PORTS: SUSTAINABLE ENERGY HUBS

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EXTRACT

Acceleration in global climate change, as well as an increase in energy demand, emphasizes the crucial role of sustainable energy solutions. Acknowledging the critical role of maritime sectors in global trade, their transition to using sustainable energy can significantly help to meet climate policies.

In this context, Iceland not only relies heavily on maritime activities but also has a unique status in renewable energy resources. Therefore, in this study, the role and potential of Icelandic ports for serving as energy hubs are investigated.

The global decarbonization policies and energy transition forecasts for the coming decades are reviewed to identify the status of Icelandic ports in the energy transition. A port SWOT analysis is conducted to determine the capacity of Icelandic ports for supporting the energy transition.

The results show that with Iceland's reliance on renewable energy sources, its ports are well-positioned to supply clean energy to ships, contributing significantly toward achieving a net-zero carbon future. This is more evident in medium and larger Icelandic ports due to their existing infrastructure and enough marine traffic.

The insights gained from this study provide valuable information for stakeholders about the potential of Icelandic ports as energy hubs and facilitate decision-making in sustainable energy transition in maritime sectors.

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SUMMARY

As the urgency for sustainable energy solutions intensifies with accelerating climate change, the potential of ports to serve as energy hubs has become a crucial area of investigation.

The international maritime sector plays an important role in the global economy since it carries over 90% of global trade (Giannakoulis, 2016). Over 80% of global merchandise trade by volume is managed through ports worldwide (United Nations, 2018). Therefore, the strategic importance of well-functioning and efficient ports for the upcoming energy transition and mitigating global warming cannot be overstated (United Nations, 2018).

Iceland's maritime territories and jurisdiction cover an area of 0.76 million square kilometers and contain a wealth of natural resources. The Icelandic economy is one of the most seafood-dependent economies worldwide and has the highest per capita sea catch in the world (Sigfusson, 2011).

The cruise industry is the fastest-growing component of mass tourism in Europe (Fridriksson et al., 2020). In 2019, Cruise Iceland noted that the country amassed around 72.6 M Euros in 2018 and created 920 jobs from the cruise sector only (Cruise Iceland, 2019). Eskafi et al. (2022) suggested adaptive actions for the cruise sector to respond to disruptions, for instance, the pandemic, and link the actions to the UN SDGs to highlight their sustainable contributions.

Almost 100% of the electricity consumed in Iceland comes from renewable energy. The only sector in Iceland that relies on fossil fuels is the transportation sector (Logadottir, 2015). The main renewable energy source in Iceland's transportation is electricity, which is made from renewable sources, hydrogen, biofuel, and e-fuel (National Energy Authority of Iceland, 2022a).

The Icelandic maritime sector used 19% of 851 tons of oil in 2022, or around 162 tons (Radarinn, n.d.). By integrating Iceland's renewable energy resources in the maritime sector, such as electricity, hydrogen, biofuel, and e-fuel, the country can significantly increase its sustainability. Indeed, given Iceland's access to renewable energy, the country's ports can be strategically positioned to facilitate energy transition and decarbonization efforts. It would promote sustainable tourism practices, support Iceland's environmental goals, as well as position Iceland as a leader in green maritime innovation.

Trends and policies in Iceland and globally, the status of Icelandic ports and shipping industries, and suggestive actions, opportunities, and challenges concerning energy transition are discussed in this study.

Furthermore, a port SWOT (strengths, weaknesses, opportunities, and threats) analysis is conducted to determine the ports' capacity for supporting energy transition. As energy demand increases, the transition to sustainable energy has become critical, and with Iceland's access to renewable energy sources, the country's ports are well-positioned to supply clean energy to ships and hence, contribute significantly toward achieving a net-zero carbon future.

Key findings highlight that the Icelandic ports, due to their importance in the Icelandic transport system, functioning as logistics centers for the flow of cargo, containers, and passengers, and strategic

locations for value-added activities wherein industries operate, can play a crucial role in achieving Iceland's ambitious decarbonization targets. However, integrating various technologies, such as photovoltaic systems, hydrogen storage, and stationary batteries, to optimize energy usage and reduce emissions requires infrastructure.

Developing energy hubs in Icelandic ports comes with opportunities to provide sustainable fuel for the transport supply chain (from the hinterland and foreland to the ports), to reduce greenhouse gas emissions, and to step closer to the net-zero carbon emission goals. The main challenges vary between the sizes of the ports. The challenges in big ports are the Capital Expenditures (CapEx) of new infrastructure to provide green fuels, including hydrogen, methanol, etc. The main challenges in smaller ports are mainly due to little marine traffic at these ports, thus, new infrastructure may not be feasible and cost-effective.

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1. INTRODUCTION

At the intersection of land and sea, ports can play a vital role in sector coupling and energy system integration as they host many industry sectors such as shipping, logistics, transportation, etc. (Eskafi, 2021).

The international maritime sector is an important part of the global economy as it carries over 90% of global trade (Giannakoulis, 2016). Most of the global merchandise trade by volume is managed through ports worldwide, therefore, the strategic importance of well-functioning and efficient ports for the upcoming energy transition cannot be overstated (United Nations, 2018). Iceland has an advantage with 90% of its primary energy consumption produced from renewable sources in 2020 (National Energy Authority of Iceland, 2022a). In Icelandic transportation, ships use about 26% of the oil used in transportation, and the transportation sector is the only sector in Iceland that uses fossil fuels as its primary energy source (National Energy Authority of Iceland, 2022b). The energy demand will rapidly grow between 2030 and 2040 (Government of Iceland, 2024), and the energy needed to fuel the entire Icelandic ship fleet is around 4.0 TWh (National Energy Authority of Iceland, 2022b). Fishing vessels contribute the most to Iceland's greenhouse gas (GHG) emissions. However, over the past two decades, emissions from fishing vessels have declined due to the consolidation of the fishing fleet and the introduction of newer ships (Government of Iceland, 2024).

Icelandic ports are located near urban areas, so air quality is an environmental concern for port users and surrounding districts (Eskafi et al., 2020). Growth in industrial fisheries, sustainable aquaculture, and further processing and warehousing has affected fishing ports. Cargo and container handling has increased in Icelandic ports (Eskafi et al., 2021). The cruise sector has been growing faster than other segments of the travel industry (Eskafi et al., 2022). In fact, many factors need to be taken into consideration when observing each port to minimize the environmental impact of ports.

Improving the energy efficiency of the maritime sector is necessary with this increase in cargo and passengers while keeping greenhouse gas emissions low. Providing Onshore Power Supply (OPS) to vessels berthing at the port (which generate 78% of harmful air emissions at the port including carbon dioxide (CO_2), (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), black carbon (BC) and organic carbon (OC) would allow them to be able to turn off their engines (IMO, 2020).

To meet, in time, decarbonization policies in maritime sectors, stakeholders need to rethink their current strategies and adapt (Eskafi et al., 2019). The increasing importance of energy trends, environmental awareness, and industry focus on energy efficiency has highlighted the need to better understand and monitor energy activities in and around ports (Acciaro et al., 2014).

Werner (2021) stated that ports can act as energy hubs, providing zero- and or low-emission energy for port users, and as over 80% of global merchandise trade by volume is conducted through ports worldwide (United Nations, 2018), and thus it is worth examining further.

The role of Icelandic ports to serve as energy hubs in the literature is scant. Therefore, in this study, energy transition trends and decarbonization policies are reviewed, opportunities and challenges in energy transition in Icelandic maritime sectors are discussed, and suggestive actions to develop energy hubs in the Icelandic ports' area are presented.

The insights gained from this study may provide valuable information for stakeholders involved in energy transition in maritime sectors and facilitate informed decision-making for developing energy hubs in Icelandic ports aiming at meeting climate and sustainability goals.

2. LITERATURE REVIEW

Ports take center stage to reduce environmental impacts. As service providers, ports are considered important locations to assist the energy transition. Therefore, it is vital to explore how ports can develop towards zero-emission energy hubs and contribute to emission reduction in the business transport where they are a part of the supply chain. In this context, there are multiple interpretations of ports acting as energy hubs and their potential for providing (almost) zero-emission energy to different users (Werner, 2021).

Europe will transition more rapidly than other continents into a renewable-dominated power system. Hydrogen will only supply 5% of global energy demand in 2050, which is only a third of the level needed for net-zero carbon emission by 2050 (Bjerager et al., 2022). The pathway to net-zero emissions requires massive action to curb record emissions. Bjerager et al. (2022) stated that oil and gas won't be needed in high-income countries after 2024, and in middle- and low-income countries after 2028. Renewable energy such as renewable electricity, hydrogen, and bioenergy is essential but insufficient for the net-zero emission goal. Almost a quarter of net zero decarbonization relies on carbon capture and removal as well as changes on land (reduction of deforestation) (Bjerager et al., 2022).

Looking at the share of global energy-related CO_2 emissions in 2019, 17% for North America, 5% for Latin America, 3% for Sub-Saharan Africa, 8% for Middle East and North Africa, 30% for Greater China, 8% for Indian Subcontinent, 5% for Southeast Asia, 6% for OECD Pacific, 10% for Europe (Bjerager et al., 2022) energy transition is a key to meet the climate goals.

Shore power infrastructure is an important step in the decarbonization process of maritime sectors, including fishing, which is a major fuel consumption of emissions in the Icelandic maritime industry (Bjerager et al., 2022). All ports in Iceland offer a shore connection of 230/400V with 50 Hz. The power network and shore connection of the Icelandic port authorities showed that no cargo ships use shore connection due to various reasons, but in December 2022, the first cargo ship from Eimskip was shore connected in Sundahofn, and this is the only port that offers cargo ships to connect to land. With this connection, the oil usage reduction in Faxafloahafnir port will be around 240 tons per year (Associated Icelandic Ports, 2022). Most cargo ships are from foreign countries that use a 60-volt outlet, which Icelandic ports do not offer. The ships often stop for a short time, 6 hours or less. Furthermore, some ships are too large for the connections that Icelandic ports that provide OPS to offer. No cruise ships that stop in Icelandic ports use shore connection as it has not yet been a request from the shipping companies; however, in September 2023, the port of Faxafloahafnir provided OPS to a small cruise ship (Vidskiptabladid, 2023). All fishing vessels in Iceland, no matter their size, as well as all ferries, are connected to shore unless they leave the port soon after docking. The result of shore connection in the Icelandic ports shows that the emission reduction is around 6000 tons of CO_2, 93 tons of NO_X, and 3,5 tons of SO_2 per year (Verkis, 2021).

In 2021, the Port Association of Iceland provided a 10-year plan for the ports and the cost for their construction plans, including the setup of electric equipment regarding energy transition. The results show that the majority of bigger ports have more plans for energy transition development in the next years than the smaller ports (Port Association of Iceland, 2021).

A baseline energy forecast for transport sectors in Iceland for the years 2023-2050 shows that the main used fuels in 2024 for road transportation are gasoline, diesel, biofuel, methane, and electricity, and for fishing vessels is diesel. However, in 2028, e-fuel will be introduced to the fishing vessel fleet, and in 2031, electricity will be included (National Energy Authority of Iceland, 2022a).

The crucial role of maritime sectors in Iceland, on one hand, and the availability of renewable energy in the country, on the other hand, calls for screening the status of energy transition in maritime sectors in Iceland. However, an analysis of the role of Icelandic ports in energy transition and potentially serving as energy hubs is scant in the literature. Therefore, this study sheds light on actions for possibly developing energy hubs in the Icelandic ports.

A summary of global decarbonization policies and energy transition trends is given in Table 1.

TABLE 1 Decarbonization policies and energy transition trends worldwide.

REGION	DECARBONIZATION POLICIES	ENERGY TRANSITION TRENDS
North America		In 2050, electricity will meet 40% of the final energy demand, and buildings will shift to electricity for 70% of the demand (Bjerager et al., 2022).
Canada	Canada‘s goal is a 40% emission reduction by 2030 compared to 2005 levels.	
Latin America		In 2050, solar photovoltaic technology and wind power will grow to account for 82% of power generation, and fossil fuels will have a 47% share of final energy demand (Bjerager et al., 2022).
Chile	Chile published a strategy in 2021 with a goal of net-zero emissions by 2050.	
Sub-Saharan Africa		In 2050, the energy demand will increase by 90% as the population almost doubles. 45% of energy demand will come from off-grid solar PV, and fossil-fueled power will provide 20% of on-grid generation. Hydropower and other renewable energy will account for the other 80% (Bjerager et al., 2022).
Nigeria	Nigeria has a net-zero target by 2060.	
Angola	Angola signed, in 2022, a declaration of intent to supply Germany with green ammonia, starting in 2024.	
Middle East and North Africa		In 2050, wind and solar will provide 69% of electricity. Annual hydrogen

REGION	DECARBONIZATION POLICIES	ENERGY TRANSITION TRENDS
The United Arab Emirates	The United Arab Emirates published a strategy in 2021 with a goal of net-zero emissions by 2050.	production is expected to grow 10-fold from less than 1 Mt in 2030 and to 10 Mt in 2050 (Bjerager et al., 2022).
Saudi Arabia	Saudi Arabia published a strategy in 2021 with a goal of net-zero emissions by 2060 and a USD 10.4bn fund to provide clean cooking fuels and investments in carbon-capture technology.	
Egypt	In 2021, Egypt's target for 42% renewable power by 2035 was brought forward to 2030.	
Turkey	Turkey published a strategy in 2021 with a goal of net-zero emissions by 2053.	
Northeast Eurasia		In 2050, the most energy demand will still be met by natural gas. Economies' dependence on fossil extraction continues but eventually will be reduced by energy transition elsewhere. Ukraine's gas and coal production has reduced due to Russia's invasion of Ukraine, but the war will not slow down the long-term transition (Bjerager et al., 2022).
Kazakhstan	Kazakhstan vowed in 2022 to reach carbon neutrality by 2060 and aims to create the Central Asian Climate Hub to address climate change.	
Ukraine	In 2022, Ukraine was granted the EU candidate status, the national council for recovery from the war, developing a post-war recovery and plan that aligns with the transformation to low-emission development principles and a green economy.	
Russia	Russia approved its strategy in 2021 with a goal of net-zero emissions by 2060, but has not specified how it will achieve that goal or its cuts by 2030.	
Greater China	In March 2022, the National Development and Reform Commission and the National Energy Administration released documents to guide decarbonization. This document includes an action plan for CO_2 peaking before 2030, including strict control of new coal-powered projects. This document also includes the 14^{th} Five-Year Plan for Modern Energy System with plans for the proportion of non-fossil energy consumption to reach 20%, non-fossil power generation at 39%, and electricity to account for 30% of final energy consumption – all by 2025. The medium and long-term plan for the development of the hydrogen energy industry 2021-2035 is also included in this document, and they aim for 5% of final energy consumption to be hydrogen energy by 2030.	In 2050, electricity's share of energy demand doubles to 47%, the highest of all regions in the world, with over 90% generated from renewable sources. Today, coal in power generation is 62% and will be reduced to 4% in 2050. The CO_2 emissions will be reduced by 66% in 2030 (Bjerager et al., 2022).
Indian Subcontinent		In 2050, more than half of the primary energy will come from fossil fuels, and 22% of that share will come from coal. Electricity demand will grow 10-fold, where electricity meets 33% of final demand. Solar and wind will have 67% of power generation combined (Bjerager et al., 2022).
India	India has a net-zero emissions target by 2070.	
Pakistan	Pakistan updated its Nationally Determined Contributions (NDCs), aiming to reduce emissions by 50% by 2030 (15% unconditional, 35% conditional). All coal projects are being stopped, and 60% of power is to come from solar by 2030. At least 30% of all new vehicles sold in various categories are to be electric.	
Sri Lanka	Sri Lanka has a carbon neutrality target by 2050, which was originally 2060.	
Bangladesh	Bangladesh's 2021 Nationally Determined Contributions (NDCs) outline 40% of power to come from renewables by 2041.	
Southeast Asia		The coal sector is entrenched in this region and is difficult to transition to a new energy source. By 2050, electricity will double in share in final energy demand to
Vietnam	Vietnam aims for net-zero emissions by 2050. Vietnam has amended the law on electricity, outlining investment of USD 148bn in the power system to 2030, allowing foreign investments in grids.	

REGION	DECARBONIZATION POLICIES	ENERGY TRANSITION TRENDS
Malaysia	Malaysia aims for net-zero emissions by 2050. Malaysia will no longer build new coal plants.	36%, and solar PV and solar + storage plants will rise late 2030s and will account for 74% of electricity (Bjerager et al., 2022).
Indonesia	Indonesia pledged to achieve net-zero emissions by 2060. Indonesia stated that between 2026 and 2030, there will be no additional coal-fired capacity, except for those that have reached financial close or are already under construction.	
Thailand	Thailand pledged to achieve net-zero emissions by 2065.	
Japan	Japan announced in 2022 a stop to loans for the construction of coal-fired electricity plants in Indonesia. Japan pledged up to USD 10bn over five years to assist Asia towards zero-carbon emissions. Japan signed the Global Methane Pledge of 30% methane cuts by 2030.	
OECD Pacific*		All capacity additions in power generation by 2030 will be from renewable energy or nuclear. Hydrogen and its derivatives will make up for 8% of final energy demand by 2050, the second-highest share of all regions (Bjerager et al., 2022).
South Korea	South Korea signed the Global Methane Pledge of 30% methane cuts by 2030. South Korea upped its Greenhouse gas (GHG) emission-reduction target to 40% below 2018 levels by 2030, which was 24.4% before. They also aim for renewable generation of around 30%.	
New Zealand	New Zealand passed a law in 2021, introducing mandatory climate-related reporting for the financial sector.	
*Australia, New Zealand, Japan, and South Korea		
Europe	Europe's goal is a 45% emission reduction compared to the 2005 level by 2030.	In 2050, electricity will meet about 43% of demand from an almost decarbonized power mix. Furthermore, wind will account for half of the generation. Hydrogen and its derivatives meet over 9% of final energy demand, the highest of all regions in the world (Bjerager et al., 2022).
Iceland	Increase the share of renewable energy in land transportation from 6% in 2017 to 10% by 2020. Registrations of new fossil fuel cars are banned by 2030. The share of renewable energy in the transport sector will increase from 6% in 2017 to 40% in 2030. The share of renewable energy in the fisheries and marine sector, from <1% in 2017, will increase to 10% by 2030. Iceland's Nationally Determined Contributions (NDCs) involve an emissions reduction target of 40% by 2030 compared to 1990 levels, aiming at meeting the Paris Agreement (Ministry for the Environment and Natural Resources, 2020). Furthermore, 35% emission reduction compared to 2005 levels in road transport by 2030, 45% emission reduction compared to 2005 levels in fisheries by 2030, 10% emission reduction compared to 2005 levels in agriculture by 2030, 40% emission reduction compared to 2005 levels in waste by 2030, and carbon neutrality by 2040 is expected (Skulason, 2020). 10% renewable energy share for the maritime industry is achieved by 2030. The maritime industry will be independent of fossil fuels by 2050 (Rivedal & Sekkesaeter, 2021).	
International Maritime Organization (IMO)	By 2030, the carbon intensity of international shipping is reduced as an average across international shipping by at least 40%. By 2030, uptake of zero or near-zero GHG emissions technologies, fuels, and/or energy sources is to represent at least 5%, striving for 10% of the energy used by international shipping. By 2050, net zero GHG emissions, considering different national circumstances, whilst pursuing efforts towards phasing them out as called for in the vision, consistent with the long-term temperature goal set out in Article 2 of the Paris Agreement (IMO, 2023).	-

The energy transition varies across each region in this forecast, where each region is experiencing its own pace and scale of change. This variation stems from geography, resources, existing technologies, economic development, and government policies, leading each region to start from a unique point and follow its transition path.

The green energy sources used in Iceland are summarized in Table 2.

TABLE 2 Green energy sources used in Iceland.

FUEL	INFORMATION
Electricity	All homes and companies use electricity (National Energy Authority of Iceland, 2022b). The number of electric cars on the roads is 30.554, where 17.164 are hybrid, fossil fuel, and electric (Icelandic Transport Authority, 2024). The direct use of electric energy in shipping and aviation is 10 GWh in 2024 (National Energy Authority of Iceland, 2022a).
Biodiesel	Biodiesel made from rapeseed is an environmentally friendly and renewable energy source with characteristics like fossil diesel, the common fuel for ship engines today. In Iceland, cultivating enough rapeseed could economically meet the domestic fuel demand (Bernodusson, 2018). 85 thousand liters of biodiesel were used in 2020 in the fishing sector (Government of Iceland, 2024). Biodiesel is currently used in Iceland, but on a small scale compared to other fuel types. The biodiesel used can replace or be blended with fossil marine gas oil (MGO) on all ships with conventional technology and therefore reduce GHG emissions and the carbon footprint of the ships without onboard technology investments (Rivedal & Sekkesaeter, 2021).
Hydrogen	Iceland has already started the transformation into a hydrogen economy with public transport buses in Reykjavik running on hydrogen-powered fuel cells. From hydropower and geothermal, hydrogen produced with electric energy heat is expected to become the main fuel in the Icelandic transport and fishing sectors. In this way, Iceland would be almost free from imported fossil fuel and its GHG emission would be reduced below 50% of the present level (Salameh, 2009).
Methanol	The world's first power-to-liquid methanol plant with large-scale electrolysis was built in Iceland. The plant produces 4.000 tons of certified renewable methanol annually using CO_2 and was then sold to international off-takers (Government of Iceland, 2024).

According to the baseline forecast by the National Energy Authority of Iceland, in 2050, the greenhouse gas emissions of road transportation and fishing vessels will be 98% and 77% lower compared to 2005 levels, respectively (National Energy Authority of Iceland, 2022a). All ports in Iceland offer shore connection of 230/400 V with 50 Hz (Verkis, 2021), and in the next 10 years, most ports will improve their shore connections to provide enough power to all vessels (Port Association of Iceland, 2021).

Geothermal and hydropower energy are Iceland's primary sources of energy, or about 85% of the total energy usage. The last 15% is the fossil fuels that are used in the transportation sector (National Energy Authority of Iceland, 2022b). Ships use 26% of the oil used in Iceland (National Energy Authority of Iceland, 2022b).

Iceland significantly relies on maritime activities. Serving as energy hubs, ports can considerably contribute to sustainability and meeting climate policies.

3. METHODS

In this study, several methods are synthesized to ensure rigorous investigation of the existing data and information.

3.1. Desk research

To gather material, desk research was used. Desk research involves gathering information from published articles, books, reports, and similar documents that are available in libraries, websites, etc. Desk research is convenient in that way that it can be completed faster than primary research and often involves analyzing and integrating existing data to answer research questions. However, it requires careful evaluation of data credibility and may not always provide the most current information. This method can reveal trends and patterns that inform more targeted primary research.

Desk research is often the first step in a research project and helps define objectives and methodologies. It involves combining data from multiple secondary sources to form a thorough overview. Examiner must consider the reliability and bias of sources to ensure data integrity (Villegas, 2021).

In this study, information was gathered from different papers on Icelandic ports, the port authorities' website, and related sources such as Araklo (2024).

3.2. Secondary data research

This report conducts qualitative research based on secondary data, which involves collecting existing data from various sources. This approach helps identify important information not addressed in previous research, thereby highlighting research gaps. In this study, to collect secondary data, a literature review is conducted, which enhances a deeper understanding of the topic under study and is required for data and information analysis (Eskafi et al., 2022).

This approach presents a thorough source of information about the topic under study, enabling the identification of gaps and informed decision-making to address them. For secondary data analysis, the content analysis method was employed. This approach is widely used for gathering data and information, enabling the understanding and interpretation of textual material and graphics, extracting meaning, and drawing informed conclusions (Eskafi et al., 2022).

3.3. System thinking

Systems thinking focuses on the whole system rather than the properties and interactions of individual elements. Systems thinking helps to understand how a system responds to the implementation of a specific strategy. The approach is often used for thinking about real social systems. Action research is carried out to construct practical conclusions that resonate with the experiences of the system. Therefore, systems thinking can serve as a foundation for action research to explore, identify, and solve problems, enabling the planning of effective actions in this study, how Icelandic ports can serve as sustainable energy hubs.

3.4. SWOT analysis

To identify the opportunities and vulnerabilities in the development of energy hubs in Icelandic ports, a port SWOT analysis was carried out. SWOT analysis is a method for recognizing both the strengths and weaknesses of a system. Widely used in literature, it includes evaluations of container development strategies, port logistics, decision-making in port development, and strategic port planning. The qualitative nature of SWOT analysis consists of categorizing port characteristics by translating its strengths and weaknesses into opportunities and threats. This process helps to clarify fundamental assumptions and their implications.

Strengths and weaknesses are recognized as internal factors of the port, whereas opportunities and threats can be from external environments. Strengths and weaknesses are factors relevant to the current situation. However, opportunities and vulnerabilities could be feasible in the future (Eskafi et al., 2021).

In this study, the SWOT analysis on the ports was developed through desk research, systems thinking, secondary data research, and literature review.

4. RESULTS

There are 72 ports in Iceland that are managed by 31 port authorities (Port Association of Iceland, 2021) (Figure 1).

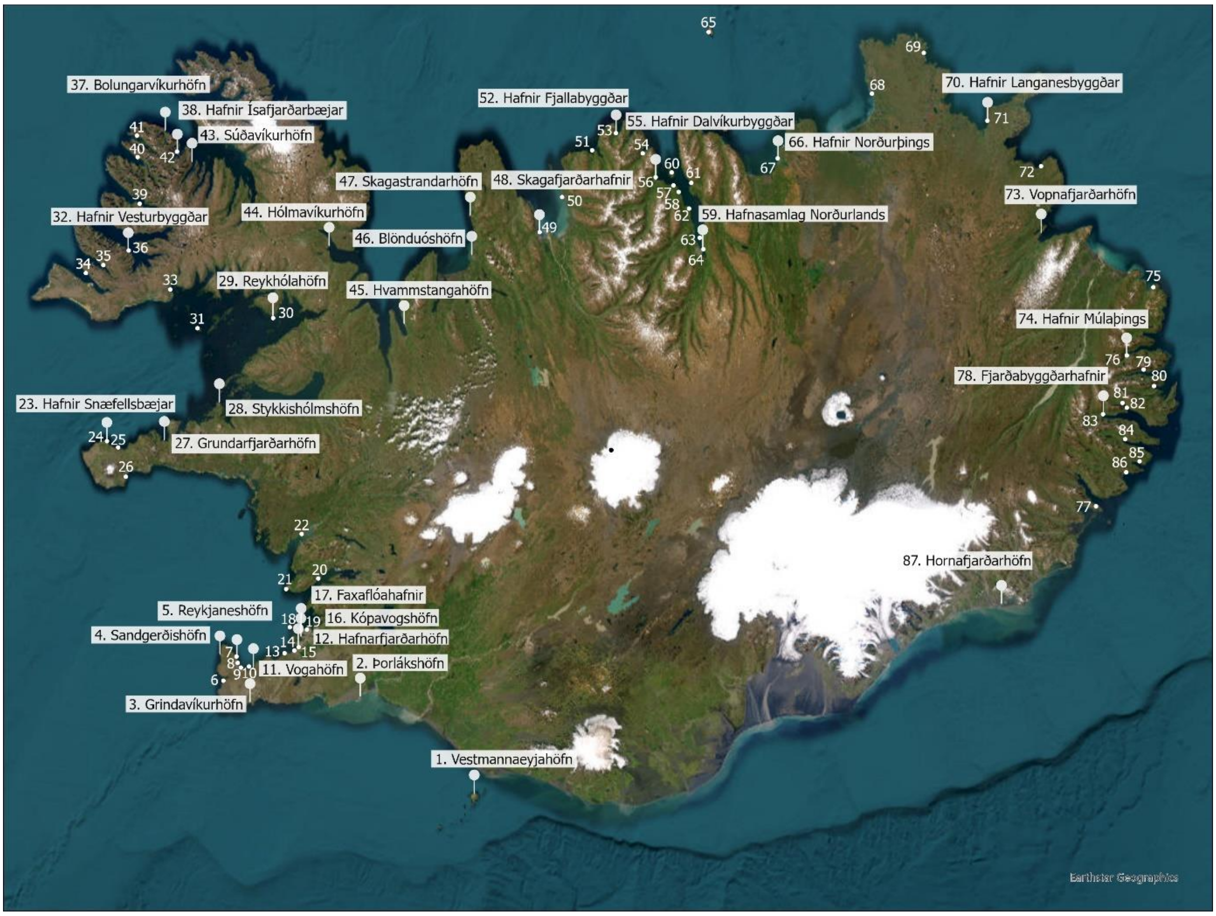

FIGURE 1 Map of the Icelandic port authorities. Names of the ports corresponding to the numbers on the map can be found in Table 3.

A SWOT analysis of port authorities focusing on energy transition as well as required action for the energy transition in the ports is given in Table 3.

TABLE 3 Port SWOT analysis and required action for the energy transition in the port.

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
1	**Vestmannaeyjahofn**	Container and small and medium-sized cruise ships call at the port. The ferry Herjolfur sails from the port multiple times each day. The port has an onshore power supply to vessels. Most of their profit comes from marine catch handling (Port Association of Iceland, 2021).	Port infrastructure is limited.	Container ships call at the port as the last port of call. It is a well-known cruise ship destination. The port authority plans to improve OPS so the port can offer larger vessels to connect (Verkis, 2021).	The geographic location of the port limits the expansion of the port.	About 4 billion ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021). The port provides services to cruise ships and cargo ships, and the likely energy transition in the larger ships is hydrogen and methanol. Thus, storage and transportation of alternative fuels for the coming transition should be considered.
2	**Thorlakshofn**	Cruise ships call at the port. The port provides services to Smyril Line Cargo. The ferry Herjolfur calls at the port during the wintertime when it cannot sail to Landeyjahofn. Most of their profit comes from cargo handling (Port Association of Iceland, 2021).	Container ships do not call at the port.	As the port provides services to cruise ships, cargo ships, and passenger ships, the ongoing expansion of the port could further increase port services. There is a 4 billion ISK construction in this port now, and the port will offer cargo ships to connect to shore (Verkis, 2021).	-	About 50 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021). The port provides services to cruise ships and cargo ships, and the likely energy transition in the larger ships is hydrogen and methanol. Thus, storage and transportation of alternative fuels for the coming transition should be considered.
3	**Grindavikurhofn**	It is one of the main fishing ports in Iceland (Port	Container and cruise ships do not call at the port.	It is planned to set up bigger electrical	The port area is not enough to provide	About 20 million ISK in electric equipment regarding energy

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
		Association of Iceland, 2021).		outlets (Verkis, 2021).	services for large ships, so they cannot dock at the port.	transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
4	**Sandgerdishofn**	Most of their profit comes from marine catch handling (Port Association of Iceland, 2021).	Container/cargo ships do not call at the port.	Cruise ships call at the port.	It is a fishing port that does not have the facilities to provide services to large ships.	Automatic energy sale for boats is in the works as well as bigger electrical outlets (Verkis, 2021).
5	**Reykjaneshofn**	Cruise ships call at the port of Keflavik. The port of Keflavik has been newly improved with good sailing conditions. The port of Helguvik is a big port with enough area for storing containers and a freezer-storage facility. The port of Hofn has been improved with a breakwater and good port conditions. The port of Njardvik is a fishing port. Freezer- and cold storage facilities are available. Most of their profit comes from cargo handling (Port Association of Iceland, 2021).	Cruise ships do not call at the ports except for the port of Keflavik. The main container ships do not call the ports.	Port of Keflavik has the facilities to provide services for smaller cruise ships and will do that in the near future.	The port of Hofn is a marina only providing services to small boats and does not have the conditions to provide service for larger vessels.	Port of Njardvik will receive bigger outlets. There is a possibility that the port of Keflavik will offer a smaller cruise ship shore connection. Port of Helguvik will possibly receive bigger outlets in the next 4 years (Verkis, 2021).
6	Hafnahofn					
7	Helguvikurhofn					
8	Grofin					
9	Keflavikurhofn					
10	Njardvikurhofn					
11	**Vogahofn**	-	It is not a functioning port.	-	A major construction in the next 10 years is not expected (Port Association of Iceland, 2021).	-

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
12	**Hafnarfjardarhofn**					
13	Straumsvikurhofn					
14	Flensborgarhofn					
15	Hafnarfjardarhofn	Cruise ships call at the port. The port of Hafnarfjordur was one of the first ports in Iceland to offer its customers OPS (Port of Hafnarfjordur, 2024a). The port of Hafnarfjordur has 207 electrical outlets and emphasizes connecting as many vessels as possible (Port of Hafnarfjordur, 2024b). By doing this, they reduce GHG emissions and the noise from the vessels' engine. They offer import and export services as well as servicing the aluminum plant and the gas company in Straumsvik. Most of the port profit comes from cargo handling (Port Association of Iceland, 2021).	Container ships do not call at the port.	It is a big port with all the necessary equipment to provide service to container ship companies. The ports could expand their import/export services. The Port of Hafnarfjordur has big plans to expand its shore connections. The port provides enough services for cruise ships. Development of the Coda Terminal facilitates the generation, bunkering, and transportati on of e-fuels as well as servicing the ships with e-fuels.	There is limited land in the port area.	About 960 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021). The ports provide services to cruise ships and cargo ships, and the likely energy transition in the larger ships is hydrogen and methanol, so they should consider storage and transportation of alternative fuels for the coming transition. Furthermore, development of e-fuel facilities in the Straumsvik port in synergy with the Coda Terminal can be planned.
16	**Kopavogshofn**	-	Cruise/cargo/ container ships do not call at the port.	When the Fossvogur bridge is ready, there will be more opportunities for the port (Verkis, 2021).	The electric equipment is still unused (Verkis, 2021). The port does not have the facilities to provide service for large ships.	The port does not expect any energy transition development in the next 10 years (Port Association of Iceland, 2021).
17	**Faxafloahafnir**	Cruise ships call at Sundahofn, the port of Akranes, and the old Reykjavik harbor. Eimskip stops in Sundahofn and the port of Grundartangi.	Cruise ships do not call at the port of Grundartangi nor the port of Borgarnes. Container ships do not stop in the Old Reykjavik	Sundahofn plans on OPS for larger cruise ships in the next two years (Verkis, 2021). Development of a cruise terminal is ongoing.	The port of Borgarnes is a small port with only one dock, which can provide services for small boats. Some ports	Over 3.135 million ISK in electric equipment regarding energy transition in the years 2021-2027 is estimated (Port Association of Iceland, 2021).
18	The old Reykjavik harbor					
19	Sundahofn					
20	Grundartangahofn					
21	Akraneshofn					
22	Borgarneshofn					

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
		Samskip stops in Sundahofn. The old Reykjavik harbor offered the first shore connection to a cruise ship in the fall of 2023 (Vidskiptabladid, 2023).	Harbor, the port of Akranes, nor the port of Borgarnes.		do not have the facilities to provide services to larger vessels. The Old Reykjavik Harbor is an old port that can provide services to smaller vessels. The port of Akranes can provide services to smaller vessels.	Providing services to cruise ships and cargo ships, along with the energy transition in the larger ships, calls for consideration of storing hydrogen and methanol. Thus, generation and storage of alternative fuels for the coming transition should be accounted for.
23	**Hafnir Snaefellsbaejar**	Most of the ports' profit comes from marine catch handling (Port Association of Iceland, 2021).	The ports do not service cruise and container ships.	Port of Olafsvik has a plan on upgrading its shore connections (Verkis, 2021).	The ports of Rif and Olafsvik are fishing ports, and the port of Arnarstapi is a marina, so they only provide services to small boats and do not have the facilities to provide services to larger vessels.	About 30 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
24	Rifshofn					
25	Olafsvikurhofn					
26	Arnarstapahofn					
27	**Grundarfjardarhofn**	Cruise ships call at the port. The port offers electricity for boats. Service providers are fish markets, landing services, crane services, and much more.	Cargo and container ships do not call at the port.	In the next years, they plan to offer shore connections to all vessels arriving except for cruise ships (Verkis, 2021).	The port does not plan to offer shore connection to cruise ships in the next years (Verkis, 2021).	About 20 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
28	**Stykkisholmshofn**	Cruise ships call at the port.	Cargo/container ships do not call at the port.	The port may provide services to smaller cargo/container ships since it can provide services to cruise ships,	The port has a relatively old electric system, so the fishing ship that calls this port cannot	About 20 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
				considering port expansion.	connect to shore.	
29	**Reykholahofn**	Freight ship stops at the port 2 times per year (Verkis, 2021).	Cruise and container ships do not stop at the port.	The port may be reconstructed to add a shore connection for the freight ship that calls this port (Verkis, 2021).	-	It is not expected for new construction in the next 10 years (Port Association of Iceland, 2021).
30	Reykholahofn					
31	Flateyjarhofn					
32	**Hafnir Vesturbyggdar**	Cruise ships stop in the port of Patreksfjordur and smaller ones in the port of Bildudalur. Most of their profit comes from marine catch handling (Port Association of Iceland, 2021).	Cruise ships do not stop in the port of Brjanslaekur nor Talknafjordur. Bigger container ship companies do not stop at any port.	The port's infrastructure may provide services to container ships since it can provide services to cruise ships, or required construction should be taken into place.	Currently not serving larger container ships.	The estimated price of construction for electrical equipment is about 500 million ISK, but the decision is yet to be made (Port Association of Iceland, 2021).
33	Brjanslaekjarhofn					
34	Patreksfjardarhofn					
35	Talknafjardarhofn					
36	Bildudalshofn					
37	**Bolungarvikurhofn**	Cruise ships start calling the port from 2024 (Gunnarsson, 2024). Most of the port profit comes from marine catch handling (Port Association of Iceland, 2021).	Container ships do not call at the port.	It is a medium-sized fishing port with plans to improve conditions in the next 10 years, and today they provide services to cruise vessels and could potentially provide services to container ships. Plan to improve their shore connections (Verkis, 2021).	It does not have enough facilities to provide services to smaller cruise ships and is categorized as a fishing port.	About 100 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
38	**Hafnir Isafjardarbaejar**	Cruise ships call at the ports. The port of Isafjordur can accommodate large cruise ships. Eimskip and Samskip stop in the port of Isafjordur.	Eimskip does not stop in the port of Thingeyri, Flateyri nor Sudureyri.	Port of Isafjordur plans on upgrading its shore connections to be able to offer electricity to freight ships and medium-sized cruise ships (Verkis, 2021).	Cruise ships only call at the ports, Thingeyri, Flateyri, and Sudureyri, but they cannot dock at the ports due to limited infrastructure.	About 820 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
39	Thingeyrarhofn					
40	Flateyrarhofn					
41	Sudureyrarhofn					
42	Isafjardarhofn					
43	**Sudavikurhofn**	Most of the port profit comes from marine catch handling (Port	Cruise ships do not call at the port.	-	There is no plan for energy transition	The energy transition construction in the next 10 years

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
		Association of Iceland, 2021).	Eimskip does not stop here.		improvements in the next 10 years (Port Association of Iceland, 2021). The port does not have the facilities to provide services to larger ships.	has not been estimated, but it should be taken into consideration since they are a fishing port and energy transition in fishing vessels will happen rapidly in the upcoming years.
44	**Holmavikurhofn**	-	Cargo ships and larger cruise ships do not stop at the port.	-	New construction in the next 10 years is not expected (Port Association of Iceland, 2021).	Energy transition construction in the next 10 years has not been estimated, but it should be considered to plan on an electric outlet since it is a fishing port and energy transition in fishing vessels will happen rapidly in the upcoming years.
45	**Hvammstangahofn**	-	Cruise and cargo ships do not stop at the port.	-	New construction in the next 10 years is not expected (Port Association of Iceland, 2021). It is a fishing port and does not have the facility to provide services to larger ships.	Energy transition construction in the next 10 years has not been estimated, but it should be considered to plan an electric outlet at the port since it is a fishing port and energy transition in fishing vessels will happen rapidly in the upcoming years.
46	**Blonduoshofn**	-	Cruise and cargo ships do not stop at the port.	-	New construction in the next 10 years is not expected (Port Association of Iceland, 2021).	Energy transition construction in the next 10 years has not been estimated, but it should be considered to plan an electric outlet at the port since it is a fishing port and

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
						energy transition in fishing vessels will happen rapidly in the upcoming years.
47	**Skagastrandarhofn**	Most of the port profit comes from marine catch handling (Port Association of Iceland, 2021).	Cruise and cargo ships do not stop at the port.	-	It is a fishing port and does not have the facility to provide services to larger vessels.	About 50 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
48	**Skagafjardarhafnir**	Cruise ships, Eimskip and Samskip ships stop in the port of Saudarkrokur. Most of the ports' profit comes from marine catch handling (Port Association of Iceland, 2021).	Cruise ships and container ships do not call at the ports of Hofsos and Haganesvik.	There is a plan to offer shore connection to larger vessels in the future (Verkis, 2021).	The port of Saudarkrokur is a medium-sized fishing and cargo port and does not have the facilities to provide services to large cruise ships. The ports of Hofsos and Haganesvik are smaller ports and cannot provide services to cruise ships or container ships.	About 50 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
49	Saudarkrokshofn					
50	Hofsoshofn					
51	Haganesvikurhofn					
52	**Hafnir Fjallabyggdar**	Cruise ships stop in the port of Siglufjordur. Most of the ports' profit comes from marine catch handling (Port Association of Iceland, 2021).	Container ships do not stop at either port. The port of Olafsfjordur does not provide services to cruise ships.	The port of Siglufjordur is a cargo port, which could provide services to container ships if the proper construction is conducted. Port of Siglufjordur plans to provide a shore connection to newer vessels.	The port of Olafsfjordur is a medium-sized fishing port and does not have the facilities to provide services to container or cargo ships.	About 5 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
53	Siglufjardarhofn					
54	Olafsfjardarhofn					
55	**Hafnir Dalvikurbyggdar**	Most of the ports' profit comes from marine catch handling (Port	Cruise ships do not stop at the ports.	The port of Dalvik is a big fishing and cargo port and	There is no plan for energy transition	Energy transition construction in the next 10 years has not been
56	Dalvikurhofn					
57	Arskogssandshofn					

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
58	Hauganeshofn	Association of Iceland, 2021).		has the facilities to provide services to larger ships.	improvements in the next 10 years (Port Association of Iceland, 2021).	estimated, but it should be considered to plan an electric outlet since they are a fishing port and energy transition in fishing vessels will happen rapidly in the upcoming years.
59 60 61 62 63 64 65	**Hafnasamlag Nordurlands** Hriseyjarhofn Grenivikurhofn Hjalteyrarhofn Svalbardsstrandar-hofn Akureyrarhofn Grimseyjarhofn	Cruise ships call at the port of Akureyri. Eimskip and Samskip container ships call at the port of Akureyri.	No port, except for the port of Akureyri, provides services to cruise ships and container ships.	In the port of Akureyri, a new electrical power system has been provided to offer shore connection to cargo ships and small cruise ships (Verkis, 2021).	All ports except for the port of Akureyri are either fishing ports or smaller ports with limited infrastructure to provide services to cruise ships or container ships.	About 4 billion ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021). As the likely energy transition in the larger ships is hydrogen and methanol, storage and transportation of alternative fuels for the coming transition should be considered.
66 67 68 69	**Hafnir Nordurthings** Husavikurhofn Kopaskerhofn Raufarhafnarhofn	Cruise ships stop in the port of Husavik and Raufarhofn. Eimskip stops in the port of Husavik. Most of their profit comes from cruise ships, but also marine catch and cargo handling (Port Association of Iceland, 2021).	Port of Raufarhofn does not provide services to container ships. The port of Kopasker does not provide services to cruise ships or container ships.	There is a plan to improve the electrical power system for shore connection in Husavik (Verkis, 2021).	The ports of Kopasker and Raufarhofn do not have enough facilities to provide services to cruise or container ships.	About 20 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
70 71 72	**Hafnir Langanesbyggdar** Thorshafnarhofn Bakkafjardarhofn	Eimskip stops in the port of Thorshofn. The port of Bakkafjordur offers small boats to connect to electricity.	Cruise ships do not call the ports.	-	The port of Bakkafjordur is a small boat port and does not have enough facilities to provide services for larger	Energy transition construction in the next 10 years has not been estimated, but the OPS plan should be considered since the port of Thorshofn provides services to Eimskip, and in

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
					container or cruise ships.	the future, container ships will run on alternative fuels.
73	**Vopnafjardarhofn**	Samskip ships call the port.	Cruise ships do not stop at the port. Eimskip ships do not stop here.	Since Samskip ships call at this port, smaller cruise ships may call at the port as well. It is a medium-sized fishing and cargo port and does not have the facilities to provide services to cruise ships.	There is no plan for energy transition improvements in the next 10 years (Port Association of Iceland, 2021).	Energy transition construction in the next 10 years has not been estimated, but it should be considered to plan an electric outlet since they are a fishing port and energy transition in fishing vessels will happen rapidly in the upcoming years.
74	**Hafnir Mulathings**	Cruise ships stop in all three ports. Smyril Line Cargo also stops in the port of Seydisfjordur, as well as the Passenger/Ro-Ro Cargo ship Norroena from Smyril Line, which sails between the port of Seydisfjordur, Faroe Islands, and Denmark. Most of their profit comes from marine catch handling, but profit from cruise ships is increasing (Port Association of Iceland, 2021).	Container ships do not call at the port.	There is a plan where the Passenger/Ro-Ro Cargo ship Norroena will be shore connected in the port of Seydisfjordur (Verkis, 2021).	The port of Borgarfjordur is a smaller boat port and does not have enough facilities to provide services for cruise or container ships. The port of Djupivogur is a medium-sized fishing port and does not have enough facilities to provide services to container or cruise vessels.	About 40 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
75	Borgarfjardarhofn					
76	Seydisfjardarhofn					
77	Djupavogshofn					
78	**Fjardabyggdarhafnir**	Cruise ships stop in the port of Eskifjordur, Nordfjordur and Mjoifjordur. Eimskip and Samskip container ships stop in the port of Reydarfjordur.	Eimskip and Samskip container ships do not stop at any of these ports except the port of Reydarfjordur.	The port of Faskrudsfjordur is a big fishing port. It could potentially provide services to container ships. The ports of Mjoifjordur,	The port of Stodvarfjordur and the port of Breiddalsvik are smaller fishing port and unable to provide	About 1000 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).
79	Nordfjardarhofn					
80	Mjoafjardarhofn					
81	Eskifjardarhofn					
82	Mjoeyrarhofn					
83	Reydarfjardarhofn					
84	Faskrudsfjardarhofn					
85	Stodvarfjardarhofn					
86	Breiddalsvikurhofn					

NO.	PORT	STRENGTH	WEAKNESS	OPPORTUNITY	THREATS	ACTION
		Most of the ports' profit comes from cargo and marine catch handling. (second largest profit in Iceland) (Port Association of Iceland, 2021).		Eskifjordur, and Nordfjordur plan on improving or setting up shore connections (Verkis, 2021).	services to larger ships.	
87	**Hornafjardarhofn**	Three cruise ships stopped at the port in 2018 with a total of 320 passengers. No cruise ships have called this port since then (Port Association of Iceland, 2021).	Container ships do not stop at the port.	It is a big cargo and fishing port which has enough infrastructure to provide services to larger ships and did so in 2018. The port could provide services to container ships if proper construction is conducted.	The current infrastructure of the port is insufficient to provide services to container ships.	About 20 million ISK in electric equipment regarding energy transition in the years 2021-2031 is estimated (Port Association of Iceland, 2021).

The Icelandic ports can be categorized based on their size into small, medium, and large ports. Small ports are to be ports that only provide services to small fishing boats, for instance, the port of Bakkafjordur and the port of Hofn. Ports that could be categorized as small ports have limited port infrastructure, and only small boats are docked at the port. Fishing, cruise, and container ships do not call at these small ports. Medium-sized ports are usually fishing ports that have enough infrastructure to provide services to fishing ships, smaller-sized general cargo ships, and expedition ships. Small-sized cruise ships that possibly call the port but do not dock at this port, for instance, the port of Vopnafjordur and the port of Thorshofn. Big ports have enough infrastructure to provide services to container ships, and cruise ships, for instance, Sundahofn and the port of Akureyri.

Information about different types of vessels and the current energy transition for each vessel type is summarized in Table 4.

TABLE 4 Types of vessels and their energy transition trends worldwide.

TYPE OF VESSEL	ENERGY TRANSITION TRENDS
Fishing vessels	Alternative fuels with high technical feasibility for the fishing sector include LNG/LBG and biodiesel for all types of fishing vessels. Hydrogen fuel cells are particularly suitable for coastal fishing ships. Additionally, battery implementations for partially electrified propulsion are considered highly feasible across the entire fishing sector. Currently, newer large trawlers have diesel electric propulsion with hybrid power supply as well as smaller battery packs on board. Although fuel oil is the primary energy source, the batteries improve the engine loads and reduce the fuel consumption, and can also, together with a shore connection, enable emission-free operation at ports (Gabrielii & Jafarzadeh, 2020). The world's first all-electric commercial fishing vessel is the 11 m hybrid-electric Norwegian boat Karoline, which can operate 2-3 hours on battery. The boat was designed in 2015 and

TYPE OF VESSEL	ENERGY TRANSITION TRENDS
	was made to run only on electricity, but it contains a small 50kW auxiliary generator as well and can be charged overnight by plugging into the electrical grid (Hansen, 2015).
Container ship	KONGSBERG is responsible for the development and delivery of all key enabling technologies on the first ever zero-emission container ship, Yara Birkeland (Skredderberget, 2018). In 2021, the Maersk company ordered the world's first methanol-enabled container vessel (Maersk, 2023). The ship, powered by green methanol, is the 172m Laura Maersk, which was built in 2023 (VesselFinder, 2024). Other container ships running on green methanol are the 349m sister ships Ane Maersk (Maersk, 2024a) and Astrid Mærsk (Maersk, 2024b) that launched in January and April 2024. Ane Mærsk is the first large methanol-enabled vessel, the biggest methanol-powered container ship. Astrid Maersk is also a sister ship.
Ferries and passenger vessels	Ferries and passenger vessels usually have frequent port calls. Most of the vessels with frequent port calls are electrically driven. Electric-driven ships are today mostly restricted to short sea segments such as ferries and passenger vessels.
Cruise ships and expedition vessels	Cruise ships use around 60% of their energy for propulsion and 40% for the hotel-related activities and operations aboard the ship. The newly ordered cruise ships feature hybrid engines, electric propulsion systems, and various energy solutions, including combinations of solar panels, wind, and liquid natural gas, or photovoltaic panels. Some are also equipped to collect energy from wind farms located at ports and have engines that emit lower levels of SOx into the environment (Kizielewicz, 2021).
Cargo ships	Heidelberg Cement Norway and Felleskjopet AGR have awarded Egil Ulvan Rederi to build and operate the first zero-emission cargo ship (Beumelburg, n.d.). It is powered by hydrogen and wind, and the hydrogen is stored in compressed form onboard. The ship is ordered in late 2021 and will be ready in early 2024 (The Maritime Executive, 2021).
Tanker	In 2020, the Japanese shipping company, Asahi Tanker, launched the world's first zero-emission tanker, a 62m all-electric tanker (Prevljak, 2021). In 2021, Grieg Edge and Wartsila collaborated in making the world's first tanker running on green ammonia, which was planned to be launched in 2024 (Wartsila, 2021).

Alternative fuels, including biodiesel and hydrogen fuel cells, are highly feasible for the fishing sector, with battery implementations enabling partial electrification and emission-free port operations. Maersk is leading the container shipping industry and is launching the world's first green methanol-powered ships. Ferries and passenger vessels are increasingly adopting electric propulsion, particularly in short sea segments. New cruise ships are integrating hybrid engines, electric systems, and renewable energy solutions such as solar panels and wind power to reduce emissions. In the cargo and tanker sectors, pioneering projects are underway to build zero-emission ships powered by hydrogen, wind, and green ammonia, with a significant number of launches expected in 2024.

5. DISCUSSION

Considered as one of the most seafood-dependent economies worldwide, and the highest per capita sea catch in the world, the Icelandic economy significantly relies on maritime activities (Sigfusson, 2011). Growth in cargo flow at the Icelandic ports (Eskafi et al., 2021) and the cruise industry has increased marine traffic in terms of the number and size of vessels and port activities. The ports function as logistics centers for the flow of cargoes, containers, and passengers (Eskafi et al., 2021). They are strategic locations for value-added activities wherein industries operate (Eskafi & Ulfarsson, 2023). This signifies the crucial role that ports play in energy transition and achieving decarbonization goals.

Icelandic ports are of different sizes. Small ports serve small boats, medium ports service fishing vessels and smaller ships, and big ports can handle the majority of ship calls. Small ports have limited capacity and infrastructure, but big ports have enough or, in some cases, limited infrastructure for the current demand of port users.

Geothermal and hydropower energy are Iceland's primary sources of energy, or about 85% of the total energy usage (National Energy Authority of Iceland, 2022b). The transportation sector is the only sector in the Icelandic economy that uses fossil fuels as its primary energy source, and ships use about 26% of the oil in transportation (National Energy Authority of Iceland, 2022b). All ports in Iceland offer a shore connection of 230/400V with 50 Hz (Verkis, 2021), and all homes and companies use electricity (National Energy Authority of Iceland, 2022b). Biodiesel is currently used in Iceland today, but on a small scale compared to other fuel types (Rivedal & Sekkesaeter, 2021). Iceland has already started the transformation into a hydrogen economy (Salameh, 2009).

Ports can serve as energy hubs by integrating various technologies to manage and optimize energy usage. By incorporating stationary batteries, ports can reduce electricity costs through the mitigation of peak demand fluctuations. Decreasing battery prices make this approach increasingly profitable, though it must be harmonized with other infrastructure and energy systems. Technologies such as photovoltaic (PV) systems, electrolyzers, fuel cells, and hydrogen storage complement the batteries, providing multiple energy sources. This integrated system enables the production and storage of electricity and hydrogen, which can be used to fuel port operations, electric vehicles, trucks, and ships, balancing short-term and long-term energy demands effectively (Werner, 2021).

The opportunities and challenges for energy transition in Icelandic ports are summarized in Table 5.

TABLE 5 Opportunities and challenges for different sizes of ports.

PORT SIZE	OPPORTUNITIES	CHALLENGES
Small	Constant/regular vessel traffic, including small-sized fishing boats/ships at the port. Development of the energy transition to service the smaller vessels does not require a significant capital investment. Only onshore power supply (OPS) can meet the demand of the vessels (i.e., small-sized fishing boats/ships) that call at the ports.	New development is required to connect the ports to the regional/national grid.
Medium	The ports provide services to container ships, fishing vessels, small cruise ships, and expedition vessels. OPS can meet the demand of the vessels that call at the ports. Some medium-sized ports have facilities or space for storing and transporting renewable energy at the ports. These ports could set up storage for green fuels, such as hydrogen or methanol, for container ships.	There might be limited power that needs to be provided to all types of vessels (fishing, cargo, cruise ships) that call the ports. Infrastructure development is required for e-fuel generation and bunkering, but the land and the possibility of facility improvement are limited.
Big	The port services cruise ships, container ships, and fishing vessels. The hinterland connection is enough. Pipelines could be a solution for big ports regarding e-fuels since there is enough demand, and marine traffic in the bigger ports is considerable. Pipelines have some advantages, such as low operational cost and long lifetime. Furthermore, there is a proven record of successful operations in the EU and the US, and often over several thousand kilometers. Moreover, transportation via pipeline is not a new technology; thus, public acceptance is expected (Weichenhain, 2021). There is good road connectivity to big ports, thus, transportation of e-fuels would be possible, to provide supplies to the end user (Weichenhain, 2021).	Grid capacity might be limited for shore connection. Transportation of hydrogen via pipelines requires a high initial capital cost for new pipelines, highly complex permitting, and authorization processes (Weichenhain, 2021). Furthermore, embrittlement and diffusion leaks should be taken into consideration. Tensile steel pipes present embrittlement issues at high mass flow rates and high pressure, and hydrogen must be pressurized to compensate for the pressure drop, but raising the pressure increases the risk of hydrogen embrittlement (d'Amore-Domenech et al., 2023). The liquefaction process of hydrogen demands significant energy, both for pre-cooling and the actual liquefaction. Additionally, the storage, handling, and transportation of liquid hydrogen (LH_2) are complex.

The main strengths of big-sized ports are their basic infrastructure and facilities to provide services to large vessels, including cruise ships and container ships. Furthermore, these ports have a plan for energy transition development. Implementation of energy transition at these ports requires significant CapEx.

In medium-sized ports, the main strength is also their existing infrastructure to provide service to general cargo and cruise ships at the ports. However, the marine traffic at these ports might be little. Furthermore, these ports have limited capacity for infrastructure development. The medium-sized ports have limited development plans for the energy transition in the coming years. Implementation of energy transition at these ports requires considerable CapEx.

In small-sized ports, infrastructure and facilities, as well as cargo flow and marine traffic, are limited. There is a limited development plan for energy transition in small ports in the next years. Significant investment in energy transition at these ports may not be feasible. Implementation of energy transition at these ports does not require a significant CapEx.

6. CONCLUSION

The findings from this study can provide crucial insights for stakeholders engaged in the maritime energy transition. This information will support informed decision-making in developing energy hubs at Icelandic ports, contributing to the climate and sustainability objectives.

The transition to sustainable energy within ports in Iceland will not only support the country's environmental objectives but also position Iceland as a contributor in green maritime innovation. Achieving the goals of meeting emerging decarbonization policies requires coordinated efforts among stakeholders, careful monitoring of energy activities, and the adaptation of current strategies.

Based on the findings presented, it is evident that Iceland's ports can play a crucial role in the country's energy transition and decarbonization. With Iceland's abundant renewable energy resources and the increasing urgency for sustainable energy solutions, transforming Icelandic ports into energy hubs offers a significant opportunity to support global climate goals. The maritime sector, which is integral to the global economy, presents a critical area for decarbonization, especially given its reliance on fossil fuels in the transportation sector. By leveraging renewable energy sources such as electricity, hydrogen, biofuel, and e-fuel, Iceland can significantly reduce the carbon footprint of its maritime activities.

Adoption of onshore power supply (OPS) systems at Icelandic ports could drastically reduce harmful emissions from berthed vessels, improving air quality and mitigating environmental impacts on urban areas surrounding ports. While the growth in the cruise and cargo sectors poses challenges, it also provides a unique opportunity to integrate sustainable practices and energy efficiency measures.

In conclusion, bigger-sized Icelandic ports hold substantial potential to act as energy hubs that drive the energy transition in the maritime sector, contribute to global sustainability efforts, and bolster Iceland's position as a contributor to a net-zero carbon future.

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