

©Economic Viability and Emissions of Multimodal Transportation Infrastructure in a Changing Arctic

MICHAEL A. GOLDSTEIN,^{a,b} AMANDA H. LYNCH,^a RUITIAN YAN,^a SIRI VELAND,^c AND WILLIAM TALLERI^b

^a Institute at Brown for Environment and Society, Brown University, Providence, Rhode Island

^b Babson College, Wellesley, Massachusetts

^c NORCE Norwegian Research Centre, Bergen, Norway

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ABSTRACT: As Arctic open water increases, shipping activity to and from mid- and western Russian Arctic ports to points south has notably increased. A number of Arctic municipalities hope increased vessel traffic will create opportunities to become a major transshipment hub. However, even with more traffic passing these ports, it might still be economically cheaper to offload cargo at a more southern port, which may also result in lower emissions. Ultimately, the question of whether to use a transshipment in the Arctic versus an established major European port is determined by the relative costs (or emissions) of sea versus land travel. This study calculates the relative competitiveness of six Norwegian coastal cities as multimodal hubs for shipments. We quantify the relative prices and CO₂ emissions for sea and land travel for routes starting at the Norwegian–Russian sea border with an ultimate destination in central Europe and find that all existing routes are not competitive with routes using the major existing Port of Rotterdam (Netherlands); even with investments in port expansion and modernization, they would be underutilized regardless of an increase in vessel traffic destined for central Europe. We then examine under what relative prices (emissions) these routes become economically viable or result in lower emissions than using existing southern ports. Notably, the cheapest routes generally produce the lowest emissions, and the most expensive routes tend to have the largest emissions. Communities should consider relative competitiveness prior to making large infrastructure investments. While some choices are physically possible, they may not be economically viable.

SIGNIFICANCE STATEMENT: Climate change, while disruptive, can also create new opportunities. Many Arctic cities hope to become a major transshipping hub as declining sea ice opens new shipping routes from western and mid-Russian Arctic ports to European ports. This paper quantifies the relative competitiveness of six Norwegian coastal cities as multimodal transportation hubs and finds that they are uncompetitive with the more southern port in Rotterdam (Netherlands). We also show that the most economically competitive routes have lower direct emissions. Thus, while Arctic ports provide critical services in support of local and regional economic activity, even with year-round Arctic navigation Arctic ports' development into major transshipment hubs for cargo destined for more distant locations may be neither economically viable nor desirable.

KEYWORDS: Arctic; Transport; Climate variability; Economic value; Policy

1. Introduction

The changing Arctic presents decision-makers with converging pressures, unforeseen opportunities, and urgent choices (Dale and Kristoffersen 2018). International agreements to address the mitigation of anthropogenic climate change are demanding a shift for most Arctic nations toward circular economies and “green ports” (Bergqvist and Egels-Zandén 2012; Leal et al. 2022; Alamoush et al. 2022; Langenus et al. 2022), even as new mineral and petroleum resources become potentially accessible (Adumene et al. 2021; Gunnarsson 2021; Huntington 2022). As temperatures warm rapidly and ice and snow retreat (Gillett et al. 2008; Pithan and Mauritsen 2014; Goldstein et al. 2018; Dai et al.

2019; Meredith et al. 2019; Bennett et al. 2020), geopolitical tensions (Heininen and Nicol 2007; Brutschin and Schubert 2016; Liu 2020) are making themselves evident in the “Race to the North” (Dale and Kristoffersen 2018; Lynch et al. 2022). Local and Indigenous communities are calling more strongly than ever for self-determination in an increasingly international economic and geopolitical setting (Koivurova and Heinämäki 2006; Arctic Monitoring and Assessment Programme 2017; Coates and Broderstad 2020).

One of the more notable changes in the Arctic is rapid sea ice loss and the increase in Arctic open water (Barnhart et al. 2016; Boeke and Taylor 2018; Goldstein et al. 2018; Meredith et al. 2019; Veland et al. 2021). There has been a notable increase in Arctic shipping (Meredith et al. 2019), particularly in the Norwegian and Barents Seas (Eguiluz et al. 2016), with over 100 000 trips during 2015–17, many of which were general cargo ships (Silber and Adams 2019). While much of this increase has been destination shipping (Humpert 2017; Bennett et al. 2020; Gunnarsson 2021), a number of papers (Melia et al. 2016; Ng et al. 2018) have speculated that over

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Corresponding author: Michael A. Goldstein, goldstein@babson.edu

time there will be increased traffic on the Northeast Passage due to transcontinental transit activity across the “Northern Sea Route” (NSR), depending on ice conditions (Milaković et al. 2018; Li et al. 2021b). The development of the NSR is considered strategically and economically important to Russia (Bennett et al. 2020; Gunnarsson 2021; Abay 2021; Goncharova and Stoyanova 2021; Yudnikova and Bedashov 2021), and, according to the Russian energy ministry, almost 33 million metric tons used the NSR in 2020, with an expectation that by 2024 this will increase to 80 million metric tons (Reuters 2021).

At the same time, there are a number of factors and risks that could affect Arctic shipping (Ng et al. 2018; Adumene et al. 2021). These factors include natural system factors such as highly variable sea ice extent (Barnhart et al. 2016; Meredith et al. 2019; Li et al. 2021a,b), fluctuating sea ice patterns and sea ice drift (Ng et al. 2018), highly variable Arctic weather (Ng et al. 2018; Veland et al. 2021), floating ice hazards (Adumene et al. 2021), and variable and uncertain transit season length (Melia et al. 2016; Li et al. 2021b). There are also human sociopolitical–economic factors such as Russian security measures (Goncharova and Stoyanova 2021), transit fees (Milaković et al. 2018), governance and passage rights (Bennett et al. 2020; Boylan 2021; Lynch et al. 2022), international Arctic shipping rules, insurance (Milaković et al. 2018), environmental concerns (Ng et al. 2018; Comer 2019; Silber and Adams 2019; Bennett et al. 2020), and concerns of Indigenous groups (Arctic Monitoring and Assessment Programme 2017; Olsen et al. 2019; Bennett et al. 2020). Beyond this are more shipping oriented factors such as bunker (ship fuel) prices (Milaković et al. 2018), time value of cargo, vessel design (Milaković et al. 2018), vessel availability, ship owner perceptions (Lasserre et al. 2016; Milaković et al. 2018), search and rescue support (Milaković et al. 2018; Benz et al. 2021), communication challenges (Milaković et al. 2018; Veland et al. 2021), and so on. These politico-socioeconomic issues are not limited to the NSR: the disruption in the Suez Canal in 2021 (Adumene et al. 2021; Lynch et al. 2022) allowed Russia to highlight the benefits of the NSR (Reuters 2021) as an alternative to the Suez Canal (Abay 2021; Hataya and Huang 2021). Other issues such as increased piracy, or border or military skirmishes in the south could temporarily make an NSR transit more attractive (Zeng et al. 2020). While there are special environmental concerns with shipping in pristine Arctic waters, the possibility of notable reductions in greenhouse gas emissions may also affect the relative attractiveness of the NSR over other shipping routes, although with increased use of the NSR these emissions will increase over time (Jing et al. 2021).

An emerging possibility is transportation on the western portions of the Northeast Passage (Meng et al. 2017; Veland et al. 2021) over Russia and Norway without a full transit (or any transit) of the NSR. The western portion of the Northeast Passage is open year-round and is increasingly active, with cargo volume also increased by a factor of 4 from 2016 to 2019 (Gunnarsson 2021). Overall, destination shipping to or from the NSR to European ports grew from 8% of all voyages in 2016 to about 21% of all voyages in 2019, with almost all of these trips originating or ending in Sabetta, Russia, in the Kara Sea (Gunnarsson 2021). Even during the pandemic mid-

Russian Arctic shipments continued: in 2020 there were 278 shipments of liquid natural gas (LNG) or gas condensate from the Yamal LNG plant in Sabetta, with 241 of those shipments heading to European ports (Center for High North Logistics 2021). Automatic Identification System (AIS) data regularly show bulk or general cargo or tanker ships traveling between western Russian Arctic ports and more southern ports in Europe.

A changing Arctic affects both route accessibility and requirements for infrastructure (Stephenson and Smith 2015; Shiklomanov et al. 2017), yet even the most recent scenarios projecting trajectories of Arctic climate change demonstrate considerable disagreement (Smith et al. 2019). Phase 6 of the Coupled Model Intercomparison Project (CMIP6) realizations of Arctic sea ice properties demonstrate considerable spread even when models are selected based upon ice simulation skill assessed using satellite era verification (Notz and SIMIP Community 2020). Analyses of the impacts of this variability on interannual and decadal time scales suggest that accessibility on the NSR will be inconsistent over the coming two to three decades (Li et al. 2021b). Thus, although transit across the entire Northeast Passage may be 40% shorter than the Suez Canal route between East Asia and Europe (Liu and Kronbak 2010; Schøyen and Bråthen 2011; Abay 2021; Yudnikova and Bedashov 2021), it will eventually compete with transpolar shipping activities (Bennett et al. 2020) and must contend with several decades of uncertainty (Choi et al. 2015) that could affect shorter, partial trips through the Northeast Passage as well. Accessibility in the Arctic and sub-Arctic waters also depends on weather forecast skill (Veland et al. 2021), regulations under the Polar Code, international commodities pricing, tariffs and duties, and a myriad of other factors (Stephenson et al. 2014).

The ability to haul goods over permafrost and along rivers to access marine transportation depends on climatic factors such as river ice thickness as well as logistical factors such as vehicle weight (Sturm et al. 2017; Streletskiy et al. 2019). The capacity for rail networks to contribute to high north transportation logistics—which may either compete with or augment sea traffic (Lu et al. 2019)—also remains an open question.

Arctic ports provide a variety of important local and regional logistical services for both local industries and regional activity. Increased local or regional activity or socio-economic development could reasonably argue for increased port investment. Many Arctic regions also wish to reinvent themselves as multimodal transportation hubs (Lavissière and Faury 2019). However, increased marine traffic does not necessarily suggest increased use of ports along the route as transshipment hubs since these northern ports may not be economically competitive. Current large multimodal terminals such as those in Rotterdam or other major European ports farther south have notable scale economic advantages due to the minimum efficient scale for multimodal terminals. Since Arctic shipping is part of a competitive global economy, additional investment in Arctic ports due to increased Arctic vessel traffic may increase interport competition from large established ports farther south (Ng et al. 2018).

While some ports may capture local traffic (Wang et al. 2019), only the most competitive will be viable as a multimodal transportation hub with transshipment services and infrastructure given international shipping's slim margins. Furthermore, the required infrastructure is expensive; investment should not occur if a route is unlikely to capture adequate revenues over time (de Langen and Saragiotis 2018). For a given ship and cargo, different sea–land routes may also generate different emissions as well (Haider et al. 2021).

In this paper, we show that regional plans based on changes in the natural environment expected from climate change may be physically but not economically viable due to the effects of global economic competition. Route choice can also affect emissions. We start by examining the relative competitiveness of coastal cities as multimodal transportation hubs, independent of additional costs of construction and the potential displacement of other economic activities.

To reduce these compounding issues of varying and changing governmental policies and exchange rates, we choose six coastal cities in a single country, Norway. About 80% of all shipping in the Arctic traverses Norwegian waters, totaling about 17 million metric tons (Olsen Carter and Dawson 2019; Veland et al. 2021). We then compare and contrast the competitiveness of these six with Rotterdam, a well-studied (Fransen and Davydenko 2021) existing major European transshipment hub in the Netherlands that is frequently used in comparative studies of Arctic shipping (Theocharis et al. 2018; Yudnikova and Bedashov 2021) and one of the biggest ports in the world (Becker et al. 2018). We analyze different routes over both existing and proposed roads and rail and consider the cost differentials between moving cargo via ship versus rail versus road, as well as transfer costs. Focusing on the active Barents and Norwegian Sea area (Eguíluz et al. 2016), our results hold for any cargo crossing the Russian–Norwegian sea border from east to west, regardless point of origin (i.e., both for cargo starting in Russia or for transshipments across the Northeast Passage.)

Sea costs are notably lower than land costs for the same item shipped (LNG, container, etc.) (Lu et al. 2019) but can vary by type of vessel and across time. Using only two limited assumptions (constant transfer costs and constant costs for land travel per kilometer), we provide more general break-even land–sea cost ratios relative to Rotterdam for each of the six cities for different routes. These assumptions provide a positive bias in favor of finding the Norwegian ports more efficient. For example, transfer costs from sea to land are likely much higher for Arctic and sub-Arctic ports with relatively low volume than they are for a high volume existing major multimodal hub like Rotterdam. In addition, many of these Norwegian ports will need to make substantial and costly infrastructure investments in order to become multimodal hubs. These costs would have to be recaptured by these Norwegian ports through additional assessed fees or costs over time. In addition, in some instances new rail lines through the Arctic (Kirkenes, Norway), new rail spurs connecting the port to major rail lines (Bodø, Norway, and others), or new roads will need to be built, incurring

additional costs that will need to be recaptured, while Rotterdam already has these linkages. We do not consider any of these additional costs for these six Norwegian sea–land routes or ports in our calculations, providing a further bias against finding Rotterdam more cost effective or efficient.

These break-even ratios abstract from any assumptions about costs, currencies, etc. and provide a reference point for the relative sea versus land costs per kilometer for any given good at any given time. The break-even ratio demonstrates how low land costs would have to drop relative to sea costs to make any given city competitive under different route characteristics. In addition, the relative nature of the break-even ratio methodology allows for comparisons of these routes with other, noneconomic factors, such as direct emissions; while we model carbon dioxide (CO₂) emissions here, this methodology can be applied to other emissions such as carbon monoxide (CO), methane (CH₄), black carbon, nitrogen oxides (NO_x), and sulfur oxides (SO_x) that, for a given ship/cargo/route, vary with fuel consumption and thus distance traveled. A break-even analysis and a comparison with relative pricing allow for future ratios of costs (or emissions) to change as a result of technological changes or economic factors. As these change over time, the relative costs (or emissions) versus sea-based transport can be compared with these ratios and the relative ranking will still hold.

It is always possible that territorial conflicts, border regulations, or even natural hazards could disrupt international shipping or make one route preferable to another. If these include disputes with Russia such that they disrupt NSR or Russian destination traffic, then it is unlikely that any of these ports will have enough volume to warrant expansion. Beyond this, the routes chosen here are unlikely to have such concerns within Europe; to the extent they exist they are also likely to prefer Rotterdam. The Rotterdam to Dresden, Germany, routes only traverse the Netherlands and Germany, both of which are in the European Union (EU) and thus have a common overarching regulations. Both also use the euro and so have a common currency. This route is also in the south where natural hazards are less likely. In contrast, Norway, while a member of the European Economic Area, is not part of the EU and does not use the euro. Some of the ports are notably more northern and thus likely to be more susceptible to natural hazards. Thus, although we abstract away from these concerns, to the extent that they exist they would also give preference to the Rotterdam routes over routes using the Norwegian ports, because either these would sufficiently disrupt volume to the point that the ports are not viable or the land routes from Rotterdam are less likely to encounter such issues.

2. Possible Arctic ports: A tale of six municipalities

Six Norwegian municipalities (Bergen, Bodø, Hammerfest, Kirkenes, Narvik, Tromsø; Fig. 1a) were selected to demonstrate a methodology to assess relative competitiveness as well as to demonstrate the global nature of competition of ports (Zhao et al. 2016). These municipalities have expressed an aspiration to reinvent or at least diversify their economic

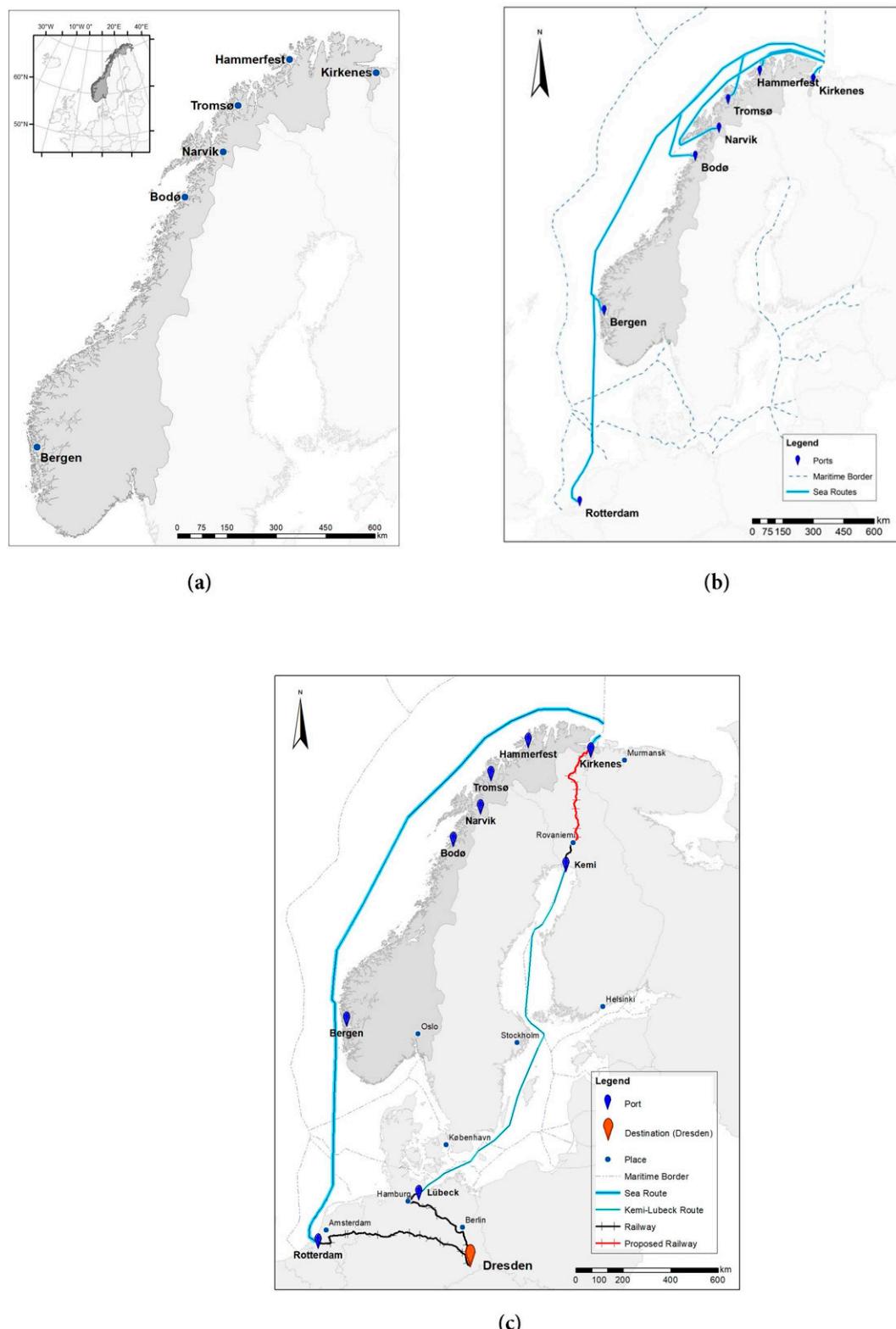


FIG. 1. Geographical locations of the ports in the study and sea route to ports. (a) Location of the six Norwegian townships: Kirkenes, Hammerfest, Tromsø, Narvik, Bodø, and Bergen; (b) sea routes from the border between Norwegian and Russian sovereign waters to each port; and (c) the most cost-effective routes to transhipment hubs (Kirkenes, proposed; Rotterdam, current) for vessels from the NSR.

TABLE 1. Six Norwegian coastal municipalities with explicit aspirations for reinvention. Note that many of the industries listed under “less extractive” cannot be considered to be completely renewable, but they are less directly connected to extractive industries and do have potential to be sustainable in some form. Population is from [Statistics Norway \(2020\)](#).

City	Population (thousands)	Major industries			Stated aspirations
		Extractive	Less extractive		
Bergen	284	Oil and gas; fisheries	Aquaculture, shipping services, research and education, technology-based businesses, and renewable energy research and development (R&D); main base of the Royal Norwegian Navy (at Haakonsvern, Norway)	1) To shift from fossil fuel to technology and renewable industries; 2) to become a national leader in innovation, entrepreneurship, and sustainable business by 2025 (Bergen City Council 2015, 2017)	
Bodø	52	Fisheries	Air, rail, and shipping services; higher education; tourism; NATO base (closing)	1) To become an attractive capital in the north for cultural exchange, sustainable designs, and businesses; 2) to continue serving as a regional transportation hub with airport and city development projects on the site of the closed NATO base (Bodø municipality 2020; Finne 2017)	
Hammerfest	11	Oil and gas; fisheries	Seafood processing	1) To support and expand the fossil fuel sector; 2) to facilitate the growth of local businesses (Hammerfest City Council 2015)	
Kirkenes	10	Iron mining; fisheries	Aquaculture; marine services; governance (Barents Cooperation; Norwegian Barents Secretariat)	1) To meet the rising demand for logistical and transshipment services as Arctic maritime traffic grows; 2) to leverage geopolitical significance and encourage cross-border collaborations by hosting international bodies; 3) to diversify the local economy by supporting small businesses and branching out into the service sector (Sør-Varanger City Council 2014, 2020)	
Narvik	22	Iron mine services (for Kiruna); fisheries	Aquaculture; air services; seafood processing	1) To establish the city as a major stop in the Arctic trading corridor by building new ports and upgrading freight infrastructure (Port of Narvik 2016)	
Tromsø	77	Fisheries	Aquaculture; higher education; R&D tourism; governance (Arctic Council)	1) To strengthen the municipality’s status as the Capital of the Arctic by diversifying the economy and attracting human capital; 2) to encourage cross-border cultural exchange in the north; 3) to improve transportation infrastructure and expand existing ports into a major logistics hub in the Arctic (Nilsen 2015; Tromsø City Council 2018)	

foundations and were chosen for their similarity in regulatory, geopolitical, and geographical environment, thereby removing confounding factors that would arise in a multicountry study. These ports were also chosen as they are perennially ice free because of the warm North Atlantic Ocean waters and have naturally deep harbors that do not require dredging.

They are all subject to low Arctic weather conditions, including seasonal darkness and extreme weather.

These municipalities are also similar in their local economies. Each presently relies on at least one major extractive industry, with varying degrees of diversification (Table 1). All six municipalities have the ocean as a major focus. All six

utilize wild-caught fisheries as an extractive industry, and all but Bodø and Hammerfest engage in aquaculture. Hammerfest also conducts seafood processing. The Norwegian Royal Navy is headquartered near Bergen. A North Atlantic Treaty Organization (NATO) base is closing in Bodø and moving to Ørland. Other extractive industries include hydrocarbons (Bergen and Hammerfest) and iron (Kirkenes and Narvik).

These municipalities have expressed an aspiration to reinvent or at least diversify their economic foundations (Table 1), although Bodø, Kirkenes, Narvik, and Tromsø would need to make costly infrastructure investments. Bodø, Kirkenes, and Narvik expect that goods passing through the Northeast Passage would benefit from a change of transportation mode at a Norwegian port, in part due to the need for ice-class vessels (Solakivi et al. 2018), required by the International Code for Ships Operating in Polar Waters (the Polar Code) (Netherlands Regulatory Framework 2011). The Polar Code applies to vessels weighing over 500 gross metric tonnage in a certain area and has requirements for hull strengthening through framing or plating and hull form. Even so, currently many ships starting in the mid-Russian Arctic or other Russian ports subject to the Polar Code continue on to European ports farther south, suggesting this constraint may not be sufficiently economically binding to warrant transfers farther north.

These six municipalities (Fig. 1b) are compared with a major competing European transshipment port, Rotterdam. Rotterdam is one of Europe's largest container ports (Langenus et al. 2022) and considered in many previous studies of the NSR (Stephenson et al. 2011; Smith and Stephenson 2013; Lasserre 2014; Melia et al. 2016; Ng et al. 2018; Theocharis et al. 2018; Yudnikova and Bedashov 2021). Rotterdam's location farther south may present a potential disadvantage for some ships since the Polar Code-compliant vessels required for the NSR may be less efficient outside Arctic waters but may still be a cheaper route choice than more northern land-based alternatives. Not all vessel traffic need be polar class, however: there is significant traffic to and from Murmansk, Russia, and many are not ice-class vessels since Murmansk is not in "Arctic waters" as defined by the Polar Code, so the Polar Code does not apply. Most destination shipping during the relatively ice-free summer/autumn periods are not ice-class vessels or have little ice strengthening (Milaković et al. 2018).

Since landlocked hubs such as central and eastern European cities require transshipment at some port, the central question relates to the most efficient transshipment location. All of these routes will result in a variety of emissions such as CO₂, CO, CH₄, black carbon, NO_x, and SO_x. These emissions may or may not change Arctic sea ice, with possible regional effects far from the ship lane (Li et al. 2021a; Lindstad et al. 2016). Many studies have examined CO₂ emissions based on fuel use, which for a given ship is a function of distance traveled (Corbett et al. 2009). Here we demonstrate the applicability of the relative valuation methodology by comparing CO₂ emissions for sea-land routes using different ports, but other emissions such as SO₂ and black carbon have also been modeled on the basis of fuel consumption (Stephenson et al. 2018), so this method can be applied to other emissions as well for these sea-land routes.

Arctic destination shipping: A tale of two ships

While most Russian seas and ports are covered by the Polar Code, that is not true for all Russian ports. As mentioned above, the Polar Code does not apply to Murmansk, so many ships that come to and from Murmansk are not ice-class vessels. On the other hand, the port of Sabetta is on the Yamal Peninsula and is within Arctic waters. Sabetta services the large Yamal LNG project; there is active ice-class vessel traffic coming in and out of Sabetta, particularly toward Europe. Below, we describe two ships, the *Falcon* (a non-ice-class general cargo ship) and the *Christophe de Margerie* (an Arc7 LNG tanker) to demonstrate these two types of traffic (non-ice class and ice class). These are examples; there are many ships of both types regularly transitioning from the Norwegian–Russian sea border to ports south or to Russian Arctic ports.

1) NON-ICE CLASS—GENERAL CARGO SHIP *FALCON*

Based on data from MarineTraffic and Bloomberg LLP, the general cargo ship *Falcon* [International Maritime Organization identifier (IMO): 7915278; gross tonnage: 31 027 t; summer deadweight tonnage (DWT): 88 666 t] left Xiamen, China, on 18 March 2021, came around the Horn of Africa, up the western coast Europe, over the top of Norway, and arrived in Murmansk on 8 June 2021 (MarineTraffic 2021a). On 10 June 2021, it left Murmansk, and by 11 June 2021 it was heading west over the top of Norway (MarineTraffic 2021a). Although the *Falcon* made a port of call in Murmansk, it regularly plies Southeast Asian waters, with port calls in China, Singapore, Malaysia, Vietnam, Indonesia, and Australia.

2) ICE CLASS—ARC7 LNG TANKER *CHRISTOPHE DE MARGERIE*

The LNG tanker *Christophe de Margerie* (IMO: 9737187; gross tonnage: 128 806 t; summer DWT: 96 779 t) is part of a fleet of 15 first-generation Arc7 LNG tankers that travel in and out of Sabetta that are designed to transport LNG to European ports "throughout all seasons of the year" (Zawadzki 2019; Ship Technology 2017), made its first NSR transit in 2017 (Comer 2019), and was the first tanker to transit the NSR without an icebreaker escort (Bennett et al. 2020). The *Christophe de Margerie* travels regularly from Sabetta to Rotterdam (or European ports) and back: for example, MarineTraffic shows it left Rotterdam on 5 June 2021 to arrive in Sabetta on 12 June 2021 (MarineTraffic 2021b). The *Christophe de Margerie* traveled eastward in May 2020 with an icebreaker and without an icebreaker in January 2021, passing the LNG tanker *Nikolay Zubov* (also without an icebreaker) along the way, and then returning (with ice-breaker support) to Sabetta in February 2021 (Chambers 2020; Humpert 2020a; Chambers 2021; Pekic 2021). Newer second-generation Arc7 LNG tankers are now designed to travel the NSR year-round possibly without ice-breaker escorts, which will further reduce per-trip costs (Humpert 2020b).

3) TRANSFERS FROM ICE CLASS TO NON-ICE CLASS

Although some LNG polar-class vessels are currently traveling south, some transfers from Arc7 LNG tankers to conventional (non-polar-class) ships are already occurring just over Norway in 2019; these continued in 2020 as the coronavirus disease 2019 (COVID-19) pandemic prevented use of Russian terminals (Humpert 2018, 2020c). By 2022, there will be a massive floating barge near Murmansk to transfer LNG from polar-class ships to conventional ships for ports south (Humpert 2020d). Ships heading south thus could be conventional ships, further reducing the economic argument for more northern sea-to-land transfers.

3. Materials and methods

We assume travel over the western portions of the Northeast Passage will continue to be viable, resulting in crossings of the Norway–Russian sea border. We then examine the relative competitiveness for different Norwegian transshipment ports assuming goods originate or are destined for a landlocked city in central Europe. (A landlocked city in central Europe was chosen as it is farther away from the coast than other major western European destinations so as to bias further against finding Rotterdam to be the most cost effective or efficient.) While the methodology described here is applied to all six cities, two of the six—Bergen and Hammerfest—have not indicated multimodal transshipment as an aspirational strategy in their public statements (Table 1) and so are hypothetical only. Geographical analysis of this study is conducted with ArcMap 10.8. Data layers are edited and analyzed in the World Geodetic System 1984 (WGS84) datum. The final maps are projected in the European Terrestrial Reference System 1989–Lambert azimuthal equal-area (ETRS89-LAEA) system.

a. Routes

We choose a single starting point and final destination to reduce complexity and for ease of comparison. All routes are assumed to start at the intersection of Murmansk-to-port routes and the Norway–Russia maritime border (around 70°18'00.0"N 32°00'00.0"E; Fig. 1b) and are calculated by summing geodesic distances between coordinate pairs along a simulated port-to-port route provided by MarineTraffic. All routes are assumed to end in Dresden, a central European transportation hub that connects efficiently—by road and rail—to eastern and southern Europe, the Middle East, and central and eastern Asia. These rail systems provide another source of competition to northern sea routes, and therefore the competitiveness of these six municipalities as transshipment hubs (Zeng et al. 2020). Single-modal land routes from ports to Dresden Central Station consist of existing routes and routes with proposed segments. A key assumption behind land route selection is that the fewer modal transfers and the shorter the routes, the more economically competitive they will be. For simplicity, the transfer cost in a single-modal route (i.e., road to road or rail to rail) is considered to be negligible. For single-modal roads (Figs. 2a,b), routes generated

by Google Maps are modified to align with the European Commission (EC) Trans-European Transport Network (TEN-T) freight infrastructure. If a route contains ferry segments, an alternative route without ferry is also investigated. Road distances are calculated by Google Maps. As for single-modal trains (Fig. 2c), TEN-T freight rails are preferred, and their lengths are available in GIS datasets published by the EC. Rail routes outside of the EC core freight zones are retrieved from OpenStreetMap and selected based on the availability of high-speed railway and distance. As road is the most expensive transportation mode, followed by rail and sea, multimodal routes (Fig. 2d) are considered if a significant portion of a single-modal route can be substituted by a cheaper mode to offset the transfer cost at the minimum.

b. Costs and relative pricing

We calculate the cost of shipping a commercial sized unit of goods, materials, or commodities from this location through Rotterdam and through each of the six Norwegian cities, using all available transport mode combinations (Figs. 1 and 2). These mode combinations include presently available options as well as routes that are proposed but not yet constructed, such as the Arctic Railway (Fig. 1c) and the Helsinki–Tallinn Tunnel (Fig. 2c).

One of the larger proposed construction is the proposed Arctic Railway from Kirkenes that envisions Kirkenes as a hub port for goods traveling over the NSR as it will be the first western port. Proposers of the Arctic Railway imagine this route capturing 10% of Asian container trade to the northern European countries of Germany, Denmark, Finland, Sweden, and Norway (as well as possible Russian cargo), resulting in 550 000 containers per year with 10 southbound trains per day (Sør-Varanger Utvikling 2018). If so, and if the NSR is active for 7–8 months per year, proposers suggest that this route will be economically competitive with the Suez Canal routes (Sør-Varanger Utvikling 2018) in around 2040, although in 2019 Finnish–Norwegian working group concluded that the route would not be financially viable, especially given its EUR 3 billion cost of construction (Quinn 2019). The Indigenous Saami also strongly oppose the construction of the railway (Quinn 2019; Nilsen 2020).

Even if it was built, the Arctic Railway may face stiff local competition: Russia plans to develop Murmansk as a major transshipment hub to capture the same traffic as well as goods going into Russia (Goncharova and Stoyanova 2021; Yudnikova and Bedashov 2021). While the Port of Kirkenes and the proposed Arctic Railway could service closer areas (Norway, Finland, and Sweden), it is not clear that this amount of traffic would be economically viable without the inclusion of Germany. In 2016, Germany accounted for 3.2 million of the 3.9 million containers estimated between China and Germany, Finland, Sweden, Denmark, and Norway and accounted for about one-half (272 000) of the estimated cargo in the future financial estimates (Sør-Varanger Utvikling 2018). The construction of the rail tunnel to the Baltic region would also be essential for capturing cargo destined for Germany (Sør-Varanger Utvikling 2018). Thus, even

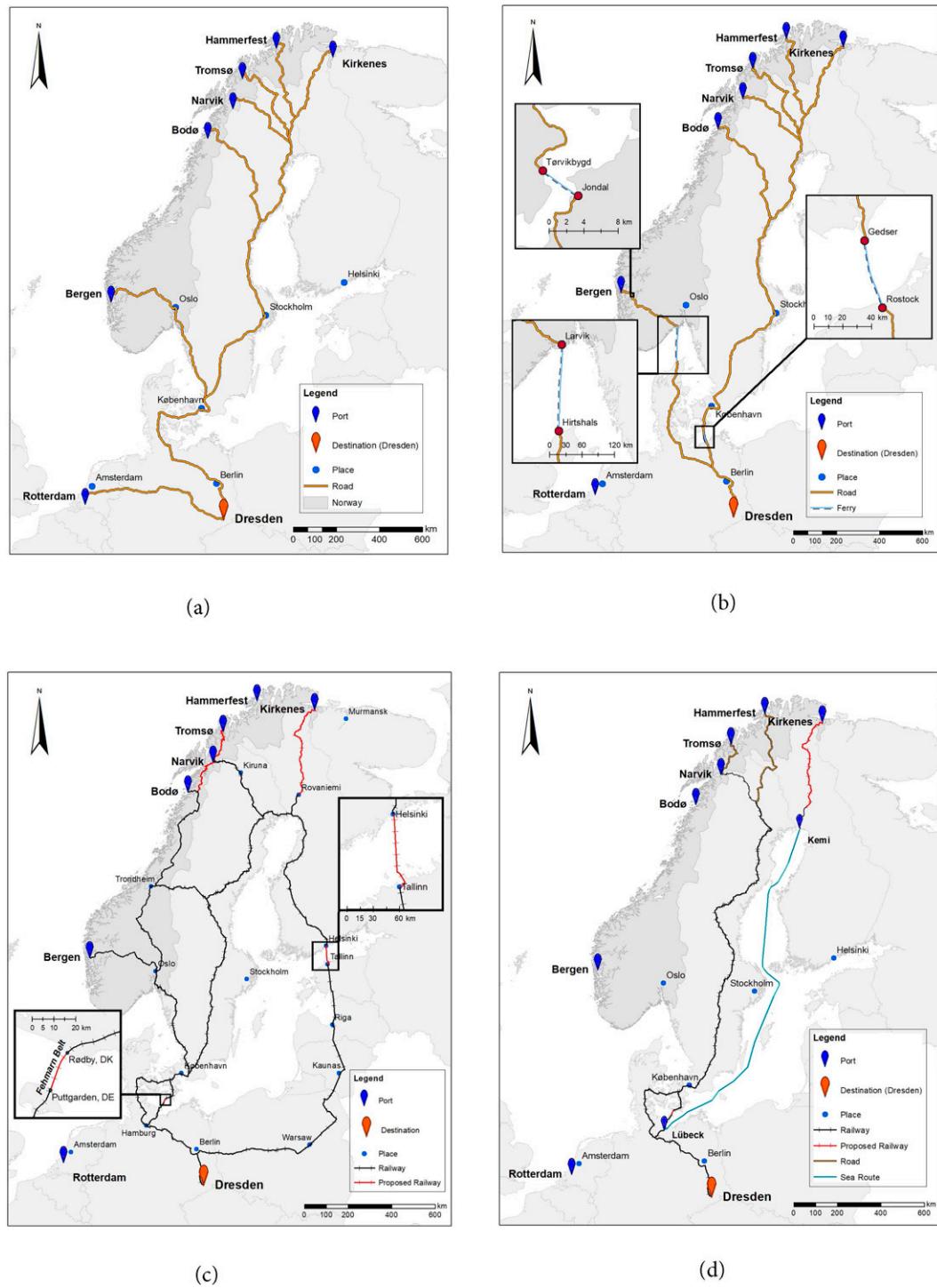


FIG. 2. Current and proposed routes over land to Dresden, separated as (a) current road routes, (b) possible road routes including ferries, (c) current and proposed rail routes, and (d) multimodal routes.

if built, it is important to see if this route would be competitive with other routes for servicing locations in Germany, as is done below; if not, it is unlikely the route would capture this traffic even if built.

Construction of either (or both) of the Arctic Railway or the Helsinki–Tallin Tunnel will be expensive. The cost of construction of the missing infrastructure is not included in the estimation, further biasing the results in favor of these ports

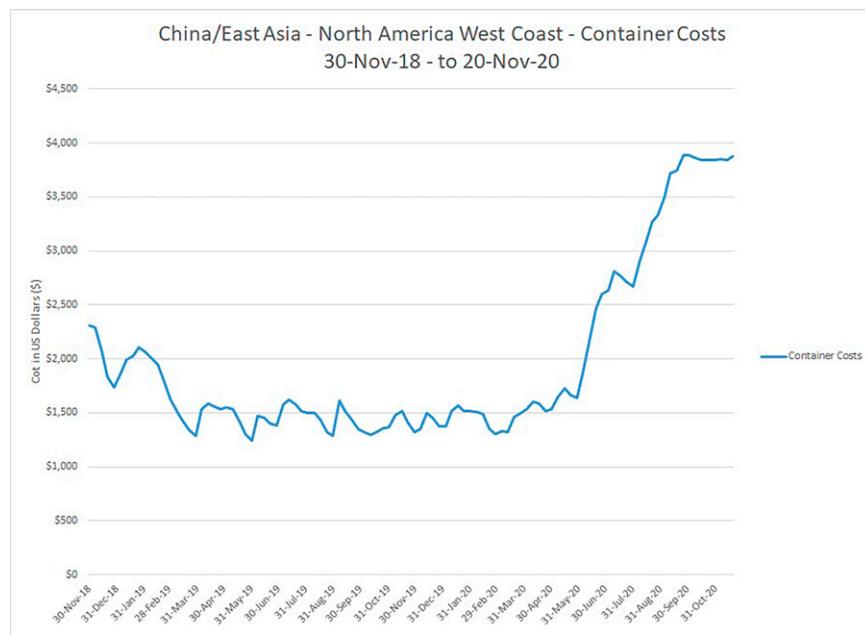


FIG. 3. Container shipping costs over a 2-yr period of time. The data series are for index FBX01, provided through the courtesy of Freightos, Ltd.

and away from Rotterdam or other existing southern ports. There is clearly a limitation on the time horizon for these plans because of ice retreat under climate change and its impact particularly on Polar Code requirements.

As noted above, the proposed Kirkenes route imagines capturing some of the Asian container trade. Therefore, although the methodology we use below will work for any cargo, it may be easiest to imagine an intermodal container as the cargo. The most frequently used container at present is a 2-TEU capacity unit, where TEU is the “twenty-foot equivalent unit” that is used to measure cargo capacity in container ships. This capacity, an inexact measure, corresponds to approximately 38.5 m^3 . However, because of the use of relative pricing (described below), this methodology is robust to the use of 1 TEU, 2 TEU, or any other volumetric measure of cargo.

Even prepandemic, shipping costs are highly variable (Fig. 3). In 2017, it cost \$4800 (U.S. dollars) to ship a container the 6000 n mi ($\sim 11\,100 \text{ km}$) from East Asia to the North American west coast (Valentine 2017). In the first week of January 2020, the cost for a “forty-foot equivalent unit” (FEU) was \$1317, in the last week of May 2020 it was \$1638, and on 24 November 2020 it was \$3870 (Freightos, Ltd. 2020).

To control for variability in both ship and land costs, we later use relative prices per kilometer of shipping by sea and by land. Using relative costs has a variety of benefits. As long as these relative shipping costs hold for other units (such as barrels of oil or containers of coal) the relative relationships between the route costs hold. In addition, to the extent shipping and rail and road costs covary, relative costs maintain the relative ranking of the routes. Last, relative pricing also

abstracts from currency units, be they kroner (Danish or Norwegian), euros, or dollars (U.S., Canadian, or Australian), rubles, or any other currency. Relative pricing in effect puts all prices in a common currency and then shows the relative costs in that currency. (If X is 2 times as expensive as Y in U.S. dollars, then after currency conversion it is also 2 times as expensive as Y in rubles or euros.) In this way, even if prices for different portions are priced in different currencies, relative pricing acts as if all prices were then converted to a common currency and then the relative values are used.

Relative pricing has another benefit. Different ships will have different transportation costs. Transportation costs will also vary across goods. However, once a particular good is loaded on a particular ship, it is that ship’s cost that matters. That particular good will stay on that particular ship until it is unloaded at a specific port. Thus, once loaded on the ship, the cost of moving that particular good over the ocean is largely a function of distance. Thus, while costs per kilometer may vary from good to good and ship to ship, once a given good and ship is chosen, that cost can then be compared with the cost per kilometer for land travel. Since for each route the distance by ship and the distance by land has been chosen and remains constant regardless of good type or ship choice, the relative cost break-even ratio can be multiplied by the cost per kilometer by ship to say how low the land cost per kilometer needs to be for that route to be cheaper than using the Rotterdam route.

For illustration purposes, we begin with a model in which sea, road, rail, and ferry costs per kilometer traveled are all different. We multiply the kilometers traveled by transportation method (sea, road, rail, or ferry) on each route by the relevant cost per kilometer for that method, resulting in a total sea, road, rail, or ferry cost for each route.

There are notable and considerable differences in terminal costs in multimodal shipping. Multimodal terminal economics suggest there is a minimum efficient scale; it is not clear that these proposed Norwegian hubs would have enough volume to meet this hurdle. In addition, a large active current port such as Rotterdam has notable scale economic advantages that would be very difficult to overcome for newer, less active Arctic ports that do not also have notable non-Arctic traffic as do coastal mid-European ports. All of these factors preference Rotterdam and other current active mid-Europe ports over these six more northern ports in terms of transfer costs. To emphasize the additional economic hurdles just due to sea- and land-based competition, we assume that all ports have the same multimodal transfer costs and therefore bias the results away from finding Rotterdam as the cheapest alternative. (While in real life these may differ, they are generally similar within an order of magnitude; using the cheaper of the two ports' transfer costs will bias the result away from the cheaper port.)

Land transportation costs are notably higher than by sea: 2017 transportation cost estimates for a container were \$0.80 per nautical mile ($1 \text{ n mi} = 1.852 \text{ km}$) for a neo-Panamax ship or just over \$0.695 per statute mile ($1 \text{ mi} \approx 1.61 \text{ km}$), and \$2.50 per mile per container by rail (Valentine 2017). Rail costs in fact tend to be lower than road costs, and it is possible in some cases that ferry costs are higher. For non-polar-class vessels, we use prices of shipping and rail based on 2017 estimates of transportation costs for a container by ship ($\$0.695 \text{ mi}^{-1}$, rounded to \$0.70, which corresponds to $\$0.43 \text{ km}^{-1}$), and by rail ($\2.50 mi^{-1}; $\$1.55 \text{ km}^{-1}$). Road costs are assumed to be more expensive than rail ($\$3.00 \text{ mi}^{-1}$; $\$1.86 \text{ km}^{-1}$) and ferry costs are assumed to be even higher ($\$4.00 \text{ mi}^{-1}$; $\$2.49 \text{ km}^{-1}$).

As noted above, some ships that travel this route are not ice-class vessels, while some are. It is possible that the extra requirements on Polar Code compliant vessels may impose a premium over shipping costs in ice-free waters. The estimates of this premium vary widely, even by the same authors: Solakivi et al. (2017) estimate Finnish–Swedish ice-class rules (similar to the Polar Code ice-class rules) may increase costs in open water by 9%, while estimates in Solakivi et al. (2018) are as high as 50%. Theocharis et al. (2018) notes a few

studies suggest the premium is around 20%. Using the high-end estimates of a 50% premium for ice vessels, we get $\$1.05 \text{ mi}^{-1}$, or $\$0.65 \text{ km}^{-1}$, since $1.5 \times \$0.70 = \1.05). We again bias in favor of the Norwegian ports over Rotterdam by using the high-end premium for ice vessels and assuming an ice-class vessel will be used, despite the many non-ice-class vessels (such as the *Falcon*, noted above) making these trips.

If, for ease of exposition, we lower that slightly to $\$1 \text{ mi}^{-1}$ and keep the other costs constant, we get a high-end estimate of relative polar vessel costs: rail is 2.5 times the polar-class sea cost; road is 3 times the polar-class sea cost, and so on. Thus, for sake of generality, X is initially set at 1 unit ($X = 1$) per kilometer traveled and all other costs are in multiples of X to emphasize the importance of relative costs: transportation costs by road are set 20% higher than rail costs so road costs are set at $Y = 3X$ and rail at $Z = 2.5X$, and any ferry costs are set at $F = 4X$. These costs as ratios are both currency and distance measurement independent (i.e., if rail costs per mile are 2.5 times sea costs, then rail costs per kilometer will also be 2.5 times sea costs; if rail costs per distance traveled are 2.5 times as expensive as sea costs per distance traveled, this will be true whether sea and rail costs are measured in dollars or euros.)

Transfer costs T are initially assumed to be about \$200 (Lin and Chang 2018). Most routes only have one transfer, but the sea-to-road-to-rail for Hammerfest and Tromsø routes have two transfers and the sea-to-rail-to-ferry-to-rail proposed for Kirkenes has three transfers. (Changes from road to ferry are not assessed a transfer because it is assumed that the truck just drives onto the ferry.)

c. Total cost

Costs per route are estimated as follows. Ocean shipping costs are estimated at a rate of X cost per distance unit. When cargo transfers from ocean ship to land-based carriers, a port transfer cost of T is applied for each transfer. Once on land, the cargo is then moved to Dresden either by road or rail, at a cost of Y per distance unit for road and Z per distance unit for rail. If a ferry is used, the cost of a ferry per distance unit is F . Thus, costs are estimated as

$$\begin{aligned} \text{Total cost} = & [\text{sea shipping distance (S)} \times \text{ocean shipping cost per unit of distance (X)}] \\ & + [\text{transfer from ship to shore costs (T)} \times \text{no. of transfers (N)}] \\ & + [(\text{road or rail}) \text{ distance (R)} \times (\text{road or rail}) \text{ cost per unit of distance (Y or Z)}] \\ & + [\text{ferry distance} \times \text{ferry cost per unit of distance (F)}]. \end{aligned} \quad (1)$$

For illustration, Table 2 provides an example of these calculations for the sea-to-road routes for two example transshipment ports: Tromsø and Rotterdam.

Next, to reduce complexity, we next set all nonsea (road, rail, or ferry) transportation costs equal to each other (so $Y = Z = F$) and are all lowered to the rail cost per

kilometer. Since some nonsea transportation costs per kilometer traveled are higher than others, this effectively lowers the higher costs to the lower level and thus reduces nonsea portions, thereby biasing the analysis toward routes with longer nonsea portions. These assumptions provide a further bias in favor of the Norwegian ports over Rotterdam.

TABLE 2. Example of calculations for total cost for Tromsø and Rotterdam sea-to-road routes. Note that the costs per kilometer have been truncated for display.

City	Sea distance (km)	Sea cost per kilometer	Sea cost (sea distance \times sea cost per kilometer)		Transfer cost	Road distance (km)	Road cost per kilometer	Road cost (road distance \times road cost per kilometer)		Total cost (sea cost + transfer cost + road cost)
			Sea cost (sea distance \times sea cost per kilometer)	Road cost (road distance \times road cost per kilometer)						
Tromsø	657	0.43	286	200	3167	1.86	5904	6389		
Rotterdam	2941	0.43	1279	200	771	1.86	1437	2916		

d. Break-even ratios

Once embarked with cargo, a ship passing the Norwegian-Russian sea border will need to dock at a transshipment port somewhere to transfer the cargo from sea to land. The question here is not what the total costs for each port/route are, but a comparison between ports/routes.

Therefore, the key question is how one port/route compares to another—which one is cheaper and under which conditions? While one can compare total costs, those total costs will change as sea costs or rail costs or transfer costs change. For example, Table 2 shows that when land costs per kilometer are about 4.3 times (1.86/0.43) that of sea costs, Rotterdam is cheaper.

At the same time, this suggests one would be indifferent between going to Tromsø or Rotterdam if the total costs were equal. One could therefore ask what is the ratio of land costs per kilometer to sea costs per kilometer that would make the total costs the same? To find this, we could define X as the ratio of land costs per kilometer to sea costs per kilometer, so land costs per kilometer = $X \times$ sea costs per kilometer.

We can then rewrite the two items in Table 2, substituting sea costs per kilometer for 0.43, and $X \times$ sea costs per kilometer for 1.86:

$$\begin{aligned} \text{Tromsø total costs} &= 657 \times \text{sea costs/km} + 200 \\ &+ 3167(X \times \text{sea costs/km}) \text{ and} \end{aligned} \quad (2)$$

$$\begin{aligned} \text{Rotterdam total costs} &= 2941 \times \text{sea costs/km} + 200 \\ &+ 771(X \times \text{sea costs/km}). \end{aligned} \quad (3)$$

By setting the Tromsø total costs = Rotterdam total costs, we can find the ratio of land costs per kilometer to sea costs per kilometer where we would be indifferent:

$$\begin{aligned} 657 \times \text{sea costs/km} + 200 + 3167(X \times \text{sea costs/km}) \\ = 2941 \times \text{sea costs/km} + 200 \\ + 771(X \times \text{sea costs/km}). \end{aligned} \quad (4)$$

Note that the transfer costs of 200 are on both sides and cancel out. We can also drop the parentheses, so now the equation is simplified to

$$\begin{aligned} 657 \times \text{sea costs/km} + 3167X \times \text{sea costs/km} \\ = 2941 \times \text{sea costs/km} + 771X \times \text{sea costs/km}. \end{aligned} \quad (5)$$

Now note that all of the remaining numbers are multiplied by sea costs per kilometer on both sides and so can be

factored out. Dividing both sides by sea costs per kilometer, we get

$$657 + 3167X = 2941 + 771X. \quad (6)$$

Solving for X we get

$$X = (2941 - 657)/(3167 - 771) = 0.953255. \quad (7)$$

So as long as land costs per kilometer are higher than 0.95 times sea costs, the Rotterdam sea-to-road route will be cheaper than the Tromsø sea-to-road route. This ratio ($X = 0.95$) is the break-even land-to-sea cost ratio.

More generally, break-even land-to-sea cost ratios are calculated to compare the particular route with the sea-road route via Rotterdam as follows:

$$\text{break-even ratio} = [T(\text{NR} - \text{NO}) + (\text{SR} - \text{SO})]/(\text{RO} - \text{RR}). \quad (8)$$

where T is the transfer and fee cost, NR is the number of transfers using Rotterdam, NO is the number of transfers using the other route in question, SR is the sea shipping distance to Rotterdam, SO is the total sea shipping distance for the other route in question, RO is the total road/rail/ferry distance for the other route in question, and RR is the land (road/rail) distance from Rotterdam to Dresden used as a comparison. For simplicity, for the break-even analysis, it is assumed that the rail and road costs in Norway and on the EU rail lines are the same and that the transfer costs are the same for all ports. In this way, the break-even analysis provides a lower bound on the premium of land-based costs to sea-based costs where that route no longer becomes competitive with the existing port in Rotterdam.

e. Direct emissions

The above methodologies may also be used to estimate CO₂ emissions. Freight metric ton-kilometer direct CO₂ emissions (gCO₂ km⁻¹) from road transport are orders of magnitude larger than ocean-based bulk carriers or tankers; rail also is many multiples of ocean-based vessels (Sims et al. 2014; Sherbaz and Duan 2014). For example, while there are, of course, ranges of emissions across categories, an ocean bulk carrier could be estimated to emit an average of ~ 3 gCO₂ km⁻¹, an ocean bulk tanker emits ~ 5 gCO₂ km⁻¹, a container ship emits ~ 10 gCO₂ km⁻¹, a roll-on/roll-off ferry emits ~ 60 gCO₂ km⁻¹, a diesel freight train emits ~ 45 gCO₂ km⁻¹, and heavy freight

TABLE 3. Estimated total transportation costs for different routes for a given unit of goods for a non-polar-class vessel. Calculations assume relative prices of shipping and rail based on 2017 estimates of transportation shipping costs for a container by ship [\\$0.70 per mile (\\$ 0.43 km⁻¹) per container for non-polar-class vessels] and by rail [\\$2.50 per mile (\\$1.55 km⁻¹) per container]. Road costs are assumed to be 20% more than rail costs [\\$/3 per mile (\\$1.86 km⁻¹) per container]. Ferry is assumed to be higher than road per distance traveled [\\$/4 per mile (\\$2.49 km⁻¹) per container]. Transfer costs are \\$200 per container per transfer.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	6206			5614		5228	3202
Hammerfest	6406		5994	5856	5754		
Tromsø	6389		5818	5823	5579	5314	
Narvik	6313	5386		5748		5146	
Bodø	5909	5274		5341		5033	
Bergen	4803	4343		4154		4104	
Oslo	4259						
Rotterdam	2916	2764					
No. of transfers	1	1	2	1	2	1	3

trucks emit ~125 gCO₂ km⁻¹ (Sims et al. 2014). For simplicity, we will assume that emissions related to transfers are negligible and set them to zero.

Similarly, an analysis of the break-even ratio calculation above shows that there are no “prices” in the equation, but only distances and transfers. As a result, while it can be used to examine the break-even point for relative costs across routes, it can also be used to examine the break-even point for other, noneconomic issues, such emissions. This method will work as long as different modes of transportation have different emissions.

This method will work for many different types of emissions; below, we apply this analysis to direct CO₂ emissions. To simplify the analysis, we assume direct CO₂ emissions due to multimodal transfer at each port are similar. Thus, even if they are nonzero, since most routes have just one transfer the number of transfers is the same, and thus the first term will cancel out to zero. (If the routes in comparison have the same number of transfers, the choice of route does not change the amount of emissions due to transfers.) To simplify the break-

even ratio analysis, we assume that all routes only have one transfer: to the extent that a route (such as the proposed Kirkenes route) has more than one transfer it would have additional emissions, and so the ratio calculated here would be a lower bound because the true break-even ratio would be even lower (again biasing in favor of these routes over Rotterdam). Not including these additional transfers therefore biases the results in favor of these alternative routes:

$$\text{Break-even ratio (simplified)} = (\text{SR} - \text{SO})]/(\text{RO} - \text{RR}). \quad (9)$$

4. Results

The results in Table 3 (non-polar-class vessel) and Table 4 (polar-class vessel at 50% premium) both suggest that shipping by sea then rail via Rotterdam is the most cost efficient. Table 3 suggests that the cost for shipping using a non-polar-class vessel to Rotterdam is cheaper by then using rail (2764) or road (2916) to get goods to Dresden. All other existing routes are notably higher: for non-polar-class vessels, costs

TABLE 4. Estimated total transportation costs for different routes for a given unit of goods for a polar-class vessel. Calculations assume relative prices of shipping and rail based on 2017 estimates of transportation costs for a container by ship (50% ice-class vessel premium over non-polar-class vessel results in \\$1.05 per mile or \\$0.65 km⁻¹ per container for polar-class vessels) and by rail (\\$2.50 per mile or \\$1.55 km⁻¹ per container). Road costs are assumed to be 20% more than rail costs (\\$3 per mile or \\$1.86 km⁻¹ per container). Ferry is assumed to be higher than road per distance traveled (\\$4 per mile or \\$2.49 km⁻¹ per container). Transfer costs are \\$200 per container per transfer.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	6224			5631		5246	3586
Hammerfest	6490		6078	5941	5839		
Tromsø	6532		5961	5966	5722	5457	
Narvik	6559	5631		5994		5392	
Bodø	6167	5532		5599		5291	
Bergen	5234	4773		4584		4534	
Oslo	4836						
Rotterdam	3556	3404					
No. of transfers	1	1	2	1	2	1	3

TABLE 5. Estimated total transportation costs for different routes for a given unit of goods. Calculations assume that land shipping costs (rail and road) and ferry shipping costs are 2.5 times that of sea shipping costs per kilometer. Transfer costs are \$200 per container per transfer.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	5227			4708		5244	3531
Hammerfest	5472		5874	4989	5635		
Tromsø	5528		5868	5031	5629	5436	
Narvik	5587	5596		5091		5357	
Bodø	5265	5495		4766		5254	
Bergen	4548	4711		3921		4472	
Oslo	4269						
Rotterdam	3225	3312					
No. of transfers	1	1	2	1	2	1	3

range from 4154 for Bergen (sea–road–ferry–road) to 6406 for Hammerfest (sea–road). Only the proposed Kirkenes sea–rail–sea–rail is close to competitive with Rotterdam at 3202; all other proposed routes are more expensive (with the cheapest per port ranging from 4104 to 5754).

These results are also true for Table 4 for a polar-class vessel with sea costs at a 50% premium. Table 4 suggests that the cost for shipping using a polar-class vessel to Rotterdam and then using rail (3404) is the cheapest; then using road from Rotterdam (3556) is the next cheapest of the existing routes. All other existing routes are notably higher, and it is still true that Bergen (4584; sea–road–ferry–road) is the next cheapest, with Narvik now the highest (6559). The proposed Kirkenes sea–rail–sea–rail is close to competitive with Rotterdam at 3586; all other proposed routes are more expensive (with the cheapest per port ranging from 4534 to 5839).

In general, these relative ranking results are invariant to the size of the transfer costs: whether transfer costs double or are cut in half does not change the relative competitiveness for almost all routes.

The overall result that Rotterdam is the most competitive is not due to the differences in costs per kilometer traveled by rail versus road versus ferry. Even if all nonsea costs are lowered to the cost of rail (and thereby make all nonsea costs equal), the results do not change. Table 5 replicates Table 4, slightly lowering the sea costs to $\$1 \text{ mi}^{-1}$ or $\$0.62 \text{ km}^{-1}$ (equivalent to a 43% ice vessel premium) to make relative

costs more apparent. In Table 5, all nonsea costs per kilometer are lowered to the rail cost (2.5 times the per-kilometer sea cost), again creating a positive bias for any route that is not rail only over land and a bias against finding for Rotterdam. The results in Table 5 also suggest that, based on current infrastructure, skipping over all Norwegian ports and continuing straight to Rotterdam is by far the most cost effective, rather than then using either road (3225) or rail (3312). All of the proposed routes are dominated by the existing Rotterdam choices; even the proposed Arctic railway from Kirkenes that terminates in the Baltic (Fig. 2c) is more expensive (3531).

In general, Rotterdam is cheaper, mostly because travel by sea (even in a polar-class vessel) is cheaper than travel by land. For each route, however, there exists a land–sea cost ratio below which that route becomes competitive with Rotterdam. Table 6 demonstrates these break-even points under the assumption that all road/rail/ferry costs are equal as in Table 5 and compares all routes with the sea–road route via Rotterdam. Whenever the land-to-sea costs are in excess of the ratios in Table 6, that port/route is not competitive with sea–road route via Rotterdam.

Even the 1.89 ratio for the proposed rail and sea route from Kirkenes is lower than the typical land to sea cost ratio, and rail costs are likely higher in the Arctic where Kirkenes is located. Thus, as long as rail costs per distance are more than 1.89 times the sea cost per distance, shipping via Rotterdam will dominate.

TABLE 6. Estimated land–sea cost break-even ratio between that route and going via Rotterdam by ship then road/rail with transfer costs. This table provides an estimate of the break-even ratio for cost per goods moved per kilometer. If land/sea cost ratio is higher than break-even then the Rotterdam sea–road route is cheaper.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	1.18			1.36		1.17	1.89
Hammerfest	1.03		0.91	1.18	0.96		
Tromsø	0.95		0.84	1.10	0.89	0.98	
Narvik	0.81	0.80		0.94		0.86	
Bodø	0.87	0.81		1.04		0.87	
Bergen	0.78	0.72		1.16		0.81	
Oslo	0.37						

Many other routes will not be competitive at all at any realistic sea/land cost ratios. Even in the unlikely scenario that sea costs per distance are the same as land transportation costs, port/routes with ratios of less than 1 remain uncompetitive, including the proposed routes that are very uncompetitive (Fig. 4a; Table 6). Even when distances are shorter (Fig. 4b), land costs result in overall route costs that are notably more expensive than going by sea alone: land over sea transportation premiums are easily over the 18%–36% are needed for Kirkenes and Hammerfest to be competitive.

While the previous analyses used monetary costs, as noted above these methodologies can also be used to estimate emissions. We assume that different modes of transportation have different emissions, so that emissions per kilometer traveled by sea are different than emissions per kilometer traveled by road, which may be different than emissions per kilometer traveled by rail. For concreteness, we provide an example using CO₂ emissions. Assuming for simplicity that the CO₂ emissions related to ship-to-shore transfers are negligible, Table 7 makes the following estimates for the scenarios in Tables 3 and 4 but for CO₂ emissions and not costs.

Again, the sea-to-Rotterdam route has the lowest emissions at 66 625. Only the proposed rail line from Kirkenes is close at 70 795. All other routes are over 100 000, with some being 4 times that amount. In general, rail routes are lower than routes by road (although even the sea-road route from Rotterdam is the fifth lowest on the list at 125 785. While the two highest or lowest cost routes in Tables 3 and 4 also respectively have the two highest or lowest emissions in Table 7, this result is not uniform: In Table 3, the sea-to-road-to-rail route from Hammerfest had a cost estimate of 5994, slightly higher but close to the sea-to-road cost for Bodø at 5909, but in Table 7 the CO₂ emissions for the Hammerfest route were 204 900, much lower than the 360 110 estimated for Bodø.

As noted, the break-even analysis can also be used as an estimate of which route will provide more emissions. Over time, there may be changes in the relative emissions by different modes of transportation, so instead of using specific emissions, we will again calculate the break-even land-sea ratio. These break-even ratios are general and can be applied to any type of emission (CO₂, SO_x, etc.) that varies with distance once a type of ship is determined.

Assuming that the amount of emissions due to multimodal transfer does not vary notably by port, Table 8 provides a break-even analysis for emissions when compared with the sea-to-rail route via Rotterdam. In Table 8, we also assume only one transfer per route, which allows the ratio to be higher for the few routes with multiple transfers and thus biases against the sea-rail route via Rotterdam.

These ratios provide another way of looking at CO₂ emissions. For comparison, using our previous rail estimates to create land-sea ratios (an ocean bulk carrier emits 3 gCO₂ km⁻¹, an ocean bulk tanker is 5 gCO₂ km⁻¹, and a container ship is 10 gCO₂ km⁻¹, and a diesel freight train emits 45 gCO₂ km⁻¹), the ratios are 15 (45/3) for bulk, 9 (45/5) for ocean bulk, and 4.5 (45/10) for the container ship (Sims et al. 2014). Since all of these ratios (15 for bulk, 9 for ocean bulk, and 4.5 for container) are higher than 3.32, it implies that the emissions are lower for

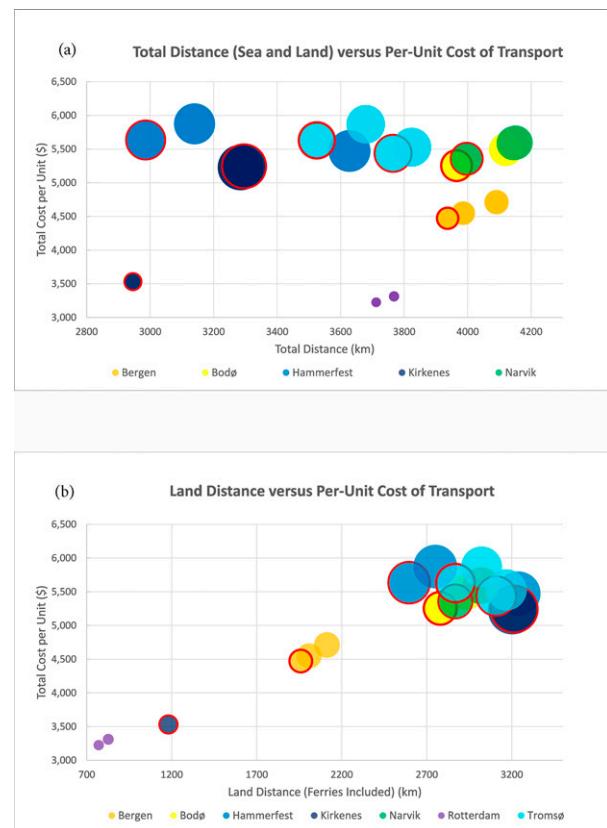


FIG. 4. The relationship between route distance (km) and per-unit cost (nominally as U.S. dollars) via each port: (a) the total distance from the Norway–Russia sea border to Dresden, with sea and land distances combined, against the total cost of each route, and (b) the distance over land (ferries included) against the total cost of each route. Bubble widths are proportional to the ratio of land distance to total distance of their corresponding routes. The red rim indicates that a route contains a segment or segments yet to be built.

the sea–rail route via Rotterdam than any other route. Thus, while the proposed Kirkenes route has a ratio of 3.32, it is likely that per metric ton per kilometer, there will be lower direct CO₂ emissions using the sea–rail route via Rotterdam since the per metric ton-kilometer gCO₂ km⁻¹ of oceangoing ships is likely more than one-third less than freight trains operating in the Arctic as noted above. Even if the Kirkenes route use an electric freight train, separate analyses show that Kirkenes would have only 15% lower emissions than the Rotterdam route assuming it also moves to using an electric freight train (Sims et al. 2014). Indeed, even if all routes move from diesel to electric freight trains, these two routes would continue to have the lowest CO₂ emissions. All other routes are even less likely to have less emissions than the sea–rail route via Rotterdam. The existing route from Kirkenes involves road and has a ratio of only 1.40. This can be applied to any emissions that vary with distance; it implies that as long as emissions from road travel per kilometer is more than 1.4 times the emissions by sea travel per kilometer, the Rotterdam route will result in lower emissions.

TABLE 7. Estimated CO₂ emissions for different routes for a given unit of goods. Calculations assume average estimated CO₂ emissions of 10 gCO₂ km⁻¹ for sea shipping via container ships, 45 g CO₂ km⁻¹ for shipping via freight rail, 60 gCO₂ km⁻¹ for roll-on/roll-off ferry shipping, and 125 gCO₂ km⁻¹ for road shipping via trucks. Transfer emissions (gCO₂) are assumed to be negligible and are therefore set to zero.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	401 195			356 325		145 450	70 795
Hammerfest	408 650		204 900	366 655	197 970		
Tromsø	402 445		171 935	359 325	165 005	146 430	
Narvik	388 290	147 280		345 295		140 350	
Bodø	360 110	143 890		316 865		136 915	
Bergen	270 780	114 865		209 425		107 935	
Oslo	221 385						
Rotterdam	125 785	66 625					

Again, we can compare this for CO₂ as an example. As noted above, a container ship emits 10 gCO₂ km⁻¹, which suggests that any emissions higher than 14 gCO₂ km⁻¹ ($10 \times 1.4 = 14$) would mean the current Kirkenes route would emit more CO₂ than the sea-rail route via Rotterdam. Since direct CO₂ emissions for heavy freight trucks range from about 75 to about 175 gCO₂ km⁻¹ (Sims et al. 2014), shipping via Rotterdam results in lower CO₂ emissions. All other ratios in Table 8 are below 1.25, suggesting that all other routes have more direct CO₂ emissions than the sea-rail route via Rotterdam unless there is a land-based transportation method where the direct CO₂ emissions is no higher than 25% more than the sea-based transportation alternative. Since the sea-rail route via Rotterdam is also less expensive, the relatively cheaper route also provides lower direct CO₂ emissions.

Collectively, these results show that both existing and proposed routes are not likely to be economically competitive with shipping by sea to Rotterdam and using existing rail or road routes. Even when a 50% ice-class premium is applied, the route employing sea to Rotterdam then rail or road to Dresden remains the cheapest alternative for reasonable shipping by land versus sea ratios. If rail is used, the direct CO₂ emissions are also lower.

5. Conclusions

The best estimates at present for a 2°C warming scenario is that a totally ice-free Arctic summer could occur once every

5 years as early as 2030 (Sigmond et al. 2018) although some models place this as late as 2050. Increasing the maximum warming threshold to 3°C increases this frequency to almost every other year by midcentury. From the perspective of transportation infrastructure planning and construction, these time horizons are very short indeed, and have ramifications for the continued enforcement of the Polar Code as a year-round requirement. As a result, the premium imposed by Polar Code compliant vessels on shipping costs has a similarly short, though highly uncertain, time horizon at least for summer season shipping, and will get shorter as the ice-free period increases.

It is apparent from this analysis that even accounting for that premium, out of the six cities Kirkenes alone emerges as a Rotterdam alternative, and “merely competitive” at that. Investments in both expanded port facilities and the Arctic Railway itself need to be weighed against opportunities that may emerge additional to transshipment services, and any opportunities foregone by this construction, as well as possible increased CO₂ emissions. It is clear that the stated aspirations of Narvik and Tromsø to become major transshipment hubs for international shipping are not economically viable under most reasonable assumptions, nor would they reduce direct CO₂ emissions. With the departure of NATO, Bodø’s focus on being a regional—rather than international—transportation nexus seems more appropriate.

There are, of course, other values at stake in this transformative moment. Given that the Kirkenes option, with Arctic

TABLE 8. Estimated land-sea cost break-even ratio between that route and going via Rotterdam by sea to rail and assuming equal transfers. This table provides a break-even analysis for emissions. If the ratio of land/sea emissions is higher than the break-even ratio, then the Rotterdam sea-rail route provides fewer emissions.

Cities	Sea to road only	Sea to rail only	Sea to road to rail	Sea to road to ferry to road	Proposed sea to road to rail	Proposed sea to rail only	Proposed sea to rail to sea to rail
Kirkenes	1.20			1.40		1.20	3.32
Hammerfest	1.06		1.00	1.21	1.07		
Tromsø	0.98		0.94	1.13	1.00	1.00	
Narvik	0.83	0.83		0.97		0.89	
Bodø	0.90	0.83		1.07		0.90	
Bergen	0.82	0.75		1.24		0.85	
Oslo	0.40						

Railway and port development, is challenging to justify on economic grounds alone and would almost certainly require significant multinational investments, it is worth exploring the other options for economic development in this long-established Arctic community. Indeed, this analysis prompts the question of the necessity for new transport infrastructure as the economic engine of the north. This is particularly germane given the existing viable alternatives and the relatively short time horizon for Polar Code premiums to have an impact. Furthermore, the Sustainable Development Goals—against which the Norwegian sovereign wealth fund does not yet report—nevertheless solicit transformed approaches to societal and industry development. The relative differential in CO₂ emissions should also be examined; depending on the efficiency of the rail transport, direct CO₂ emissions may be lower using sea transport to more southern ports.

Kirkenes may be one of several Arctic population centers to see an uptick in activity resulting from new trade routes and resource developments. These regions will benefit from early information about alternative future pathways to help them prepare, whether these pathways include the flux of goods and services, workers, or tourists. Hence, the methods used in this study provide a model for decision support in other potential infrastructure development arenas.

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Data availability statement. All routes will be posted to the Arctic Data Center, which is linked from the project website (<https://nna-cpad.org/data-and-code>). Datasets for distance calculation and route maps are provided by Google Maps (<https://www.google.com/maps>; accessed 15 May 2020), [MarineTraffic \(2020\)](#), OpenStreetMap through [Geofabrik Download Server \(2020\)](#), the European Commission's Trans-European Transport Network (TENtec) portal ([European Commission 2018](#)), as well as the Mobility and Transport department of the EC and [National Geospatial-Intelligence Agency \(2017\)](#), both hosted by ArcGIS Hub. Data for FBX01 were provided through the courtesy of Freightos, Ltd. Calculations are fully documented in the methods section of the paper.

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