways, and Arkhangelsk authorities, combines rail and

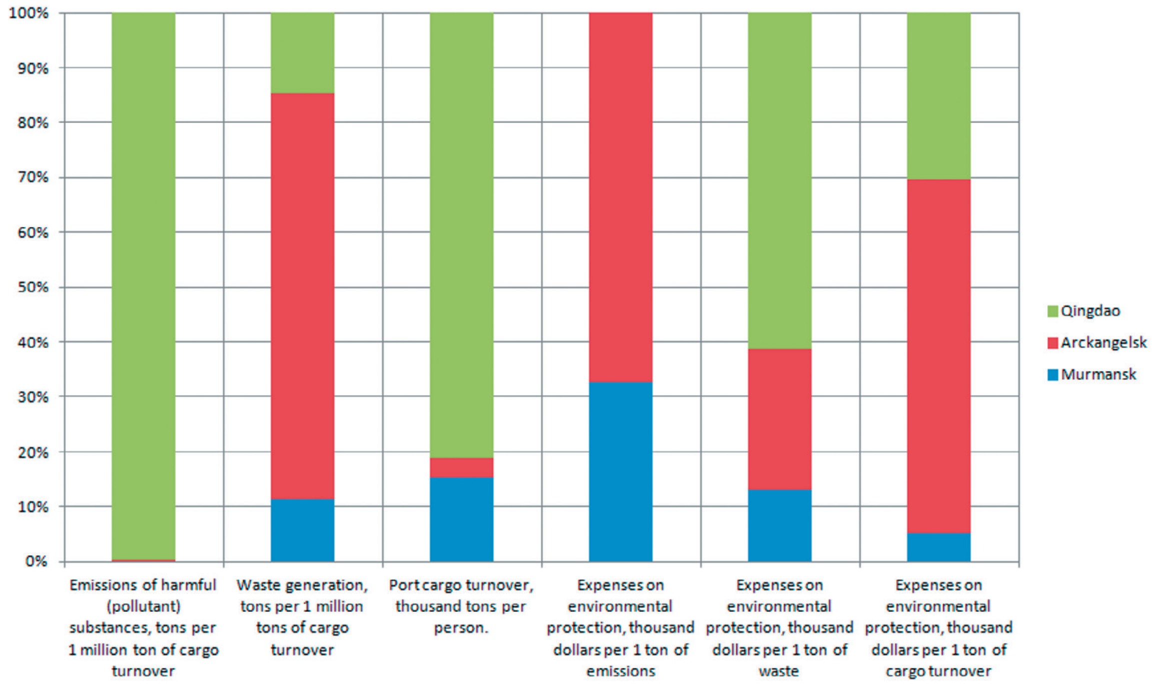

Fig.2. *Comparison of Port Indicators: CO_2 Emissions and Waste Utilization in Murmansk, Arkhangelsk, and Qingdao (2021–2023). Source: compiled by the authors*[*]

Qingdao Port Sustainability Report 2022 https://sustainabilityreports.com/reports/qingdao-port-international-co-ltd-2022-sustainability-report-pdf/ ; Rosmorport data for Archangelsk https://www.rosmorport.ru/filials/arf_ecology/?ysclid=m6ryi4t752447167499 ; Rosmorport data for Murmansk https://www.rosmorport.ru/filials/mur_ecology/?ysclid=m6ryiycjiw372893699 (Date of access: 05.02.2025)

sea transport to accelerate delivery times and reduce reliance on traditional routes.

The Arctic Express begins in Bely Rast, a railway junction near Moscow, then transports goods by rail to Arkhangelsk, where they continue by sea to Shanghai. The route covers approximately 1,200 kilometres by rail and 6,600 nautical miles by sea. Its opening is expected to reduce transportation time from Moscow to Chinese ports by 35–55 %, with an annual capacity of over 20,000 TEU.

This new route allows exporters from Central Russia and the Northwest to ship directly to China without transiting through third countries. Additionally, the Arctic Express helps divert cargo flows to Arctic routes, alleviating congestion in the Eastern Polygon of Russian Railways.

The Arctic Express project is part of the broader Polar Silk Road initiative, a joint Russian-Chinese effort to develop the shortest transportation corridor between the Pacific and Atlantic Oceans via the Arctic.

Discussion

The Polar Silk Road is gradually taking shape. In spring 2023, a Russian–Chinese working group was established to coordinate the development of the Northern Sea Route (NSR). That same year, Chinese companies successfully completed voyages along the Murmansk–Qingdao and Murmansk–Dalian routes. In 2024, navigation expanded to include the Arkhangelsk–Shanghai, Arkhangelsk–Tianjin, St. Petersburg–Ningbo, and St. Petersburg–Shanghai routes (Pitukhina et al., 2024).

The cargo turnover of the port of Arkhangelsk in 2022 amounted to 7 million tonnes, which is 31.2 % more than in 2021[1]. In the same year, the port of Murmansk handled 56.3 million tonnes of cargo. Looking ahead to 2030, both ports are expected to see further growth, driven by the launch of two large infrastructure projects: the Murmansk transportation hub and the Arkhangelsk transportation hub.

Against this background of expanding routes and increasing cargo volumes, in this section we are going to compare the main capacity indicators of Murmansk and Arkhangelsk, the two largest ports along the NSR.

The development of the Murmansk transportation hub is being implemented under the State Program Development of the Transport System and the Comprehensive Plan for the Modernization and Expansion of the Main Infrastructure of the

[1] Port of Arkhangelsk helps to develop Arctic projects (2023). Maritime News of Russia. https://morvesti.ru/exclusive/102906/ (Date of access: 08.09.2024).

Russian Federation for the period up to 2024. For this purpose, the Russian government has allocated 37.7 billion rubles. The main goal of the large-scale infrastructure project Murmansk Transport Hub[1] is to increase the carrying capacity of railway approaches to the Lavna coal terminal to 18 million tonnes per year. In addition, the project aims to establish a year-round deep-water marine hub that will serve as a centre for processing oil cargo, transshipping coal and mineral fertilizers, and integrating these operations into the international North–South transport corridor.

In early October 2023, the Russian Government has approved a plan for the development of the Arkhangelsk transport hub until 2035[2]. The centrepiece of the plan is the construction of a new deep-water terminal in the Arkhangelsk seaport, located in the Dry Sea area.

The project will be implemented in several stages. In the first stage, a terminal for mineral fertilizers will be built with a capacity of up to 3 million tonnes per year to serve PhosAgro. The second stage will involve the construction of a bulk terminal for oil and gas condensate with a capacity of up to 4 million tonnes per year in the interests of Gazprom. The third stage will see the creation of a universal terminal with a capacity of 38 million tonnes per year for the Russian Transport Company.

In addition, the plan includes the construction of a sea terminal on the Novaya Zemlya archipelago for shipping lead–zinc concentrate for the state corporation Rosatom, with commissioning scheduled for 2026.

Arkhangelsk port is gaining a competitive advantage under current conditions due to its closer proximity to Asian partners and the long-standing ties between Chinese businesses and the region. Arkhangelsk is also striving to develop and attract new cargo through its expanding terminal and infrastructure. For example, Russian Railways launched a regular service “Arctic Express”, which connects Arkhangelsk, not Murmansk, and the main ports of China (Shanghai and Ningbo) along the Northern Sea Route[3].

[1] The Murmansk transportation hub is among the important areas of the approved plan for the development of the NSR for the period until 2035 (2022). Government of Murmansk Oblast. https://gov-murman.ru/info/news/460596/ (Date of access: 08.09.2024).

[2] The government approved a comprehensive development plan for the Arkhangelsk transportation hub until 2035 (2023). Russian Government. http://static.government.ru/media/files/AGnbnoSG6CVR6ECeirsalr5tpObBHVbO.pdf (Date of access: 08.09.2024).

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Qingdao Port is one of the fully automated ports in Asia, possessing the world’s first smart and green terminal with the “Hydrogen +5G” model. Qingdao Port’s “Hydrogen +5G” is a crane system powered by hydrogen energy. The use of hydrogen saves 21000 tonnes of carbon dioxide and 640 tonnes of sulfur dioxide emissions every year. The operation model of container terminals has undergone a complete transformation over the past decades. Compared to traditional manual terminals, AI-powered terminals have increased operational efficiency by 30 % and achieved a level of automation surpassing world-class ports such as Rotterdam. Qingdao Port’s first terminal was constructed in just three years, while the second terminal is scheduled to be completed in only 1.5 years. In 2022, the terminal’s bridge cranes reached an operating efficiency of 52.7 containers per hour, setting a new world record by increasing loading and unloading speed eightfold.

Qingdao Port ranks first in the world in operational efficiency. In 2023, the container ship Dexiang Shimin set a new world record by handling 60.18 containers per hour. In line with the global shift toward advanced energy technologies, Qingdao has established China’s hydrogen energy pilot port through projects such as “Hydrogen + 5G.” By integrating low costs, short lead times, artificial intelligence, high efficiency, enhanced safety, and zero emissions, the port aims to position itself at the forefront of carbon neutrality. This approach is shaping the port model of Shandong Province, and Qingdao has earned recognition for its outstanding technological achievements in China’s port infrastructure.

The findings of this study indicate that Chinese partners show interest not only in NSR navigation and the development of Polar Silk Road ports, but also in enhancing railway infrastructure in the Russian Arctic, for example, through the Arctic Express project (Arkhangelsk–Moscow railway).

However, the majority of NSR ports, aside from Murmansk and Arkhangelsk, remain relatively small, with outdated infrastructure and underdeveloped logistics chains. At present, the NSR’s economic efficiency is modest, yet its long-term potential is substantial. This potential could be further unlocked if the cost of icebreaker assistance along the NSR were to drop to less than 80 % of the Suez Canal fee ($375,000 vs. $250,000).

Although the Polar Silk Road project is already under way, a notable challenge remains as China’s largest state-owned shipping companies have been reluctant to operate along the NSR due to sanctions. In 2022, none of them participated in Arctic navigation. This situation began to change in 2023 and 2024, when private Chinese shipping companies Hainan Yungpu and New New Shipping successfully operated along the NSR, helping to overcome the navigation gap left by state-owned enterprises.

Conclusion

The results of the study bring us to the following conclusions.

Murmansk and Arkhangelsk ports possess significant capacity to accommodate the growing cargo flows along the Northern Sea Route (NSR). However, unlocking this potential depends heavily on accurate forecasting of ice conditions, which is critical for both operational reliability and long-term shipping development. Since China is one of the key stakeholders in NSR and Polar Silk Road projects, and has developed advanced methods for predicting sea ice dynamics, part of this study examines Chinese forecasting models to assess their applicability to Arctic navigation.

Long-term monitoring of temperature trends in the Arctic enables projections of ice conditions along the NSR through to 2100. According to calculations by the Russian Academy of Sciences, by 2100 the NSR navigation window is expected to last from June through the end of January, allowing for more than eight months of uninterrupted operation each year.

While these climatic changes create opportunities for longer navigation periods, they also imply environmental risks. A substantial increase in cargo turnover at Arctic ports would inevitably raise emissions of harmful substances (e.g., CO_2, NO_x, SO_2, particulate matter). Chinese "green" and AI-driven solutions, such as the Hydrogen + 5G model at Qingdao port, offer notable progress in waste management, but they do not address the challenge of reducing CO_2 emissions.

To meet modern environmental requirements, including those established by the International Maritime Organization (IMO), it will be necessary for Qingdao, Murmansk, and Arkhangelsk to commission new vessels powered by liquefied natural gas (LNG) rather than traditional fuels, to install gas cleaning systems (scrubbers), and adopt alternative energy sources.

The combined potential of the three Polar Silk Road ports—Murmansk, Arkhangelsk, and Qingdao—opens promising opportunities for further research, particularly in applied science. This study contributes practical recommendations for the development of Russian Arctic ports, encourages innovation in port infrastructure, and identifies priority investment areas.

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About the authors

Maria A. Pitukhina — Dr Sci. (Polit.), Professor, Petrozavodsk state University; Scopus Author ID: 56728867600; https://orcid.org/0000-0001-7012-2079 (33, Lenina Ave., 185011, Petrozavodsk, Russian Federation, e-mail: maria.pitukhina@gmail.com).

Oleg V. Tolstoguzov — Dr Sci. (Econ.), Associate professor, Petrozavodsk State University; Scopus Author ID: 57210840176; https://orcid.org/0000-0002-4162-8342 (33, Lenina Ave., 185011, Petrozavodsk, Russian Federation, e-mail: olvito@mail.ru).

Anastasia D. Belykh — analyst, Petrozavodsk State University; Scopus Author ID: 57994424800; https://orcid.org/0000-0002-7361-6696 (33, Lenina Ave., 185910, Petrozavodsk, Russian Federation, e-mail: anastasiya.belykh098@gmail.com).

Информация об авторах

Питухина Мария Александровна — доктор политических наук, профессор, Петрозаводский государственный университет, Scopus Author ID: 56728867600; https://orcid.org/0000-0001-7012-2079 (Российская Федерация, 185005, г. Петрозаводск, пр. Ленина 33, e-mail: maria.pitukhina@gmail.com).

Толстогузов Олег Викторович — доктор экономических наук, доцент, Петрозаводский государственный университет; Scopus Author ID: 57210840176; https://orcid.org/0000-0002-4162-8342 (Российская Федерация, 185011, г. Петрозаводск, пр. Ленина 33, e-mail: olvito@mail.ru).

Белых Анастасия Дмитриевна — специалист управления научных исследований, Петрозаводский государственный университет, Scopus Author ID: 57994424800; https://orcid.org/0000-0002-7361-6696 (Российская Федерация, 185910, г. Петрозаводск, пр. Ленина 33, e-mail: anastasiya.belykh098@gmail.com).

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