Economic Viability and Emissions of Multi-modal Transportation Infrastructure in a Changing Arctic

Michael A. Goldstein,\textsuperscript{a,b}, Amanda H. Lynch\textsuperscript{a}, Ruitian Yan\textsuperscript{a}, Siri Veland\textsuperscript{c}, William Talleri\textsuperscript{b}

\textsuperscript{a} Institute at Brown for Environment and Society, Brown University, Providence, RI, USA
\textsuperscript{b} Babson College, Babson Park, MA, USA
\textsuperscript{c} NORCE Norwegian Research Centre, Bergen, Norway

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

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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 and also result in lower emissions; ultimately, the question of whether to use a transshipment in the Arctic vs. an established major European port is determined by the relative costs (or emissions) of sea vs. land travel.

This study calculates the relative competitiveness of six Norwegian coastal cities as multi-modal 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 all existing routes are not competitive with routes using the major existing Port of Rotterdam; 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 multi-modal transportation hubs and finds that they are uncompetitive with the more southern port in Rotterdam. 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 either economically viable or desirable.

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 Junior et al. 2021; Alamoush, Ölçer, and Ballini 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, Norchi, and Li 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; AMAP 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. 2015; 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 2015-2017, 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, Haines, and Hawkins 2016; Ng et al. 2018) have speculated that over time there will be increased traffic on the Northeast Passage due to trans-continental transit activity across the Northern Sea Route (NSR), depending on ice conditions (Milakovic et al. 2018; Li et al. 2021). 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 tonnes used the NSR in 2020 with an expectation that by 2024 this will increase to 80 million tonnes ( 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 highly variable sea ice extent (Barnhart et al. 2015; Meredith et al. 2019; Li et al. 2021), 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, Haines, and Hawkins 2016; Li et al. 2021). There are also human socio-politico-economic factors such as Russian security measures (Goncharova and Stoyanova 2021), transit fees (Milakovic et al. 2018), governance
and passage rights (Bennett et al. 2020; Boylan 2021; Lynch, Norchi, and Li 2022), international Arctic shipping rules, insurance (Milakovic et al. 2018), environmental concerns (Ng et al. 2018; Comer 2019; Silber and Adams 2019; Bennett et al. 2020), and concerns of indigenous groups (AMAP 2017; Olsen, Carter, and Dawson 2019; Bennett et al. 2020). Beyond this are more shipping oriented factors such as bunker (ship fuel) prices (Milakovic et al. 2018), time value of cargo, vessel design (Milakovic et al. 2018), vessel availability, ship owner perceptions (Lasserre et al. 2016; Milakovic et al. 2018), search and rescue support (Milakovic et al. 2018; Benz, Münch, and Hartmann 2021), communication challenges (Milakovic et al. 2018; Veland et al. 2021), and so on. These politico-socio-economic issues are not limited to the NSR: the disruption in the Suez in 2021 (Adumene et al. 2021; Lynch, Norchi, and Li 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 (GHG) 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 four from 2016-2019 (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 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). AIS data regularly shows 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). The Coupled Model Intercomparison Project Phase 6 (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 (Community 2020). Analyses of the impacts of this variability on interannual and decadal timescales suggest that accessibility on the NSR will be inconsistent over the coming two to three decades (Li et al. 2021). 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) which 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 multi-modal 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 further 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 inter-port competition from large established ports further 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 multi-modal 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 Saragirotis 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 multi-modal 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 tonnes (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 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 vs. rail vs. road, as well as transfer costs. Focusing on the active Barents and Norwegian sea area (Eguiluz 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 land travel per km costs), 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), new rail spurs connecting the port to major rail lines (Bodo 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 vs. land costs per km 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 to other, non-economic 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, nitrous oxide (NOx), sulfur oxides (SOx), etc. 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 allows for future ratios of costs (or emissions) to change due to technological changes or economic factors. As these change over time, the relative costs (or emissions) vs. sea based transport can be compared with these ratios and the relative ranking will still hold.

Finally, 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 preference Rotterdam. The Rotterdam to Dresden 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, while we abstract away from these concerns, to the extent they exist they would also preference the Rotterdam routes over routes using the Norwegian ports, either because these would sufficiently disrupt volume to the point that the ports are not viable, or because 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; Figure 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 foundations, and were chosen for their similarity in regulatory, geopolitical, and geographical environment, thereby removing confounding factors that would arise in a multi-country study. These ports were also chosen as they are perennially ice-free due to the warm North Atlantic 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.
Figure 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 transshipment hubs (Kirkenes, proposed; Rotterdam, current) for vessels from the NSR.

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 NATO base is closing in Bodø and moving to Ørland. Other extractive industries include hydrocarbons (Bergen and Hammerfest) and iron (Kirkenes and Narvik).

<table>
<thead>
<tr>
<th>City</th>
<th>Population ('000)</th>
<th>Major industries</th>
<th>Stated aspirations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Extractive</td>
<td>Less-Extractive</td>
</tr>
<tr>
<td>Bergen</td>
<td>284</td>
<td>Oil and gas</td>
<td>Aquaculture Shipping services Research and education Technology-based businesses</td>
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<td></td>
<td></td>
<td>Fisheries</td>
<td>Renewable energy</td>
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<td>R&amp;D</td>
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<td></td>
<td></td>
<td></td>
<td>Main base of Royal Norwegian Navy (at Haakonsvern)</td>
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<tr>
<td>Bodø</td>
<td>52</td>
<td>Fisheries</td>
<td>Air, rail and shipping services Higher education Tourism NATO base (closing)</td>
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<tr>
<td>Location</td>
<td>Pop.</td>
<td>Industry/Activities</td>
<td>Strategy</td>
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<tr>
<td>NATO base (Bodo Municipality, 2020; Finn 2017)</td>
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| 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 n.d.) |
Table 1. Six Norwegian coastal municipalities with explicit aspirations for reinvention. Note that many of the industries listed here could not 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 from Statistics Norway (2020).

<table>
<thead>
<tr>
<th>Tromsø</th>
<th>77</th>
<th>Fisheries</th>
<th>Aquaculture Higher education R&amp;D Tourism Governance (Arctic Council)</th>
</tr>
</thead>
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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)

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) (NeRF n.d.). The Polar Code applies to vessels weighing over 500 gross 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 further south, suggesting this constraint may not be sufficiently economically binding to warrant transfers further north.

These six municipalities (Figure 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, Haines, and Hawkins 2016; Ng et al. 2018; Theocharis et al. 2018; Yudnikova and Bedashov 2021). Rotterdam’s location further 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

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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, 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/fall periods are not Ice Class vessels or have little ice-strengthening (Milakovic et al. 2018).

Since land-locked 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 carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), black carbon, nitrous oxide (NOx), sulfur oxides (SOx), etc. These emissions may or may not change Arctic sea ice, with possible regional effects far from the ship lane (Li et al. 2021; 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). While here we demonstrate the applicability of the relative valuation methodology by comparing CO2 emissions for sea/land routes using different ports, other emissions such as SO2 and black carbon have also been modeled based on fuel consumption (Stephenson et al. 2018), so this methodology can be applied to other emissions as well for these sea/land routes.

a. 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 towards 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 (IMO: 7915278; Gross Tonnage: 31,027; Summer 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, Russia on 8 June 2021 (MarineTraffic n.d.). On 10 June 2021 it left Murmansk and by 11 June 2021 it was heading west over the top of Norway (MarineTraffic n.d.). While 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; 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 Traffic n.d.) which 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 n.d.). 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 icebreaker 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).

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 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 further 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 multi-modal 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 WGS84 datum. The final maps are projected in the ETRS89-LAEA system.

(a)  

(b)
Figure 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) multi-modal routes.

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, Figure 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 negligible. For single-modal roads (Figure 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 (Figure 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 (Figure 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 (Figure 1 and Figure 2.) These mode combinations include presently available options as well as routes that are proposed but not yet constructed, such as the Arctic Railway (Figure 1c) and the Helsinki - Tallinn Tunnel (Figure 2c).

One of the larger proposed construction is the proposed Arctic Railway from Kirkenes which 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 a year with 10 southbound trains per day (Sør-Varanger Utvikling 2018). If so, and if the NSR is active for 7-8 months a year, proposers suggest 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 3 billion euro 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 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 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 and away from Rotterdam or other existing southern ports. There is clearly a limitation on the time horizon for these plans due to 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 around 38.5 cubic meters. However, due to 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 pre-pandemic, shipping costs are highly variable (Figure 3). In 2017, it cost $4,800 to ship a container the 6,000 nautical miles from East Asia to the North American West Coast (Valentime 2017). In the first week of January 2020, the cost was $1,317; in the last week of May 2020 it was $1,638; and on November 24, 2020 it was $3,870 (Freightos 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 co-vary, relative costs maintain the relative ranking of the routes. Finally, 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 twice as expensive as Y in U.S. dollars, then after currency conversion it is also twice 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.

**Figure 3.** Container shipping costs over time. Container shipping costs over a two year period. Data series for index FBX01, courtesy of Freightos, Ltd.
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/km 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/km 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 breakeven ratio can be multiplied by the cost/km by ship to say how low the land cost/km needs to be for that route to be cheaper than using the Rotterdam route.

For illustration purposes, we begin with a model where sea, road, rail, and ferry costs per kilometer traveled are all different. We multiply the kilometers traveled by transportation method (sea, road, rail, 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 due 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 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/nautical mile for a neo-Panamax ship or just over $0.695/mile (1 nautical mile = 1.15078 statute miles), and $2.50/mile/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/mile, rounded to $0.70, which corresponds to $0.43/km), and by rail ($2.50/mile;
$1.55/km). Road costs are assumed to be more expensive than rail ($3.00/mile; $1.86/km) and ferry costs are assumed to be even higher ($4.00/mile; $2.49/km).

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/mile, or $0.65/km, since $1.50 * $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/mile 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, etc. 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 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 travelled are 2.5 times as expensive as sea costs per distance travelled, 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 times the cost of transporting a TEU per km (Lin and Chang 2018). Using the data from 2017, this is around €100 per TEU, ($1/mile * €0.85/$ *0.62137 miles/km = 0.52817 €/km cost of transportation, so 100 / 0.52817 = 189 or around 200). 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 as it is assumed 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

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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

Total cost \[= \text{Sea Shipping distance (S)} \times \text{Ocean shipping cost per unit of distance (X)}\]

+ Transfer from ship to shore costs (T) * number of transfers (N)

+ (road or rail) distance (R)* (road or rail) cost per unit of distance (Y or Z)

+ Ferry distance * ferry cost per unit of distance (F)

(Equation 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.

<table>
<thead>
<tr>
<th>City</th>
<th>Sea distance (km)</th>
<th>Sea cost unit/km</th>
<th>Sea Cost $c=a*b$ (in units)</th>
<th>Transfer cost (in units)</th>
<th>Road distance (km)</th>
<th>Road cost units/km</th>
<th>Road Cost $g=e*f$</th>
<th>Total Cost $h=c+d+g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tromsø</td>
<td>657</td>
<td>0.70</td>
<td>460</td>
<td>200</td>
<td>3167</td>
<td>3.00</td>
<td>9,501</td>
<td>10,161</td>
</tr>
<tr>
<td>Rotterdam</td>
<td>2941</td>
<td>0.70</td>
<td>2059</td>
<td>200</td>
<td>771</td>
<td>3.00</td>
<td>2,313</td>
<td>4,572</td>
</tr>
</tbody>
</table>

Table 2. Example of calculations for total cost for Tromsø and Rotterdam sea-to-road routes.

Next, to reduce complexity, we next set all non-sea (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 non-sea transportation costs per kilometer traveled are higher than others, this effectively lowers the higher costs to the lower level and thus reduces non-sea portions, thereby biasing the analysis towards routes with longer non-sea portions. These assumptions provide a further bias in favor of the Norwegian ports over Rotterdam.

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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 with 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/km are about 4.3 times (3/0.7) 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/km to sea costs/km which would make the total costs the same? To find this, we could make define X as the ratio of land costs/km to sea costs/km, so land costs/km = X * sea costs/km.

We can then rewrite the two lines in Table 2, substituting sea costs/km for .70, and X*sea costs/km for 3.00:

\[
\text{Tromsø Total Costs} = 657 \times \text{sea costs/km} + 200 + 3167 \times (X \times \text{sea costs/km})
\]  
\[\text{(Equation 2)}\]

\[
\text{Rotterdam Total Costs} = 2941 \times \text{sea costs/km} + 200 + 771 \times (X \times \text{sea costs/km})
\]  
\[\text{(Equation 3)}\]

By setting the Tromsø Total Costs = Rotterdam Total Costs, we can find the ratio of land costs/km to sea costs/km where we would be indifferent:

\[
657 \times \text{sea costs/km} + 200 + 3167 \times (X \times \text{sea costs/km}) = 2941 \times \text{sea costs/km} + 200 + 771 \times (X \times \text{sea costs/km})
\]  
\[\text{(Equation 4)}\]

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:

\[
657 \times \text{sea costs/km} + 3167 \times X \times \text{sea costs/km} = 2941 \times \text{sea costs/km} + 771 \times X \times \text{sea costs/km}
\]
Now note that all the remaining numbers are multiplied by sea costs/km on both sides and so can be factored out. Dividing both sides by sea costs/km, we get:

\[ 657 + 3167X = 2941 + 771X \]  

(Equation 6)

Solving for X we get:

\[ X = \frac{(2941 - 657)}{(3167 - 771)} = 0.953255 \]

(Equation 7)

So as long as land costs/km 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:

\[ \text{Break-even-Ratio} = \frac{T \times (NR - NO) + (SR - SO)}{(RO - RR)} \]

(Equation 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 breakeven 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 breakeven 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.

d. Direct Emissions
The above methodologies may also be used to estimate CO2 emissions. Freight tonne-kilometer direct CO2 emissions (gCO2/km) 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 about 3 gCO2/km, an ocean bulk tanker about 5 gCO2/km, a container ship about 10 gCO2/km, a roll-on/roll-off ferry about 60 gCO2/km, a diesel freight train about 45 gCO2/km, and heavy freight trucks about 125 gCO2/km (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, non-economic 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 non-zero, since most routes have just one transfer the number of transfers are 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 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 as 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.

Break-even-Ratio (simplified) = \( \frac{(SR – SO)}{(RO – RR)} \) 

(Equation 9)

4. Results

The results in Tables 3a (non-polar class vessel) and Table 3b (polar class vessel at 50% premium) both suggest that shipping by sea then rail via Rotterdam is the most cost efficient. Table 3a suggests the cost for shipping using a non-polar class vessel to Rotterdam is cheaper by then using rail (4,326) or
road (4,572) to get goods to Dresden. All other existing routes are notably higher: for non-polar-class vessels, costs range from 6,564 for Bergen (sea-road-ferry-road) to 10,187 for Hammerfest (sea-road). Only the proposed Kirkenes sea-rail-sea-rail is close to competitive with Rotterdam at 4,788; all other proposed routes are more expensive (with the cheapest per port ranging from 6,482 to 9,017).
Sea Shipping Cost: Units per km 0.70
Transfer Cost: Units per Transfer 200.00
Road Shipping Cost: Units per km 3.00
Ferry Shipping Cost: Units per km 4.00
Rail Shipping Cost: Units per km 2.50

<table>
<thead>
<tr>
<th>Cities</th>
<th>Sea to Sea to</th>
<th>Sea to Road to</th>
<th>Sea to Sea to</th>
<th>Sea to Rail to</th>
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</thead>
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<td>8,912</td>
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<td>4,572</td>
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</table>

Number of Transfers 1 1 2 1 2 1 3

Table 3a: Non-polar-class vessel. Estimated total transportation costs for different routes for a given unit of goods. Calculations assume relative prices of shipping and rail based on 2017 estimates of transportation costs for a container by ship ($0.70 mile/container for non-polar-class vessels); and by rail ($2.50/mile/container). Road costs are assumed to be 20% more than rail costs ($3 mile/container). Ferry is assumed to be higher than road per distance travelled ($4 mile/container).

These results are also true for Table 3b for a polar class vessel with sea costs at a 50% premium. Table 3b suggests the cost for shipping using a polar class vessel to Rotterdam and then using rail (5,356) is the cheapest; then using road from Rotterdam (5,601) is the next cheapest of the existing
routes. All other existing routes are notably higher, and it is still true that Bergen (7,256; sea-road-ferry-road) is the next cheapest, with Tromso now the highest (10,391). The proposed Kirkenes sea-rail-sea-rail is close to competitive with Rotterdam at 5,406; all other proposed routes are more expensive (with the cheapest per port ranging from 7,174 to 9,154).
<table>
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<td>Ferry Shipping Cost: Units per km</td>
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<td>Rail Shipping Cost: Units per km</td>
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<td>Number of Transfers</td>
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**Table 3b: Polar-Class Vessel.** Estimated total transportation costs for different routes for a given unit of goods. 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/mile/container for polar class vessels) and by rail ($2.50/mile/container). Road costs are assumed to be 20% more than rail costs ($3 mile/container). Ferry is assumed to be higher than road per distance travelled ($4 mile/container).
Generally, these relative ranking results are invariant to the size of the transfer costs: whether transfer costs double or 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 vs. road vs. ferry. Even if all non-sea costs are lowered to the cost of rail (and thereby make all non-sea costs equal), the results do not change. Table 4 replicates Table 3b, slightly lowering the sea costs to $1/mile (equivalent to a 43% ice vessel premium) to make relative costs more apparent. In Table 4, all non-sea 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 4 also suggests that based on current infrastructure, skipping over all Norwegian ports and continuing straight to Rotterdam is by far the most cost effective, either then using road (5,069) or rail (5,209). All of the proposed routes are dominated by the existing Rotterdam choices; even the proposed Arctic railway from Kirkenes that terminates in the Baltic (Figure 2c) is more expensive (5,318).
<table>
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<tr>
<th>Cities</th>
<th>Sea Shipping Cost</th>
<th>Transfer Cost</th>
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<th>Ferry Shipping Cost</th>
<th>Rail Shipping Cost</th>
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<td>Sea to</td>
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</tr>
<tr>
<td></td>
<td>Sea to</td>
<td>Sea to</td>
<td>Sea to</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Sea to</td>
<td>Sea to</td>
<td>Sea to</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Road</td>
<td>Ferry to</td>
</tr>
<tr>
<td></td>
<td>Road</td>
<td>Rail</td>
<td>Only</td>
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<td></td>
<td>Only</td>
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<td>Only</td>
</tr>
<tr>
<td></td>
<td>Only</td>
<td>Rail</td>
<td>Only</td>
</tr>
<tr>
<td>Kirkenes</td>
<td>8,290</td>
<td>7,455</td>
<td>8,317</td>
</tr>
<tr>
<td>Hammerfest</td>
<td>8,685</td>
<td>9,210</td>
<td>7,908</td>
</tr>
<tr>
<td>Tromsø</td>
<td>8,775</td>
<td>9,200</td>
<td>7,975</td>
</tr>
<tr>
<td>Narvik</td>
<td>8,869</td>
<td>8,884</td>
<td>8,072</td>
</tr>
<tr>
<td>Bodø</td>
<td>8,351</td>
<td>8,721</td>
<td>7,549</td>
</tr>
<tr>
<td>Bergen</td>
<td>7,198</td>
<td>7,461</td>
<td>6,188</td>
</tr>
<tr>
<td>Oslo</td>
<td>6,749</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotterdam</td>
<td>5,069</td>
<td>5,209</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.** Estimated total transportation costs for different routes for a given unit of goods. Calculations assume land costs (rail and road) are 2.5 times that of sea costs; transfer costs are 200 times sea cost.
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 5 demonstrates these break-even points under the assumption that all road/rail/ferry costs are equal as in Table 4 and compares all routes to the sea-road route via Rotterdam. Whenever the land to sea costs are in excess of the ratios in Table 5, that port/route is not competitive with sea-road route via Rotterdam.

<table>
<thead>
<tr>
<th>Cities</th>
<th>Proposed Sea to Only</th>
<th>Proposed Sea to Rail</th>
<th>Proposed Sea to Road</th>
<th>Proposed Sea to Only</th>
<th>Proposed Sea to Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirkenes</td>
<td>1.18</td>
<td>1.36</td>
<td>1.17</td>
<td>1.89</td>
<td></td>
</tr>
<tr>
<td>Hammerfest</td>
<td>1.03</td>
<td>0.91</td>
<td>1.18</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Tromsø</td>
<td>0.95</td>
<td>0.84</td>
<td>1.10</td>
<td>0.89</td>
<td>0.98</td>
</tr>
<tr>
<td>Narvik</td>
<td>0.81</td>
<td>0.80</td>
<td>0.94</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Bodø</td>
<td>0.87</td>
<td>0.81</td>
<td>1.04</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Bergen</td>
<td>0.78</td>
<td>0.72</td>
<td>1.16</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Oslo</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Estimated Land/Sea cost break-even ratio between that route and going via Rotterdam by ship then road/rail with transfer costs. Table 5 provides an estimate of the break-even ratio for cost/goods moved/km. If Land/Sea cost ratio is higher than break-even then Rotterdam sea-road route is cheaper.

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.
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 less than one remain uncompetitive, including the proposed routes which are very uncompetitive (Figure 4a and Table 5). Even when distances are shorter (Figure 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% to 36% are needed for Kirkenes and Hammerfest to be competitive.

(a)
Figure 4. The relationship between route distance (km) and per-unit cost (nominally as $) via each port. a) The total distance from Norway/Russia sea border to Dresden, sea and land distances combined, against the total cost of each route. 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 a route contains segment(s) yet to be built.

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 km travelled by sea are different than emissions per km travelled by road, which may be different than emissions per km travelled 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 6 makes the following estimates for the scenarios in Table 3 but for CO2 emissions and not costs:
Table 6. Estimated CO2 emissions for different routes for a given unit of goods. Calculations assume average estimated CO2 emissions of 10 gCO2/km for container ships, 45 gCO2/km for freight rail, 60 gCO2/km for roll-on/roll-off ferries, and 125 gCO2/km for trucks. Transfer emissions are assumed to be negligible and are therefore set to zero.

| Cities | Sea to Sea to Sea to Sea to Sea to Sea to Proposed Proposed Proposed |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|        | Road Road Road Road Road Road Rail Rail Rail Rail |
|        | Only Only Only Only Only Only Only Only Only Only |
| 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, 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 four 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 (least) cost routes in Table 3 also have the two highest (lowest) emissions in Table 6, this result is not uniform: In Table 3a, the sea-to-road-to-rail route from Hammerfest had a cost estimate of 9,402, slightly higher but close to the sea-to-road cost for Bodø at 9,388, but in Table 6 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 (CO$_2$, SO$_x$, etc.) which varies with distance once a type of ship is determined.

Assuming the amount of emissions due to multimodal transfer does not vary notably by port, Table 7 provides a break-even analysis for emissions when compared to the sea-to-rail route via Rotterdam. In Table 7, 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.

<table>
<thead>
<tr>
<th>Cities</th>
<th>Proposed Sea to Sea to</th>
<th>Proposed Sea to Road to Rail</th>
<th>Proposed Sea to Rail Only</th>
<th>Proposed Sea to Road Only</th>
<th>Proposed Sea to Rail Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirkenes</td>
<td>1.20</td>
<td>1.40</td>
<td>1.20</td>
<td>3.32</td>
<td></td>
</tr>
<tr>
<td>Hammerfest</td>
<td>1.06</td>
<td>1.00</td>
<td>1.21</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Tromsø</td>
<td>0.98</td>
<td>0.94</td>
<td>1.13</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Narvik</td>
<td>0.83</td>
<td>0.83</td>
<td>0.97</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Bodø</td>
<td>0.90</td>
<td>0.83</td>
<td>1.07</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Bergen</td>
<td>0.82</td>
<td>0.75</td>
<td>1.24</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Oslo</td>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7.** Estimated Land/Sea cost break-even ratio between that route and going via Rotterdam by sea-to-rail and assuming equal transfers. Table 6 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 less emissions.

These ratios provide another way of looking at CO$_2$ emissions. For comparison, using our previous rail estimates to create land/sea ratios (an ocean bulk carrier emits 3 gCO$_2$/km, an ocean bulk tanker is 5 gCO$_2$/km, and a container ship is 10 gCO$_2$/km, and a diesel freight train emits 45 gCO$_2$/km), 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 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 tonne-kilometer, there will be lower direct CO\textsubscript{2} emissions using the sea-rail route via Rotterdam since the per tonne-kilometer gCO\textsubscript{2}/km of ocean-going ships is likely more than a 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 CO\textsubscript{2} 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 km is more than 1.4 times the emissions by sea travel per km, the Rotterdam route will result in lower emissions.

Again, we can compare this for CO\textsubscript{2} as an example. As noted above, a container ship emits 10 gCO\textsubscript{2}/km, which suggests that any emissions higher than 14 gCO\textsubscript{2}/km (10*1.4=14) would mean the current Kirkenes route would emit more CO\textsubscript{2} than the sea-rail route via Rotterdam. Since direct CO\textsubscript{2} emissions for heavy freight trucks range from about 75 to about 175 gCO\textsubscript{2}/km (Sims et al. 2014), shipping via Rotterdam results in lower CO\textsubscript{2} emissions. All other ratios in Table 7 are below 1.25, suggesting that all other routes have more direct CO\textsubscript{2} emissions than the sea-rail route via Rotterdam unless there is a land-based transportation method where the direct CO\textsubscript{2} 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 CO\textsubscript{2} 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 vs. sea ratios. If rail is used, the direct CO\textsubscript{2} 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 mid-century. 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 Railway and port development, is challenging to justify on economic grounds alone and would almost certainly require significant multi-national investments, it is worth exploring the other options for economic development in this long-established Arctic community. Indeed, this analysis begs the question of the necessity for new transport infrastructure as the economic motor 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.

Acknowledgments.
The authors acknowledge the useful discussions with many decision-makers in Bodø and Tromsø, who helped to inspire this research. This research was supported in part by National Science Foundation grants CNH-S 1824829 and NNA 2022599.

Data Availability Statement.

All routes will be posted to the Arctic Data Center, which is linked from the project website at https://nna-cpad.org/data-and-code. Datasets for distance calculation and route maps are provided by Google Maps (n.d.), MarineTraffic (n.d.), OpenStreetMap through Geofabrik Download Server (2020), the European Commission’s Trans-European Transport Network (TENtec) portal (European Commission- DG MOVE 2018), as well as Mobility and Transport department of the EC (FRANSMA_MOVE_ENER (EC DG-MOVE) 2016) and National Geospatial-Intelligence Agency (2017), both hosted by ArcGIS Hub. Data for FBX01 courtesy of Freightos, Ltd. Calculations are fully documented in the methods section of the paper.
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