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Energy management framework in the zero-emission port

Theme 2: Future opportunities and challenges of the sustainability of maritime industry

By
Baltic Fishing Fleet State Academy of
Kaliningrad State Technical University

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Abstract A roadmap for a competitive low-carbon Europe by 2050 was put forward by the European Commission in 2011, aiming to deliver EU greenhouse gas (GHG) reductions in line with the 80 to 95% target. A new strategic vision (2050 long-term strategy) of the economy with net-zero GHG emissions, November 2018, addresses all the key economic sectors, including energy, transport, industry, and agriculture. In the maritime sector the Directive (EU) 2018/410 of the European Parliament and the Council emphasizes the need to act on shipping emissions. This relies to a significant degree on adequate land-based infrastructure. The Commission already supports its development, for example, port electrification through financial incentives and regulatory measures. Net-zero GHG emissions can be reached with existing technological solutions including maximization of renewable deployment and the development of an adequate smart network infrastructure. This results in IMO's initiative on reducing the ship's GHG emissions during her berthing at port (cold ironing). Ports have already invested in relevant infrastructure. This solution (i.e., connection with the main electrical grid) is not fully ecological due to the main grid's operation with fossil fuel. The use of renewable energies (wind turbines, solar panels, etc.) is recommended for a "Zero emissions port". The paradigm of the smart grid working as a hybrid (i.e., main grid + renewables + energy storage) has introduced new algorithms for energy management in real-time. In this work, we introduce a new framework customized for each port for energy management. The proposed framework is based on continuous consultation with stakeholders for requirement capturing and final evaluation.

Keywords: *zero emission port, smart grid, management framework, cold ironing*

1. Introduction

1.1 Background

The increase in the volume of global maritime transport and the rapid development of maritime infrastructure determines the urgency of adopting modern technologies and managing technics for the stable, economic and ecological operation of ports.

The maritime transport sector controls over 85% of world trade [1]. The sector is gaining momentum due to its enormous impact on the climate and the environment. Air quality in the port area is a top priority, so modern port concepts are based primarily on reducing greenhouse gas and pollutant emissions [2]. Global emissions from the marine sector account for 10-15% of anthropogenic emissions of sulphur (SOx) and nitrogen oxides (NOx) and about 3% of carbon dioxide (CO_2) emissions [3]. In response, in 2018, the member countries of the International Maritime Organization (IMO) set an absolute target to reduce greenhouse gas emissions by 50% by 2050 compared to the 2008 "Paris Agreement for shipping" [4]. Bringing the maritime sector to zero carbon will require huge efforts in the field of new technologies scaled up to economically effective use and other measures. The point is that efforts to reduce emissions should not hinder growth and international trade [5]. This will be achieved through the introduction of modern energy transmission systems, hybrid loading mechanisms, onshore and offshore renewable energy sources (RES), cold ironing, energy demand management, and port's power consumption energy flow reduction by replacing the existing sources with renewables [6]. Ensuring the normal operation of these multi-agent systems is a complex scientific and technological task and would not be possible without the introduction of an adequate management framework. The management of joint operation of energy storage systems (ESS), renewable sources, and energy consumers in return requires monitoring and prediction systems that must be built on artificial intelligence algorithms.

The development of such a management framework will need close cooperation of all stakeholders such as port and ship owners, ship holders', local authorities, local power system operators, equipment producers, and so on.

1.2 Research aims and objectives

According to the proposed application of the research team, the project aimed to define the framework for energy management in the zero-emission port and to develop a minimum viable product software to be easily customized for every port's real-time energy management.

The objectives of the project are:

1) Identify and develop the specific information to establish a framework for energy management in zero-emission ports.

2) Perform market and stakeholders' consultations to set realistic goals for the contribution of the zero-emission port.

3) Mobilize resources to support the implementation of an energy management framework in a zero-emission port and track their performance.

1.3 Significance of this research

Ports connect countries and the world via maritime transport networks. Ports consume a significant amount of energy for daily operations, especially during various ship operations such as loading, unloading, lighting, cooling, and so on. Ports hurt the environment due to related industrial activities.

Since 1996, the European Commission has annually formulated a rating of ten environmental priorities for European ports, which are aimed at reducing the negative impact on the environment and the biosphere (Fig. 1)

Fig. 1. Environmental priorities of European ports for 2020

Today, most ports rely on diesel engines, which produce significant amounts of pollutants, including particulate matter (PM), sulphur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). In addition, port activities are often related to various effects such as noise and light pollution, water and soil pollution, sea level rise, coastal erosion and flooding, road congestion, accidents, vibration, and landslides, which are results of three different activities: port operations, shipping operations and inland transportation. All these factors negatively affect the working environment and the quality of life of the inhabitants of the city located near the port. Zero-emission port concept promotes the use of renewable energy sources, cold ironing, and smart operation of the energy system of the port. This is not possible without managing framework, utilizing recent AI technologies for optimization of renewables and battery capacities, and electrical energy load curve prediction.

The 1st step in the development of complex control system architecture is the creation of a simplified framework for energy management, based on a modern optimization tool. This project is devoted to solving this problem.

1.4 Report structure

The rest of this report is structured as follows:

Section 1 is devoted to introduction to the project, research aim, objectives and justification of importance of the research.

Section 2 presents a systematic literature review with the identification of the zero-emission port concept

Section 3 describes the approach and the basic methodology for zero-emission port energy management framework development.

Section 4 presents the justification for selecting a port as a case study research and calculation results.

Section 5 is devoted to the description and discussion of calculated scenarios and conclusions.

Section 6 gives additional information on project dissemination results.

2. Analysis and state of art review

2.1 The PRISMA 2020 statement sources screening

Providing a comprehensive analysis of previously completed and ongoing research by other authors is important in determining the scope, goals, and objectives of future research.

For the 1st glance, the keyword analysis in the Scopus database for different aspects of the initial field of study was provided. The interest in the green port concept was continually growing over the last 30 years (fig. 2). The term was updated a few times and resulted in the zero-emission port concept, which is under consideration in the last decade.

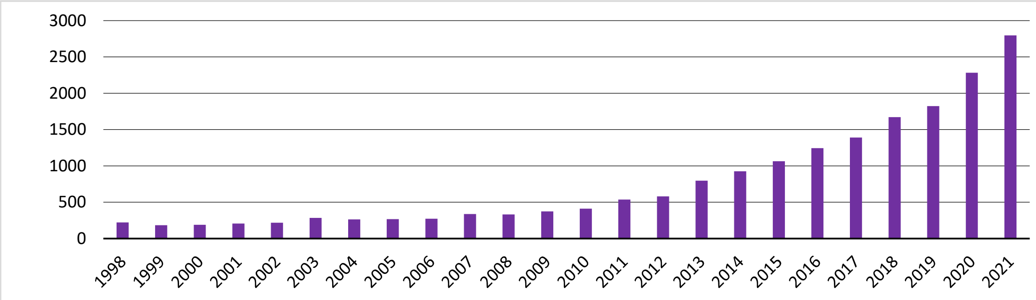


Fig. 2. Search "Green port" in Scopus in Engineering, Environmental Science by year

Let us have a closer look at the development of the interest in some important aspects of zero-emission port management framework issues.

If we are interested in the question of the methods for energy management of the port, the most modern are AI applications. As can be seen from Figure 3, interest in the application of artificial intelligence in the marine sector can be divided into three periods. In the early 1980s, the first peak of general interest in the fundamental algorithms of artificial intelligence occurred. The computing power of available computers was limited, so the interest was largely theoretical. Aspects of the implementation of simple artificial intelligence algorithms in real-world applications justify the second peak of interest, evident in the early 2000s. The increase in available computing power has made it possible to implement more complex algorithms in real-world applications. The third wave of releases, launched in 2010, continues to grow.

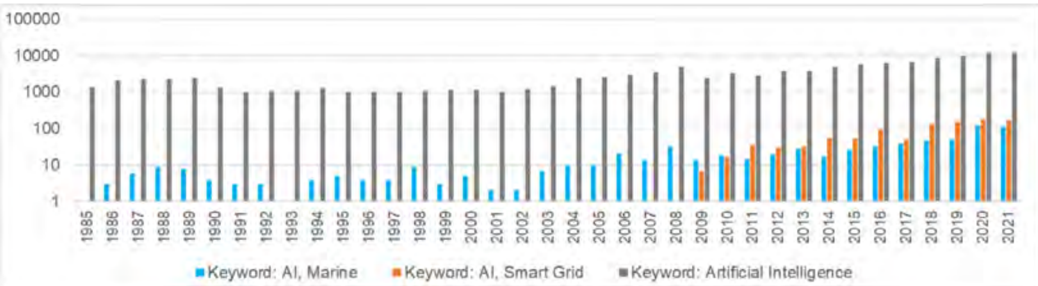


Fig. 3. Scopus publications on artificial intelligence in the marine sector and smart grid from 1985 to 2021

The past decade has shown a steady increase in interest in the use of artificial intelligence applications in the energy and marine sectors. But this is still a small fraction of the total output performance of AI methods. Thanks to the use of artificial intelligence methods to control and optimally manage the work of the port energy supply system, the number of exits is an order of magnitude smaller than in the energy and marine sectors.

The second important example, of how the interest grows is the so-called electrical storage system (ESS), the technology, which helps to optimize power flows with an energy system, which is using conventional generation, saving renewable energy during excessive outputs, and supplying it to the loads in low renewable production periods [7].
Analysis of ESS devoted publications in the Scopus database shows a constant interest in electricity storage topics (Fig. 4).

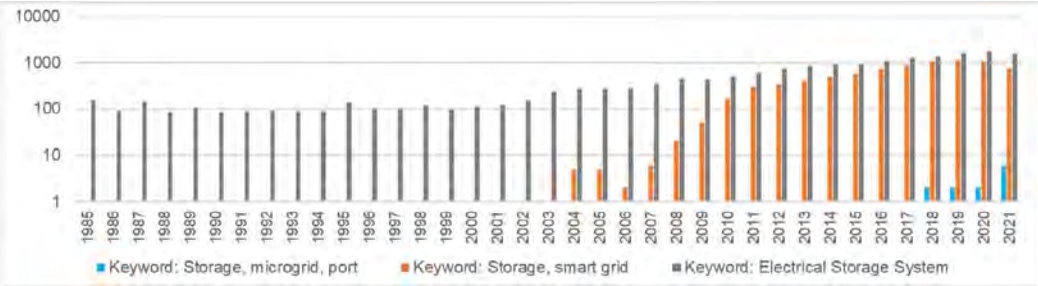


Fig. 4. Number of Scopus publications on energy storage systems in the marine sector from 1985 to 2021

As a result of the development of the smart grid concept, ESS is actively considered an integral part of such new systems. However, the challenge of using ESS as part of a port microgrid is relatively new due to the high conservatism of these systems.
An analysis of publication activity on ESS in the Scopus database shows a steady interest in electrical energy storage issues (Fig. 3). As a result of the smart grid concept development, ESS is beginning to be actively considered as an integral part of new systems. However, the problem of using ESS as part of the seaport's microgrid is relatively new due to the high degree of conservatism of these systems.
Considering the results of the analysis of citations from thirty senior journals in Scopus and Web of Science major journals, the engineering and computer science sector at the intersection of the fields of transportation, electrical industry, and sustainable energy were selected. Several publications indexed in Google Scholar and Scopus databases were accepted for further review as shown in Figure 4 [8]. The graph with the results of the selection of publications is shown in Figure 4.
The state-of-the-art review should be conducted by the established methodology and taking into account the amount of information available in scientific books, journals, and conference materials.
The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 [9] is the one approach to the systematic literature review that provides a constructive way to organize the material. The PRISMA statement was first published in 2009 [10] and is regularly updated. The method consists of clear steps. The result of PRISMA sorting is a series of articles for detailed review with the topic of future research that is removed from duplicates or unrelated articles. Discussing the choice of scientific databases for analysis is a fundamental first step. The most important databases are Google Scholar, Scopus, Web of Science, Microsoft Academic, Dimensions, and COCI. The first three are useful for engineering topics. PRISMA 2020 flow diagram template describes the process of dismission of unpromising material. Keywords used for the source's selection are green ports, zero-emission ports, and sustainable ports. Refining keywords on the screening steps are smart grid, cold ironing, renewable sources, electrical storage system, and electrical management system.
Using PRISMA 2020 approach for a basic systematic literature review was provided by the authors for the topic of zero-emission port power consumption management. The main focus was on the use of renewable energy sources and energy storage systems (ESS) as part of the port's electricity supply system, optimization of electricity consumption and production, and the use of artificial intelligence (AI) techniques for optimal power and energy flow control for such systems.

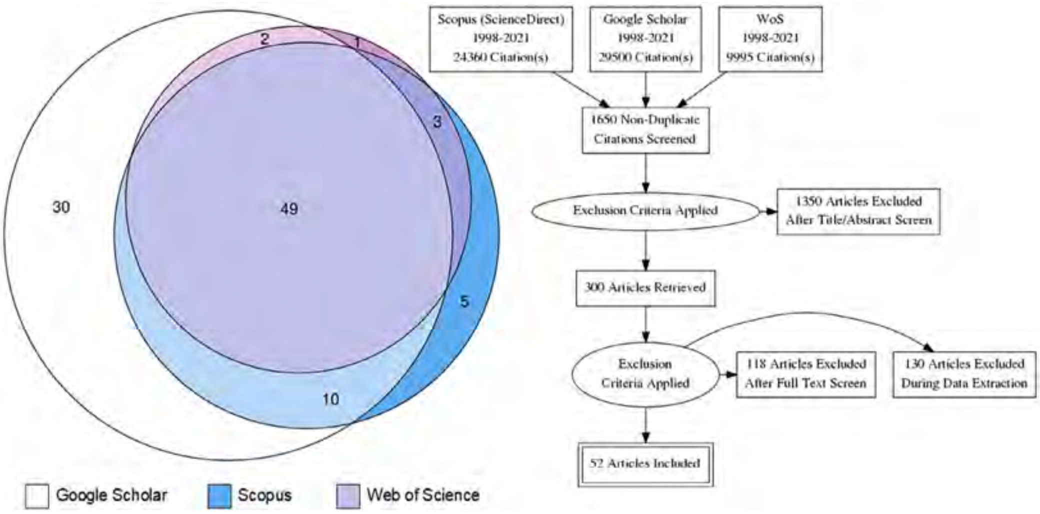


Fig. 5 - Overlap of 63,326 citations to 30 highly-cited documents in the fields of Artificial Intelligence, Power Engineering, and Sustainable Energy [8] and a PRISMA Flow Diagram of the selection process for literature overview according to [10]

2.2 Analysis of technical, legal and counties/port regulations

In the section we have carried out an overview of the national and international technical and legal framework as well as some countries' measures and strategies to facilitate the transition to a zero-emission ports or to turn them into decarburization hubs. In these terms the EU, the Russian Federation and China cases have been considered.

In April 2015 the countries (among the 190 ones) signed the Paris Agreement and confirmed their commitment to follow the international climate change policy including the necessity to limit global temperatures rising below 2 C.

This requires a rethinking of policies for clean energy supply across the economy, industry, production and consumption, large scale infrastructure, transport and many other sectors. Ports can play a key role in this context [11].

Shipping accounts for between 70% and 100 % of pollution at seaports in developed countries [12,13] and ship emissions are able to travel up to 500 km of land [14,15]. The maritime sector's global emissions amount to more than 15% of NOx and SOx emissions, and almost 3% of the total CO2 emissions [16]. Let us consider the state of affairs in terms of legal and technical issues moving forward a zero-emission ports in the project countries.

2.2.1 The European Union

It should be noted that 74% of EU's imports and exports are transported by the sea, clearly indicating a huge dependency on seaports for trade, not only with the rest of the world, but within each country's borders [17].

In this case, ship operations have become a major cause of environmental pollution in port cities and neighboring areas.

Thus, apart from harmful emission onboard diesel generators produce noise and vibration in the proximity of ports.

In this spirit, European countries adopted EU Directive 2014/94/EU to support the development of the alternative fuel market for the transport sector and the deployment of the relevant infrastructure.

Directive 2014/94/EU covers all forms of transport and is included as part of the Clean Mobility Package. Also, in 2014, 328
European ports joined the Trans-European Transport Network (TEN-T) network. TEN-T supports the application of innovation to all modes of transport and has an objective to reduce the environmental impact of transport. TEN-T includes the European network of inland waterways, maritime shipping routes and the infrastructure at ports.

Shore power is identified as one of the alternative fuel technologies in this directive and EU Directive 2014/94/EU requires the ports of Europe to install shore power facilities on priority basis by December 31, 2025.

The Environmental Ship Index (ESI) set by International Association of Ports and Harbors (IAPH), is a formula that evaluates the amount of NOx and Sox that is emitted by a vessel and rewards vessels that use onshore power supply while at port. Based on their ESI, discounts offered by the ports vary according to the number of points earned by the vessels, which range from 10 to 100.

The Environmental Port Index (EPI), developed by Det Norske Veritas (DNV), calculates a maximum tolerable environmental impact (NOx, CO2, Sox, and particle levels) while at port. The EPI allows vessel owners to enhance operational efficiency and vessels will also be able to take advantages of incentives offered by the EPI ports.

Incentives have encouraged the installation of both shore side and on-board shore power systems. To date, most major European ports have joined the ESI program, and over 4000 vessels around the globe have already deployed environment friendly technologies including shore power enabling themselves to receive discounts on port services.

On-shore power supply represents an attractive solution to reduce local pollution generated by vessels at berth in EU ports.

This potential has already fully been recognized by Article 4(5) of Directive 2014/94/UE on Alternative Fuel Infrastructure [18], according to which shore-side electricity supply shall be installed as a priority in ports of the Trans-European Transport Network (TEN-T) Core Network, and in other ports, by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits. The preparatory work for the evaluation of Directive 2014/94 has been launched this year and should identify, inter alia, how effective these provisions have been to deploy on-shore power supply in European ports.

In addition to the regulatory approach, the Commission has also identified the promotion of shore-side electricity as a priority for transport investment. It is highlighted in the TEN-T Guidelines and the Commission has been supporting this through the Connecting Europe Facility since 2014. Moreover, alternative fuel infrastructure, such as on-shore power supply, is eligible under the General Block Exemption Regulation and can thus be funded with public support.

To further incentivize the deployment and use of cold ironing, Member States can also ask an authorization to apply a reduced rate of taxation on electricity directly provided to vessels at berth in a port in accordance with Article 19 of the directive of the Energy Taxation Directive [19].

European Commission elaborated a plan until 2050 that implies priority actions in terms of efficient, safe and secure energy to mitigate climate change encouraging sustainable ways of production and services.

In 2018, Renewable Energy Systems (RES) accounted for almost 25% of all energy produced and comprise 18.9% of the European Union's (EU) energy sector. EC endorsed a target of at least EU decided to become the world leader in the implementation and use of RES; the number of installations and investments is projected to rocket-up soon (European Commission, 2015) [20].

2.2.2 The Russian Federation

Russia takes part in the formation of international climate policy, being a party to the UN Framework Convention on Climate Change, its Kyoto Protocol, the Paris Agreement and international treaties for the protection of the ozone layer. At the national level, strategic documents in the field of combating and adapting to climate change have been adopted and are being developed, measures are being taken to reduce GHG emissions, and a goal has been set to reduce them by 2030. Russian climate policy focuses on measures to adapt to climate change, unleashing the potential of energy efficiency (a draft of a new comprehensive plan for improving energy efficiency has been prepared), protecting and restoring forests, as well as implementing environmental and environmental initiatives. Separately, to stimulate alternative renewable energy sources in the electric power industry, the regulatory framework for their support in the wholesale and retail markets, in isolated energy regions, and for microgeneration has been formed and is being specified.

Russia has adopted a regulatory framework designed in accordance with national strategic goals to provide support for projects in the field of renewable energy. Initially the main element in the Russian approach to supporting RES was a premium on the price of electricity on the wholesale electricity market. In December 2010 Russian the authorities decided to switch to a renewable energy support scheme based on payment for power. At the time of writing the report, the necessary executive documents, intended for the practical implementation of RES support schemes are not accepted.

The Russian government has approved a strategy for the socio-economic development of Russia with low greenhouse gas emissions until 2050.

Achieving carbon neutrality with sustainable economic growth - such goals are stated in the new low-carbon development strategy which was approved by Prime Minister Mikhail Mishustin by his order.

According to the document, the achievement of carbon neutrality is expected no later than 2060.

The implementation of the target (intensive) scenario will allow the Russian Federation to achieve a balance between anthropogenic emissions of greenhouse gases and their absorption no later than 2060.

There are two Strategy Scenarios. The strategy includes two scenarios - inertial and target (intensive). The target scenario is taken as a basis. The scenarios differ in the set of measures to decarbonize the Russian economy.

In the target scenario, ensuring the competitiveness and sustainable economic growth of Russia in the context of the global energy transition is designated as a key task. The macroeconomic conditions of the target scenario assume outstripping growth rates of non-energy exports (up to 4.4% annually). The contribution to sustainable economic growth will be made as outstripping rates growth in investment in fixed assets (3.7% annually) and stable growth in real disposable income (2.5% annually).

As a result, in the target scenario, annual economic growth rates remain above the world average until 2050 (up to 3% per year).

The implementation of the target scenario will require investments in reducing greenhouse gas emissions in the amount of about 1% of GDP in 2022-2030 and up to 1.5-2% of GDP in 2031-2050.

Among the decarbonization measures announced are: providing support measures for the introduction, replication and scaling of low- and non-carbon technologies, stimulating the use of secondary energy resources, changing tax, customs and budgetary policies, developing "green" financing, measures to preserve and increase the absorptive capacity of forests and other ecosystems, support for technologies for capturing, using and utilizing greenhouse gases.

Thus, within the framework of the target scenario, it will be possible to grow the economy while reducing greenhouse gas emissions: by 2050 by 60% from the level of 2019 and by 80% from the level of 1990. Further implementation of this scenario will allow Russia to achieve carbon neutrality by 2060.

An action plan for the implementation of the strategy is planned to be developed within six months.

Strategy for the development of Russian sea ports infrastructure until 2030 implies development of economic mechanisms to stimulate the transition of the industry to environmentally friendly and energy-efficient technologies, including the transition for alternative energy sources, shore power supply of transport ships while moored in the port.

2.2.3 The People's Republic of China

1. Policy issued by the government of China

The use of shore power by ships at ports is an effective means of reducing ship pollutant emissions. Since China first adopted the high-voltage shore power system in 2010, the use of shore power technology for berthing ships has gradually spread across the country. During the "Twelfth Five-Year Plan" period, the ministry successively issued the "Twelfth Five-Year Plan for the Implementation of Overall Promotion of Energy Conservation and Emission Reduction in Water Transport" and "Guiding Opinions on Port Energy Conservation and Emission Reduction Work". A lot of work has been carried out in support, publicity and training, which has laid a good foundation for the promotion and application of shore power technology.

In recent years, national ecological civilization strategies and laws and regulations have imposed new and higher requirements on the use of shore power by ships calling at ports. The "People's Republic of China Air Pollution Control Law" implemented on January 1, 2016 states: "Newly built wharves should plan, design and build shore-based power supply facilities; completed wharves should gradually implement shore-based power supply facilities renovation. After ships arrive at the port, Priority should be given to using shore power. "State Council's" Thirteenth Five-Year Plan "Ecological Environmental Protection Plan," 13th Five-Year Plan "Comprehensive Work Plan for Energy Conservation and Emission Reduction, and our Ministry's Implementation Plan for Special Actions on Ship and Port Pollution Prevention and Control (2015-2020" (Hereinafter referred to as the "Action Plan") have all put forward clear requirements for promoting the use of shore power by ships. The ship emission control area policy proposes that ships can take alternative measures such as connection to shore power. The "13th Five-Year Plan for Development of Transportation Energy Conservation and Environmental Protection" and the "Implementation Plan for Promoting the Construction of Ecological Civilization in Transportation" clearly define the "development plan for port and shore power distribution." In order to implement relevant laws, regulations and documents, and to promote the orderly construction of port and shore power facilities, the Ministry of Transport has formulated the "Plan".

On July 24, 2017, the Ministry of Transport issued the "Port and Shore Power Layout Plan". The "Plan" is China's first top-level design document for the construction of port and shore power facilities, and its promulgation will play an active role in promoting the orderly construction of port and shore power facilities in China, and guiding ships to use shore power by port. Structural reform and green development are of great significance.

Based on the "Action Plan" mentioned above, the "Plan", in accordance with the principle of highlighting key points, combined with emission control zone policies and regional air pollution prevention and control requirements, proposes to promote the construction of shore power facilities in major ports and ports in emission control zones by 2020. Meets the requirement of shore power for ships berthed from vessel pollution emissions relatively concentrated and severe area, reducing pollution emissions from ports in key areas. There are 69 major ports and ports in emission control zones. According to the port statistics at the end of 2015, the port cargo throughput within the scope of the layout accounted for 75% of the total national cargo throughput, of which container throughput reached approximately 90% of the national container throughput.

The "Plan" is based on the "Action Plan" , in addition to the layout of three types of specialized berths, such as containers, cruises and passenger rolls, which are suitable for ships to use shore power in ports, in order to adapt to large tourist ships on the Yangtze River in recent years (Mostly above 3,000 tons) and the need for the rapid development of large-scale bulk cargo terminals in the country, taking fully into account the suitability of large-scale tourist ships and bulk carriers for using shore power in ports, a better promotion basis, and large emission reductions Potential, clearly including passenger transportation above 3,000 tons and specialized berths for dry bulk cargo above 50,000 tons into the scope of shore power distribution.

The Port and Shore Power Layout Plan " issued in 2017 clearly proposed that by 2020, more than 50% of the major ports, such as containers, cruise ships, passenger rolls, passenger transports above 3,000 tons and dry bulk cargo above 50,000 tons, will be provided the berth which are able to provide shore power.

The "Port Engineering Construction Management Regulations" revised and promulgated in 2018 implemented the requirements for the simultaneous construction of shore power facilities at new terminals. Relevant departments also issued the "Guiding Opinions on Promoting the Replacement of Electricity", strengthened the guidance of the central government's shore power incentive fund policy, and promoted the construction of shore power facilities in ports, water service areas, and anchorages to be locked. Aiming at the prominent problems restricting the development of shore power, such as high shore power prices and the inability of ports to collect electricity tariffs, the Opinions on the Innovation and Improvement of Green Development Price Mechanisms issued in 2018 clearly stated that "By the end of 2025, Port electricity operators are exempt from demand (capacity) electricity charges "; the" Action Plan for Fighting Tackling the Challenges of Pollution Control of Diesel Trucks "issued at the end of 2018 further clarified" allowing terminals and other shore power facilities operating companies to collect electricity charges from ships according to the current electricity price policy. The port's shore-based power supply implements large industrial electricity prices and is free of accommodation (requirement) electricity charges.

With the joint efforts of all parties, the construction of shore power facilities has progressed rapidly. According to preliminary statistics, more than 2,400 sets of shore power equipment have been completed nationwide, covering more than 3,200 berths, of which about 40% of the tasks of the "Port Shore Power Layout Plan" have been completed. Beijing-Hangzhou canal water service area basically achieves full coverage of shore power. However, the promotion of shore power still has problems such as high construction costs, uneconomical use, and low enthusiasm for ship reconstruction and use of shore power. The overall utilization rate of shore power is not high.

2.3 Advantages and disadvantages analysis

To investigate the elements of a zero-emission port concept and prospect of transition to a zero- emission or nearly zero emission ports the comprehensive /holistic state of the art literature review has been carried out.

Necessary to have in-depth consideration of all possible aspects and factors, features concerned with ports such as geographical location, size, typology, ownership, management, legal status, climate change effects and possible obstacles and solutions of transition to zero-energy.

First of all, we have to take into account that ports are a vital node to the global transportation sector [21, 22] and play a very important role in global economy and in socioeconomic development of neighboring cities [23, 24, 25].

The extent of the influence largely depends on the port geographical location, size, ownership [26, 27]. Thus, the typology of ports includes three categories of ports: local, national, international ones.

Local ports are small-sized usually are not able to handle large cruise vessels and deal with small vessels. Mostly have insular location and limited logistic processes.

National ports are of medium-size able to handle some cruise vessels and carry out insufficient logistics, mainly regional needs intended.

International ports are large-sized and play crucial part in international logistics and present a specific interest for possible transition to zero-energy concept.

All the circumstances should be taken into account due to the fact that they crucially influence conditions for the transition.

2.3.1 Ownership

Ports are owned, managed, and maintained by various administration types and stakeholders which affect their final decisions [28, 29, 30]. Some central public ports are regulated, including all regulatory and landlord functions; others operate by hybrid public and private custody [31, 32]. They are sometimes entirely privatized with all legislative and operating responsibilities shifted from the public sector, targeting increasing revenues with the minimum investment cost [33].

The legal status of a port is very important in terms of having opportunities for sustainable development, green initiatives and to combat climate change [34, 35].

It influences the cooperation between interested parties, port stakeholders and decision-makers who are able to move forward the initiatives. Researchers observe the lack of the cooperation [36, 37].

After state of the art review of publications on general aspects of a modern port features and function it is possible to proceed on capacity and measures for energy transition or potential of green technologies deployment towards the use of renewable energy sources (RES) and smart energy management systems (SEMS) to mitigate climate change.

While planning transition to a nearly zero-emission port we inevitably face the obstacles stipulated by the above-mentioned reasons /factors i.e., geographical location [38] that crucially affect feasibility of the use of RES due to adverse weather conditions (strong winds, lack of space) and some other factors preventing from quick introduction of RES installations (obsolete infrastructure that requires long-term considerable investments).

Some ports are not obliged or motivated to use the RES/SEMS and in this case, they tend to increase revenues with minimum investment cost [39] and each inch of available space becomes a matter of profit for them.

Otherwise, some ports have successful or less successful practices in terms of sustainability and energy consumption [40, 41, 42].

2.3.2 Steps towards planning transition to a low-carbon or nearly zero-emissions port

1. Air monitoring

The use of air monitoring environmental stations with sensitive smart sensors with zero offset allowing to carry out measurements of the level Hydrogen Sulfide (H2S), Methyl Mercaptan (CH3SH), Carbon dioxide (CO2).

This technology allows to obtain air quality index on daily, monthly and yearly basis.

Most of publications are dedicated to monitoring of the air quality in port areas and this is due to the World Port Climate Initiative encouraging port authorities to achieve GHG reduction goals [43].

2.Real -time energy data monitoring and reporting systems

Taking into account that ports are high energy demanding facilities the deployment of the system would enable to produce energy efficiency scenarios. For some of the ports it seems complicated to introduce the system due to extra investments to complete upgrade of existing systems and cyber security measures. Some EU ports and worldwide have already installed the systems [44,45] and they have won greatly in terms of energy efficiency [46, 47].

3.Energy efficiency road map

Some ports have to follow the internal and national standards on energy efficiency. Usually these are the measures towards renovation of obsolete indoor/outdoor lighting equipment replacing the old one with light-emitting diode lights [48], use automated systems with smart sensors for the lights and tapped water control [49, 50], use of energy saving windows.

4.On-shore power supply or cold –ironing.

It should be noted that while at dock vessels tend to use auxiliary and for loading/unloading main fossil-fuel engines that causes significant air and water pollution. To avoid the negative impact, the cold – ironing technology has been introduced. It allows to shut down the fossil-fuel engines [51] and use on-shore power supply [52, 53].

Cold-ironing or offshore power supply can essentially diminish GHG emissions and tackle climate change [54]. Cold-ironing can achieve over 95% energy and GHGs savings. However, on the other side of the coin, the high infrastructure cost and the connectivity complexity are critical bottlenecks for some ports [55]. So far only 28 ports worldwide have applied the measure [56].

5.Peak-shaving technology

The technique allows to avoid peaks in energy consumption that are inefficient, unnecessary and costly as well as to reduce GHGs substantially [57]. There is a little number of publications towards the high potential of the technology use to mitigate climate change [58, 59].

6.Micro or smart grids.

Another very high demanding technology for future transition to a green port that would enable to control and automate a whole industry [60]. In spite of the fact that there are few publications on how to apply this in port energy sector but the capacity of the technology in terms of cost-efficiency and for integration it with RESs makes it very productive for green energy of future [61, 62, 63].

7. Electrification of port transport/equipment/hybrid electric vehicles

In the scientific literature we can find some proofs that the replacement of the old fossil fuel transport to electric or hybrid one can bring energy and GHG reduction up to 60-70% [64, 65].

The main obstacle is that the modernization will require considerable investments and inevitably cause the problem of the batteries disposal.

8. Renewable energy systems

The RES installations [66] can be considered as rather sustainable technology for supplying green energy to reduce ports' environmental footprint [67].

There are set of publications investigating the potential and high demand on energy from RES: wind [68, 69], solar [70, 71], tidal [72], wave [73, 74] and geothermal one [75].

On the basis of the literature state of the art review we can draw a conclusion that planning to move forward to a zero-emission port requires comprehensive analysis of all aspects of a port functioning taking into account its geographical location, legal status, size, level of cooperation or motivation of stakeholders involved in its activities to encourage sustainable initiatives.

The review enabled to identify the possible energy efficient green solutions within a port area to mitigate the climate change and to assess their advantages and disadvantages in terms of feasibility of a technology implementation.

3. Approach and methodology description

3.1 Modern tools for Zero-emission Port energy management

As mentioned earlier, the main sources of pollution are cargo transportation in ports, port activities, and berthed ships [76] (Figure 1). This leads to a paradigm shift from shipping companies to port authorities and operators as key actors in the sustainability of maritime transport [77]. In response, a framework called "Zero-emission Port" has been an important direction for port development in recent years.

In such a condition 3 most promising trends in power supply system modernization for port emissions reduction could be discussed:

- power system electrical efficiency increase;
- using of smart microgrid concept with renewables and an electrical energy storage system;
- implementation of cold ironing.

3.1.1 Power supply system modernization measures for port emissions reduction

Decreasing losses in the port electric power supply system means using less electrical energy from the external energy system, supplied by conventional power plants to perform the same operations in the port, and results in fewer emissions. This is the reason, why energy efficient electric power supply system is part of the Zero-emission Port strategy.

Normally, the marine port power supply system is a traditional distribution system with well-developed infrastructure and is similar to a metropolis energy supply system in terms of complexity [78]. Its structure and capacity will depend very much on the size of the port and usually consists of:

- connection to the local energy system (on middle or high voltage level);
- middle voltage distribution networks (6 – 10 kV);
- transformer substations that reduce voltage to low voltage level 380/220 V;
- low voltage distribution networks;
- connection stations for mobile electric consumers: loading machines, mooring, and portal cranes.

The marine port electrical supply system has some specific features. The distribution grid is mainly made of cable lines, which are widely used due to the impossibility of the usage of overhead lines on the port territory. Substations are one- and two-transformers. The trolley power supply is used to supply electricity to moving loads. The nature of the load is highly variable due to the operating mode of the reloading machines. The load is seasonal, which is also a specific feature of Russian ports. Consumers are normally organized in long low voltage lines, which results in large energy losses. In such a condition increase in power supply system operation efficiency has the biggest potential and is mainly associated with the decrease in energy and power losses in the port distribution grid.

3.1.2 Potential strategies to increase marine ports' electrical power supply system efficiency

As mentioned before, the main idea of the marine port zero-emission strategy is to respond to the global environmental challenge, through the continuous improvement of its energy efficiency.

An analysis by [79] showed that more than 75% of network losses are related to low-voltage lines, high-voltage lines, and distribution transformers, which are the main components of the port distribution system. Globally: up to 47% of total losses are in low-voltage networks. The load losses of the distribution transformer are up to 13% of the loss. Up to 10% of the losses are the no-load losses of the distribution transformer. up to 27% in high voltage networks; Up to 24% of total losses are in primary transformers and high voltage lines (over 110 kV).

Considering the technical characteristics of the port power system mentioned above, it can be said that these systems have a great potential to reduce power losses and optimize power supply.

Classification of power losses in distribution networks is given in [80]. The same classification can be applied to port distribution systems (Table 1).

Conventional measures to reduce power losses in distribution networks are shown in Figure 6. All of these can be implemented in ports. As mentioned above, the overall contribution to reducing emissions is not high, but without the implementation of these measures, the efficient operation of the energy supply system is not possible.

Table 1. Classification of the power losses in marine ports distribution grids.

Level 1	Level 2	Level 3	Components of Level 3
Losses	Technical Losses	Fixed Losses	Hysteresis losses Eddy current losses Dielectric losses
		Variable Losses	Ohmic losses
		Network Services	Uncontracted consumption of network equipment
	Non-Technical Losses	Network equipment issues	Theft and fraud Measurement errors
		Network information issues	Missing or unregistered connection points Incorrect location or energization status of connection points Incorrect information about measurement equipment
		Energy data processing issues	Estimation of unmetered consumption Estimation of consumptions between meter readings and calculations Estimation of technical losses Estimation of detected issues Other energy data processing issues

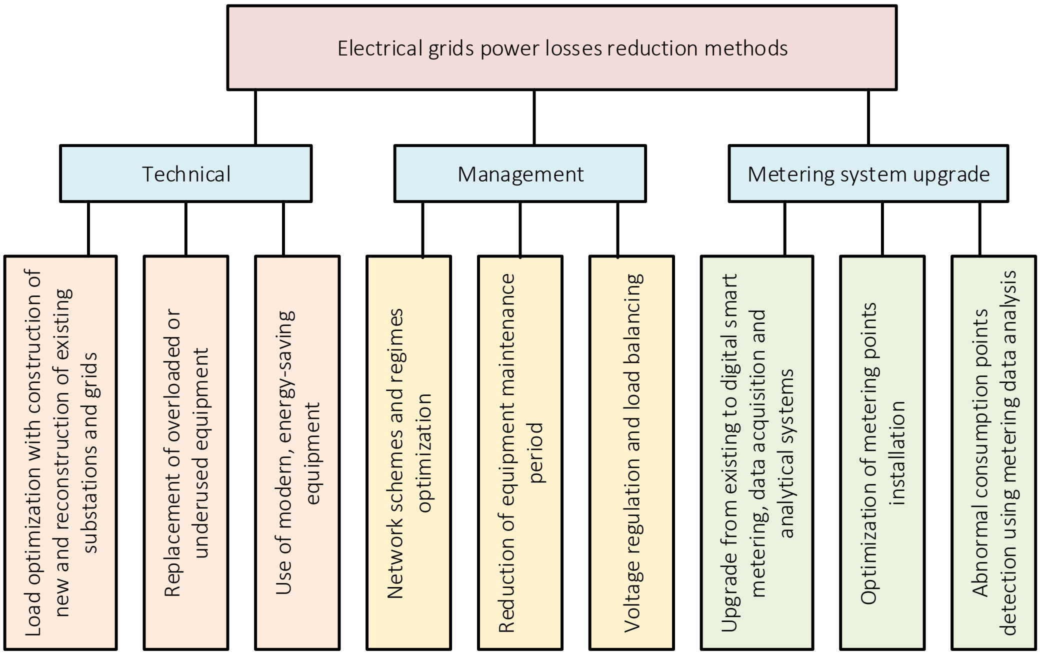


Fig. 6. Measures to reduce energy losses in the power supply system.

Management and metering system measures require the development of digital metering infrastructure and in-depth analysis of consumption data. Over the past decade, this approach has become part of the modern smart microgrid concept. A comprehensive system upgrade should be considered to implement this concept for the port distribution network.

3.1.3 Smart microgrid concept with renewables and energy storage system for Zero-emission port

A port's power supply system is usually a traditional distribution system with a well-developed infrastructure, and its complexity is similar to that of a large city's power supply system [81]. Port energy consumption has increased significantly over the past decade and will continue to increase due to operational, regulatory, and environmental factors. Managing and optimizing these systems is becoming increasingly complex. New technologies are coming to address the challenges of port sustainability and environmental compliance and achieve zero emission aims. A possible solution is to use a promising type of energy system, a "smart grid" concept (Figure 7) [82].

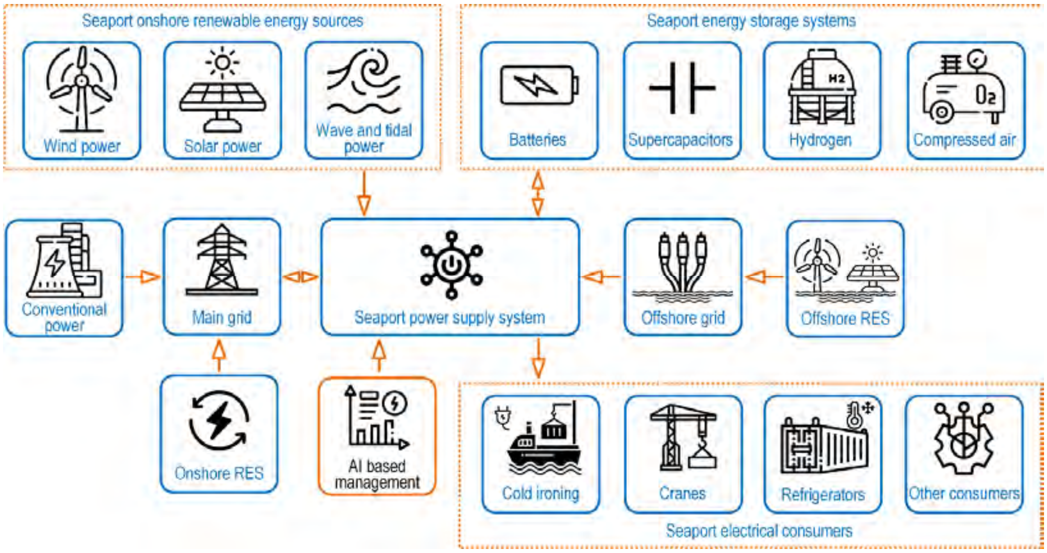


Fig. 7. Schematic diagram of marine port power supply system microgrid concept [83]

The "smart grid" concept [84] defines a self-healing network with dynamic optimization methods that use real-time measurements to reduce network losses, maintain voltage levels, increase reliability, and improve asset management. Operational data collected by the Smart Grid and its subsystems help system administrators protect against attacks, vulnerabilities, and more from a variety of unexpected situations. You can quickly recognize the best protection strategy. However, the smart grid will depend primarily on identifying and studying key performance indicators, designing and testing appropriate tools, and developing the right training programs to equip current and future workforces with the knowledge and skills needed to implement these advanced systems.

Control and distribution centers are operating a variety of renewable energy sources, including offshore wind turbines, solar energy sources (parks or buildings), wave or tidal energy based on port potential, and geothermal energy based on port capacity. The center is connected to a traditional power grid used as needed and a digital metering system (in various areas such as docks and port facilities) to monitor the port's power demand and distribute the required power.

Ensuring the normal operation of these multi-agent systems is a complex scientific and technological task and would not be possible without the introduction of a suitable electrical energy storage and storage system that balances the production and consumption of active power. We strive to minimize the exchange of energy with energy systems that serve as a backup to cover the main loads from renewable

sources. The joint operation of energy storage systems, renewable sources, and consumers requires monitoring and prediction systems that must be built based on artificial intelligence algorithms.
Surplus energy generated from renewable resources can also be converted into hydrogen. The hydrogen produced is used in electric vehicles for port services. For the moment hydrogen technologies appear to be expensive and will not be considered in the study.

3.1.4 Cold ironing as a part of the zero-emission port strategy

A "zero-emission port" concept implies environmentally friendly and sustainable operations of the port infrastructure and berths. This framework represents an important trend in port development in recent years. Emissions from shipboard auxiliary engines at a berth to supply power to vessel consumers are estimated to be ten times higher than emissions from port operations. Possibilities for their reduction are also much more significant [82]. One of the most viable options for a substantial decrease in greenhouse gas emissions at ports is the implementation of cold ironing.
Shore-to-ship electrification, also known as Cold Ironing, is an old expression from the shipping industry that first came into use when all ships had coal-fired iron-clad engines. The term cold ironing refers to the gradual cooling of the iron engines and eventually their complete cooling. This happens when a ship ties up at the port and there is no need of feeding the fire of the iron engines. Cold ironing, the meaning of shore-to-ship electrification, has been used by the military at naval bases for many years when ships are docked for long periods. For example, in Russia, such systems were introduced in the early 70s of the 20th century. As the world's vessel fleet is increasing, calls at ports are becoming more regular. Furthermore, hoteling power requirements have increased, and thus the generator emissions during docking periods have become the main air pollution issue.
In the process of developing the fleet and port infrastructure, the requirements for cold ironing systems have increased. Currently, cold ironing systems are complex structures within the port's power supply system, including its substations, converters, and cable systems. In general, cold ironing systems have the following structure and elements:

- Connection to the electrical grid and electrical energy transfer 20-100 kV to a local station when transformed to 6-20 kV.
- The energy of 6-20 kV is delivered from the local station to the port's terminal station.
- There is a frequency conversion from 50 Hz to 60 Hz, depending ship's type.
- Next distributed to all electrical connections of terminals. For safety reasons, it is required special cable handling. This mechanism could be electro-mechanic or electrohydraulic.
- Onboard the ship-specific adaptation for connection is required.
- Depending on the power of the ship, the voltage is transformed to 400 V. The transformer usually is placed in the engine room.
- The two systems are coordinated to work in parallel.

There are practical problems associated with shore-to-ship electrification related to the frequency and voltage adaptation and safety aspects.
Frequency aspects. The electricity of a ship can be 50 Hz or 60Hz according to the ship type while the frequency of the Russian, Chinese, and European Union electrical grid is constant at 50 Hz. Some equipment of many ships which is designed to operate at 60 Hz may be able to operate at 50 Hz as well. This equipment is only limited to lighting and heating and is a small amount of the total power demanded by the ship. Motor-driven equipment like pumps and cranes, will not operate at their design speed and that will lead to damaging effects on the equipment. Consequently, a ship using 60 Hz electricity will require the conversion of the frequency of the port grid from 50 Hz to 60 Hz via a frequency converter.
Voltage aspects. The difference in voltage between shore power and ship's power requires a specific onboard transformer (Fig. 8).

Safety aspects. Cold ironing produces a risk of injuries due to the requirement of direct handling of cumbersome HV cables & connectors. Health is also an issue by requiring handling of heavy loads in awkward positions, and cold ironing exposes, in the long term, quayside personnel to back injuries. Non-Compliance with National regulation, especially the European Directive 90/269/EEC3 is also an issue.
Power consumption aspects. There are a variety of onboard power demands, system voltages, and system frequency vessels when they are at berth. The vessel types usually are Container vessels, Ro/Ro- and Vehicle vessels, Oil and product tankers, and finally cruisers. The docking pattern of each kind of ship and the usage of cranes is also a problem. Additionally, Table 2 and Fig. 9 show a summary of power demand for typical types of ships.

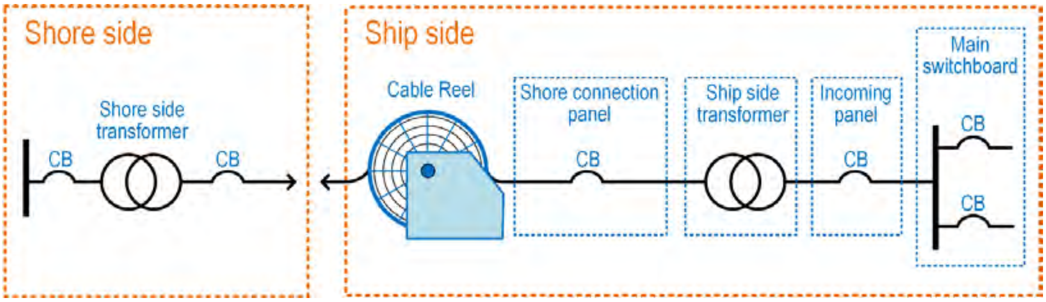


Fig. 8. General arrangement of cold ironing [85][86]

Table 2. Summary of Power Demand for different types of vessels [82]

	Average Power Demand	Peak Power Demand	Peak Power Demand for 95 % of the vessels
Container vessels (< 140 m)	170 kW	1 000 kW	800 kW
Container vessels (> 140 m)	1 200 kW	8 000 kW	5 000 kW
Container vessels (total)	800 kW	8 000 kW	4 000 kW
Ro/Ro- and Vehicle vessels	1 500 kW	2 000 kW	1 800 kW
Oil- and Product tankers	1 400 kW	2 700 kW	2 500 kW
Cruise ships (< 200 m)	4 100 kW	7 300 kW	6 700 kW
Cruise ships (> 200 m)	7 500 kW	11 000 kW	9 500 kW
Cruise ships (total)	5 800 kW	11 000 kW	7 300 kW

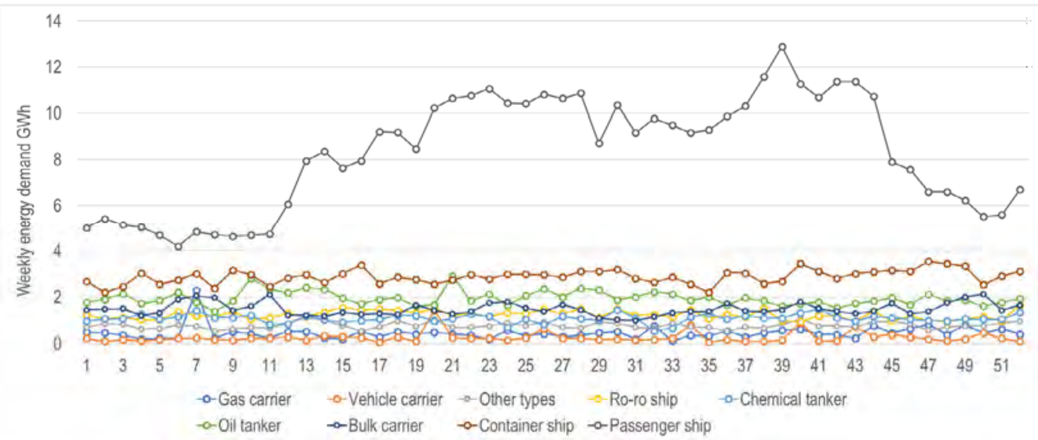


Fig. 9. Weekly energy demand of ships at berth in Italian ports (2018) [87]

To sum up, the main barriers to the implementation of cold ironing in ports are the need to reconstruct the port's electrical networks, problems with the harmonization of the voltage class and frequency of the ship and shore networks, and interaction between the port and the ship as participants in the electricity market.

Thus, the introduction of a shore power system into the existing power supply systems of ports is still a challenge.

To assess the environmental and economic benefits, prospects, main approaches, and difficulties, it is necessary to analyze the best modern practices in the field of shore-to-ship electrification using the example of a real port. In this study, the Dalian port was chosen for such an analysis.

3.2 Assessment of renewable energy source's potential

3.2.1 Evaluation criteria for the selection of renewable energy technology

Choosing the most suitable energy alternative can be a challenging issue as many criteria have to be considered, such as technical, economic, social, spatial, and environmental which may conflict with each other. So, such a selection process is usually performed using a decision-making tool based on multi-criteria analysis and AHP which is a powerful technique that handles such multiple attribute problems. Although there are many types of renewable energy sources, they may not all be suitable for a particular site or industrial sector such as a port. Based on the case study resource availability, and previous studies on the potential for the development of renewable energy sources in the port area, the following technologies have been selected for further consideration: wind turbines (onshore and offshore), solar panels (onshore and offshore) and wave devices. To select the most appropriate energy alternative for marine port electrification, this initial stage of methodology accepts that there are graduations in the five renewable energy technologies, which result from the assessment of alternatives in several parameters i.e., Evaluation criteria. Ten evaluation criteria are defined based on the international literature and the judgment of experts through interviews, as follows: (Table 3) [88-95]:

- Resource availability: Availability of renewable sources for energy production.
- Technological maturity is the degree of diffusion of technology at the regional, national and international level, and shows that a specific technology has reached the theoretical performance limit or that the technology still needs improvements.
- Know-how: Availability of specialized human resources in the region/country for installation, operation, and maintenance purposes.
- The capacity factor: is the ratio of electricity generated over some time to the energy that could have been generated in continuous full-power operation during the same period. It also shows how much useful energy can be obtained from a source.
- Investment cost: is the total cost resulting from the installation of an energy unit, including equipment, labour, infrastructure, and commissioning costs.
- O&M cost is the operating cost of the energy unit, including employees’ salaries, the cost of spare parts required for maintenance purposes, etc.
- Land requirements: Each energy unit takes up space. The already use of the (marine) space by other users may prevent the installation and license of the unit.
- Job creation: The possibility of creating employment opportunities, especially for local communities.
- Social acceptance: is the public opinion toward a type of power unit.
- Impact on the ecosystem: this is a measure of the potential impact of the energy plant on the (marine) environment.

Table 3. Evaluation criteria

Evaluation criteria	Abbreviation	Type of criterion
Resource availability	RA	Technical
Technological maturity	TM	Technical
Know-how	K-H	Technical
Capacity factor	CF	Technical
Investment cost	IC	Economic
O&M cost	O&M	Economic
Land requirements	LR	Spatial
Job creation	JC	Social
Social acceptance	SA	Social
Impact on ecosystem	IOE	Environmental

3.2.2 The analytic hierarchy process

In addition, the ten evaluation criteria may not be of equal importance. Therefore, the most important criteria should be weighted more than the others. This can be achieved through the Analytical Hierarchy Process (AHP) and the development of a pair-wise comparison matrix.

The initial stage of AHP includes developing the hierarchical structure of the selection problem, as shown in Fig. 10. The overall goal of the problem is at the top, the ten evaluation criteria in the middle, and the energy alternatives at the bottom.

The next step is the development of the pair-wise comparison matrix of evaluation criteria according to the nine-point scale of Saaty (1980) (Table 4). Through the pair-wise comparison, the preferences of decision-makers involved in the process are quantified and integrated into the modelling.

The third step is to calculate the weights of the ten evaluation criteria. The sub-steps are as follows: a) aggregate the values of each column of the pair-wise comparison matrix, b) divide each item in the table by the total sum of the column to which the item belongs (often referred to as normalized comparison matrix), c) calculate the average of the items of each row of the normalized table. The pair-wise comparison matrix and the weights of the evaluation criteria as obtained from the above steps are presented in Table 5.

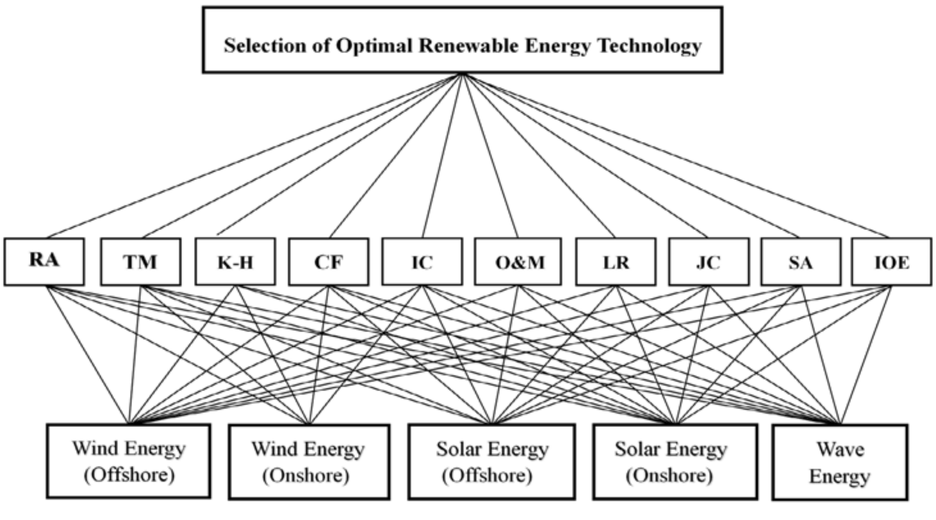


Fig. 10. Hierarchical structure for the selection of the most appropriate renewable energy sources technology

Table 4. The nine-point scale of AHP

If the criterion A is…compared to B:	Then the corresponding preference number is:
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgments

The final stage of AHP is the calculation of Consistency Ration (CR). The CR is a very useful indicator, as it secures that the judgments taken into consideration were consistent. The calculation of CR is as follows:
In the first step, the Consistency Index (CI) is calculated by the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{10.37 - 10}{10 - 1} = 0.041 \qquad (1)$$

Where n is the number of criteria and λ_max is the maximum eigenvalue. Finally, the CI is calculated as follows:

$$R = \frac{CI}{RI} = \frac{0.041}{1.49} = 0.027 \qquad (2)$$

Table 5. Pair-wise comparison matrix and weights

Criteria	RA	TM	IC	O&M	IOE	SA	LR	JC	K-H	CF	Weights (%)
RA	0.316	0.383	0.349	0.349	0.297	0.259	0.23	0.206	0.188	0.173	27.5
TM	0.158	0.191	0.232	0.232	0.223	0.207	0.191	0.177	0.164	0.154	19.4
IC	0.105	0.097	0.116	0.116	0.148	0.155	0.153	0.147	0.141	0.134	13.2
O&M	0.105	0.097	0.116	0.116	0.148	0.155	0.153	0.147	0.141	0.134	13.2
IOE	0.079	0.063	0.058	0.058	0.074	0.103	0.115	0.118	0.117	0.115	9
SA	0.063	0.048	0.038	0.038	0.037	0.051	0.076	0.088	0.094	0.096	6.3
LR	0.052	0.038	0.029	0.029	0.024	0.026	0.038	0.059	0.07	0.077	4.5
JC	0.045	0.032	0.023	0.023	0.018	0.017	0.019	0.029	0.047	0.057	3.1
K-H	0.039	0.027	0.019	0.019	0.014	0.013	0.012	0.014	0.023	0.038	2.2
CF	0.035	0.024	0.016	0.016	0.012	0.01	0.009	0.009	0.011	0.019	1.6

Where the RI is the Random Consistency Index of a random-like matrix. The CR value must not be higher than 0.1.

3.3 Selecting the type of energy storage system

It was determined in [96] that energy storage systems provide a method of converting electrical energy into a form that can be stored for energy use when needed.
In other words, the energy storage system is designed to accumulate, store and deliver electricity to the network or load to maintain the functioning of the power system with the required quality of electricity and the implementation of the necessary modes.
The use of electric energy storage devices in electric power systems opens up new opportunities for improving the quality of mode control and improving the economic performance of power systems. ESS can distribute stored energy when RES energy production is low and will help to save energy surplus when energy production is high. In addition to supporting this type of generation, ESS can also mitigate some of the problems in the conventional generation sector, such as peak reduction and energy arbitrage

[97]. ESS is a flexible power electronic device that supports the network in solving the problem of constant power supply while maintaining the quality and reliability of electricity.

Within the framework of this section, an analysis of the areas of application of energy storage devices was carried out, the types of ESS existing today were considered, and the choice of the type of storage device.

3.3.1 Analysis of ESS applications

The introduction of ESS in power grids is a smart step in solving the problems of the power system, from the large-scale application of generation and transmission networks to small-scale application of distribution networks and microgrid networks. The services offered by the ESS are numerous and are expected to develop in the future.

Possible areas of application for energy storage systems are shown in Fig. 11. Further, within the framework of this subsection, a brief description of the field of application of accumulation systems is given [98].

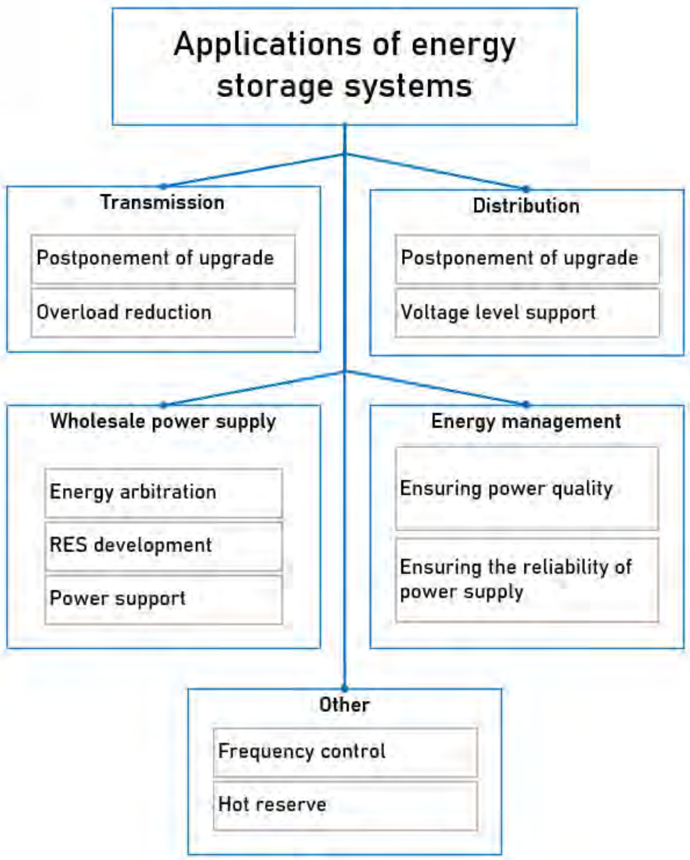


Fig. 11. Areas of application of energy storage systems

Wholesale energy supply services

The first possible storage function in this area is energy arbitrage. ESS provides flexibility by accumulating more energy during certain periods for use during peak demand to arbitrage the price of production in these two periods to ensure an even load.

Generating systems are installed according to expected peak demand. Therefore, they may be highly-priced due to the overestimation of this demand. The cost of a generator is based on its rated power and often depends on peak demand. Therefore, there are losses because demand does not peak all the time. ESS has the potential to solve this problem by providing additional power supply capacity during peak demand and reducing the need to install large generating systems.

Finally, the development of RES to solve environmental problems and provide an inexhaustible supply of energy has generated significant interest among power system engineers in integrating SNS into the system to reduce fluctuations in power output.

Electricity transmission services

The ever-growing demand for electricity leads to complication and threats to the safety of the operation of electrical networks. Expansion of networks to reduce congestion can lead to significant capital costs, including environmental ones. ESSS in this case can be a viable solution, allowing devices to be discharged during peak hours to ensure the stability of the power line, thereby postponing its modernization [98].

Electricity distribution services

Currently, the pace of development of renewable energy is increasing. The ever-growing demand for electricity leads to complications and threats to the safety of the operation of electrical networks. Expansion of networks to reduce congestion can lead to significant capital costs, including environmental ones. ESS in this case can be a viable solution, allowing devices to be discharged during peak hours to ensure the stability of the power line, thereby postponing its modernization [98].

Energy management

Power quality distortion refers to the existence of harmonics in busbar voltage and loads current, which can affect the sensitivity of some equipment [99]. As a consequence, large power losses occur and the efficiency of the system is reduced. The ESS can be integrated into flexible AC transmission system devices for reactive power compensation to reduce these harmonic signals. The use of ESS can also mitigate the problems caused by the dynamic nature of RES generation as they can serve as a compensator. Thus, the supply of high-quality electrical energy can increase the reliability of the energy system as a whole, ensuring the security of the energy supply [100].

Other services

Frequency throttling is a technique that helps maintain a certain frequency level to achieve a balance between generation and load. ESS can compensate for rapid power fluctuations in power systems integrated with RES. During transients, the ESS can dynamically adjust the network frequency by stabilizing the corner frequency [98]. High-power ESSs are suitable for providing spinning standby service because they have a fast time response to regulate the frequency to the desired level.

3.3.2 Analysis of types of energy storage systems

Direct storage of electricity in the form of alternating current is not possible. However, it is possible to convert electricity into another form of energy that can accumulate and, if necessary, be converted into electricity. Energy can be stored in many forms - mechanical, chemical, thermal, or electromagnetic. The scheme for classifying energy storage systems by type of stored energy is shown in Fig. 12.

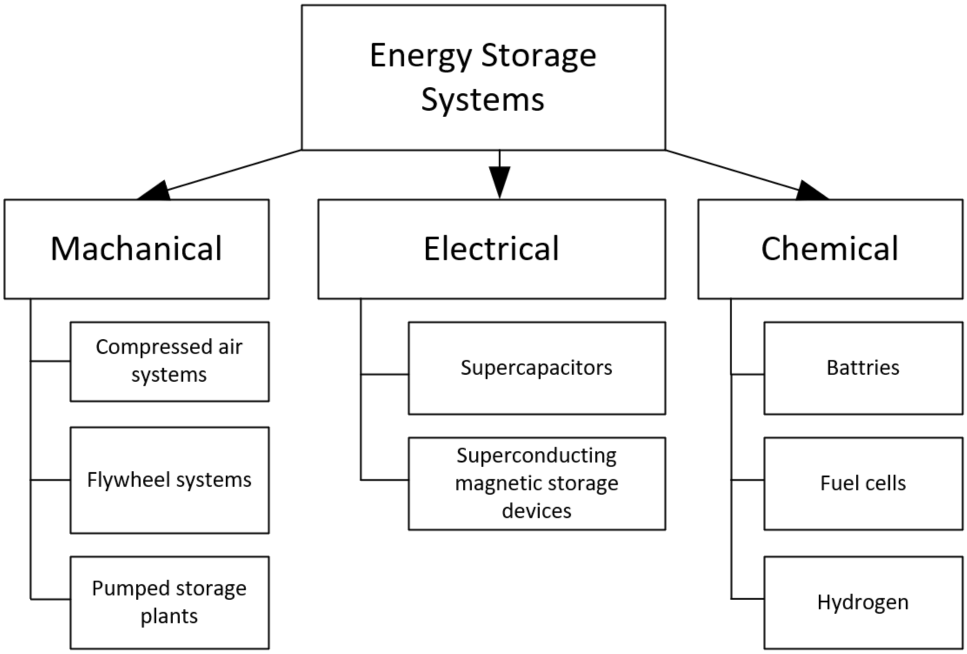


Fig. 12. Classification of modern energy storage systems

Further, within the framework of this subsection, a brief description of the currently existing energy storage technologies is given.

Superconducting magnetic storage

Superconducting magnetic storage systems (SMSS) are energy storage devices with great promise in terms of efficiency in terms of capacity and efficiency [102].

The SMSS unit is a device that stores energy in a magnetic field created by a direct current flowing through a superconducting coil. The SMSS unit consists of a large superconducting coil at cryogenic temperatures. This temperature is maintained using a cryostat or a Dewar unit containing vessels with helium or nitrogen. The power converter connects the SMSS unit to the AC mains and is used to charge/discharge the coil.

The charge/discharge/standby modes are achieved by controlling the voltage on the SMSS coil. The coil is charged or discharged by applying a positive or negative voltage to it. If there is no voltage on the coil, the system goes into standby mode.

Fig. 13 shows a diagram of an ESS built on a superconducting magnetic storage device of a solenoid type.

The main features of the system include its high energy efficiency and fast response capability (MW per millisecond), which allows the system to be used at all levels of electric power systems to solve the following problems:

– frequency support (spinning reserve) during generation loss;
– an increase of transient and dynamic stability;
– dynamic voltage support (reactive power compensation);
– improving the quality of electricity;
- increasing the capacity of power lines.

The dynamic performance of the SMSS system is far superior to other energy storage technologies. Faster and more efficient access to stored energy and shorter response times are the main benefits. But there are several problems with its large-scale application [101].
One of the main problems is the price of SMSS. Compared to other energy storage technologies, current superconducting magnetic storage systems are still expensive. However, integrating the SMSS coil into existing flexible AC transmission system devices eliminates the cost of the inverter unit, which would normally account for the majority of the cost of the entire system.
The use of high-temperature superconductors should also make SMSS cost-effective by reducing the need for cooling [103].

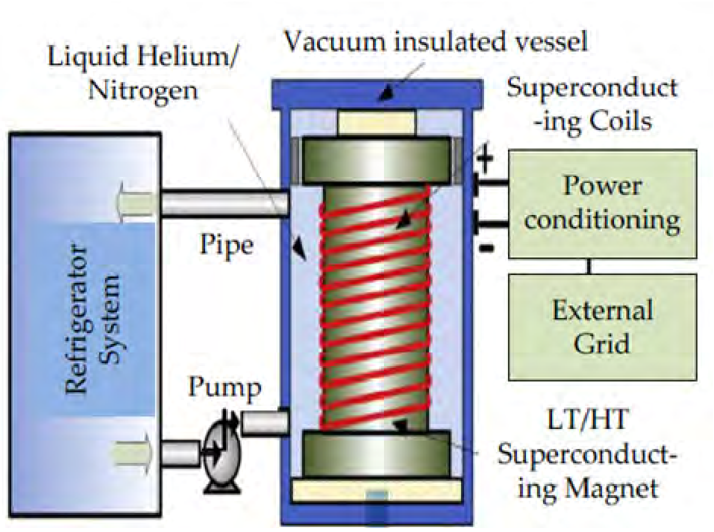


Fig. 13. Superconducting magnetic storage

Supercapacitors
Supercapacitors (SCs) are double-layer capacitors that increase energy storage capabilities due to the large increase in the surface area through the use of a porous electrolyte (they still have relatively low permeability and voltage-carrying capacity) [102].
Capacitors store electrical energy by storing positive and negative charges (often on parallel plates) separated by an insulating dielectric (Fig. 14). The capacitance is the relationship between the stored charge and the voltage between the plates. The energy stored in a capacitor depends on the capacitance and the square of the voltage. The capacitance of the SC is limited by the maximum voltage that the dielectric can withstand.
Supercapacitors provide direct storage of energy in an electric field by applying a constant voltage to the SC electrodes. This requires an appropriate power converter and a charge/discharge switch. SCs never need to be replaced because, unlike batteries, they do not undergo life-limiting irreversible chemical reactions, and unlike electrolytic capacitors, they do not experience problems with drying out [101].
It is possible to make a comparison between batteries and SC. A battery pack weighs more than twice as much as an SC of the same size, since the battery stores energy through chemical reactions, it usually takes much longer to charge it. The SC can be charged to 60-80% in just 30-60 seconds. Rechargeable batteries have 500 to 1000 life cycles. On the other hand, the SC can go through charge-discharge cycles

over 1 million times without any reduction in energy storage capacity. Incorrect installation causing reverse voltage will not damage the supercapacitor while the battery will be destroyed within a minute.

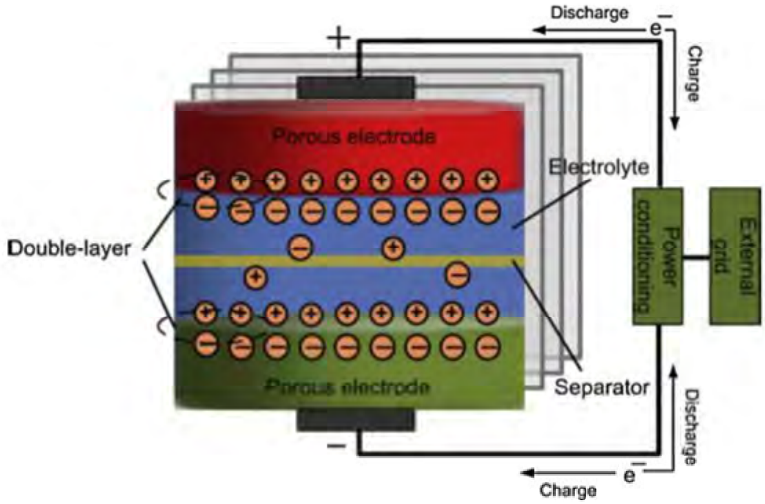


Fig. 14. Diagram of a supercapacitor

SCs are a new electrical energy storage device with an extremely high capacitance density (typical capacitors reach barely 40 pF/cm2). They have a virtually unlimited lifespan, fast charge-discharge capability, and very low leakage current.

The main areas of application of SC, based on their technical characteristics [103]:

- in power transmission and distribution systems to compensate for voltage dips;
– as large-scale storage devices that require short-term energy storage and fast response;
– in uninterruptible power supplies;
– in all other applications of drives in a hybrid system with batteries.

Compressed air energy storage systems

Compressed air energy storage systems use off-peak electricity generated by base power plants or renewable energy sources to compress air in an underground tank or above-ground tank. Most often, during periods of high electricity demand, compressed air is mixed with natural gas and the two are burned together, just as in a conventional turbine plant. This method is more efficient because compressed air loses less energy [101].

The compressed air energy storage system operates with a large motor-driven compressor that stores energy in the form of compressed air in a shaft (Fig. 15). Contraction occurs outside of periods of peak demand. The compression process cools the air before it is pumped to make the best use of the available storage space. The air is then injected at a pressure of about 75 bar.

To supply electricity to consumers, the air is taken from the cavity. First, it is preheated in the recuperator. The recuperator reuses the energy recovered by the compressor coolers. The heated air is then mixed with a small amount of oil or gas, which is burned on a burner. The hot gas from the burner is expanded in a turbine to generate electricity.

A compressed air energy storage system does not require a huge and expensive installation. In addition, greenhouse gas emissions are significantly lower than conventional gas stations. The only disadvantage of this system is that underground caverns must be searched, which significantly limits the use of this storage method. However, in places where it is possible to install it, it can become a viable option for storing energy in large quantities and for a long time [103].

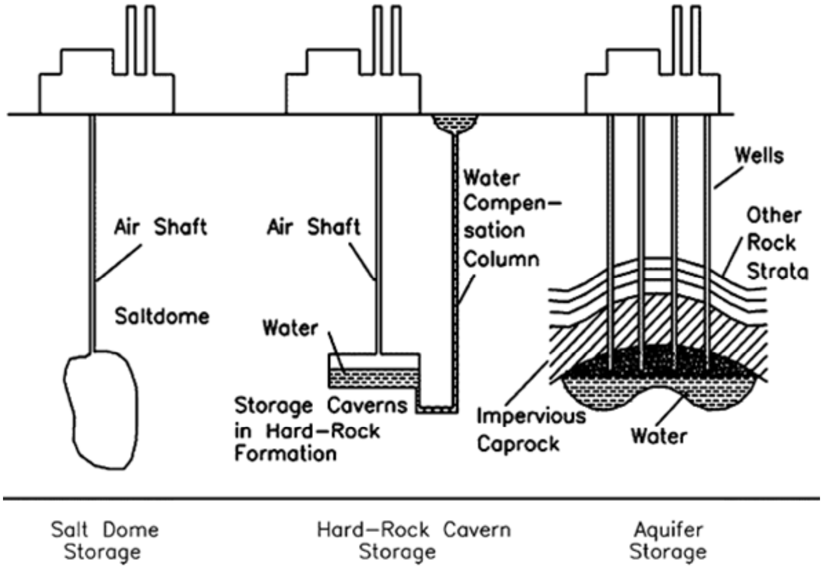


Fig. 15. Types of compressed air energy storage tanks

Flywheel Energy Storage System

Flywheel storage is an electromechanical device that connects a motor generator to a rotating mass to store energy for short periods. Conventional flywheels are charged and discharged by an onboard motor/generator. The engine or generator receives power from the mains, which are used to drive the flywheel rotor. The kinetic energy stored in the rotor is converted into DC electrical energy by the generator, and the energy is supplied at a constant frequency and voltage through an inverter and a control system. The scheme of the flywheel drive is shown in Fig. 16.

The devices store energy in the form of kinetic energy in high-speed rotors [102]. The main function of the flywheel is to smooth out fluctuations in shaft speed caused by torque fluctuations. The flywheel absorbs mechanical energy, increasing its angular velocity, and releases the accumulated energy, decreasing its speed. In most cases, a power converter is used to drive an electrical machine, providing a wider operating range. The stored energy depends on the moment of inertia of the rotor and the square of the flywheel speed.

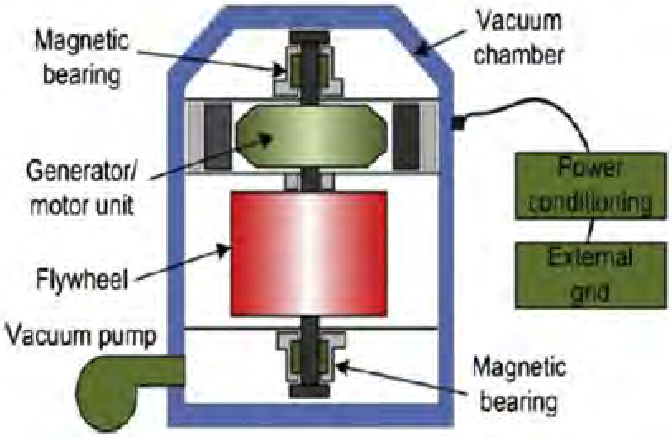


Fig. 16. Energy storage system with a flywheel

A flywheel energy storage system is a short-term energy storage method that is generally sufficient to improve power quality compared to other storage methods.

The systems have a long service life (from 105 to 107 cycles of use), high energy density (100-130 Wh/kg), and high maximum power. Typical capacity ranges from 3 to 33 kWh. The system is fast charged in less than 15 minutes. The overall efficiency of the flywheel drive, including electronics, bearings, and flywheel, is 80-85%. With a life expectancy of around 20 years, current flywheel designs are modular and can vary in size up to systems of 10 MW or more.

Fuel cells

A hydrogen fuel cell is an energy conversion device that is comparable in principle to a battery. Both are electrochemical devices for converting chemical energy into electrical energy. In a battery, chemical energy is stored internally, while in a fuel cell, chemical energy (fuel and oxidizer) comes from outside and can be constantly replenished [102].

The overall reaction in a fuel cell is the spontaneous reaction of hydrogen and oxygen to produce electricity in the water. During fuel cell operation, hydrogen is ionized into protons and electrons at the anode, hydrogen ions are transported through the electrolyte to the cathode using an external circuit (load). At the cathode, oxygen combines with hydrogen ions and electrons to form water. The operation diagram of a hydrogen fuel cell is shown in Fig. 17.

The hydrogen fuel cell system can be reversible, allowing electricity to be consumed to produce hydrogen, and this hydrogen can be stored for later use in the fuel cell.

Today, several types of fuel cells can be characterized by the electrolyte used as well as the operating temperature. Hydrogen is the fuel required for all low and medium-temperature fuel cells, alkaline fuel cells, proton exchange membrane fuel cells, and phosphoric acid fuel cells.

The instability of hydrogen and the small size of its atomic size make the hydrogen storage tank a critical element in this device. Currently, hydrogen fuel cell systems are becoming one of the most sought-after energy storage technologies to solve the problem of integrating renewable energy sources. Price and overall effectiveness are its main limitations.

Batteries

Batteries belong to the category of devices that convert chemical energy, which is formed as a result of electrochemical reactions, into electrical energy and vice versa (Fig. 18). There is a wide range of technologies used in the manufacture of batteries (lead-acid, nickel-cadmium, nickel-metal hydride, nickel-iron, zinc-air, iron-air, sodium-sulphur, lithium-ion, lithium-polymer, and others).

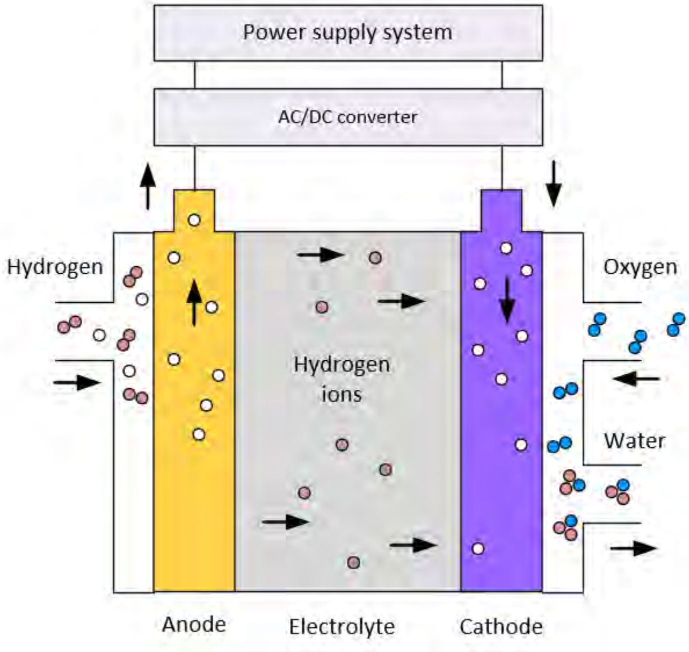


Fig. 17. Scheme of a hydrogen fuel cell

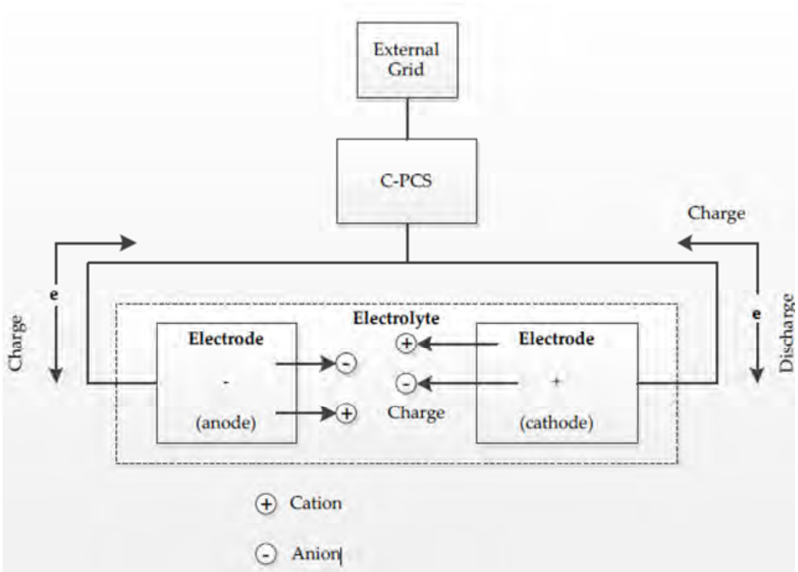


Fig. 18. Scheme of the battery

The main advantages of batteries are high energy density (up to 2000 Wh/kg for lithium) and technological maturity.

However, the main inconvenience of batteries is their relatively low durability at large amplitudes in charge-discharge cycles (from several hundred to several thousand cycles).

Batteries are used both in portable energy storage systems and in power systems for redundancy in networks, storage of RES energy, and solving other problems.
The minimum discharge period of electrochemical batteries rarely reaches less than 15 minutes. However, depending on the application, the power density can reach 100 W/kg or even several kW/kg for a few seconds or minutes.
Unlike capacitors, the voltage of batteries remains stable depending on the level of charge. However, the ratio of voltage during the accumulation of energy into the network at a practically maximum charge level and the output of energy into the network at a low charge level can reach two.
The class of accumulator batteries also includes flow batteries [103]. Flow batteries are a dual-electrolyte system in which the chemical compounds used to store energy are in a liquid state in a solution with an electrolyte. They overcome the capacity limitations of standard electrochemical batteries (such as lead-acid or nickel-cadmium batteries), in which solid compounds are formed as a result of electrochemical reactions, and deposited directly on the electrodes [104].
Various types of electrolytes have been developed using bromine as the center element: zinc (ZnBr), sodium (NaBr), vanadium (VBr), and, more recently, sodium polysulfide. The reversibility of the charge-discharge cycle is ensured by the presence of a membrane (porous lining) [105].
By using large reservoirs and connecting a large number of cells, large amounts of energy can be stored and then released by pumping the electrolyte into the reservoirs (Fig. 19).

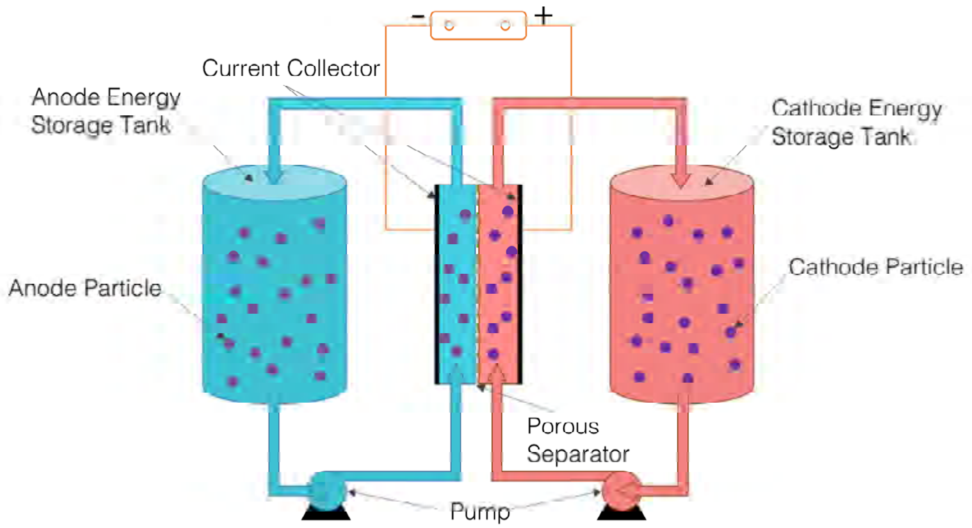


Fig. 19. Diagram of a flow battery

3.4 Sizing of Hybrid Renewable Energy System elements for Zero-emission port

The intention is that 100% power for all ports from renewable sources, and thus the power availability and the weather conditions should be carefully examined.
A hybrid energy system using various RES together with ESS and backup units can provide a cost-effective and reliable energy solution as well as low emissions [106]. However, due to the non-linear response of system components and the random nature of RES and load profiles, smart grids are used to coordinate and integrate these devices to transport power through the system as efficiently and economically as possible [107].
In this case, an optimization algorithm will be very helpful to optimize the size of the power storage devices and the renewable sources. Furthermore, a power management algorithm can provide optimization of the power balance between renewable sources, storage devices, and the electrical grid.

It can also perform optimum scheduling of the storage devices to increase the lifetime of such devices as batteries, decreasing maintenance costs and increasing the overall profit in the power market.

One of the main challenges of recent research is to optimize hybrid renewable energy system (HRES) components to meet load requirements at the lowest possible cost and highest reliability. Considering the complexity of HRES optimization, it was necessary to find an efficient optimization method to obtain accurate optimization results. The Particle Swarm Optimization (PSO) algorithm is proposed as one of the most valuable and promising HRES optimization methods because it uses the global optimum to find the optimal solution [108].

The PSO algorithm is based on swarm intelligence and is used to solve complex optimization problems [109]. Like other population-based optimization algorithms, PSO starts with the random initialization of particles in the search space. Each particle is initially invested with a random position and velocity, then adjusts its search pattern based on its own and other individuals' experiences [120]. Due to their simplicity, efficiency, and low computational cost, PSOs have become much more popular and improved [111].

The zero-emission port energy system for most reasons operates as a hybrid renewable energy system, meaning, the same approach and methods could be used for optimization.

3.4.1 Zero-emission port hybrid renewable energy system model elements description

The schematic drawing of the Zero-emission port hybrid renewable energy system model is shown in Figure 20. It consists of wind turbines (WT), a PV array, and an electrical storage system with a battery controller to charge the battery bank from the respective WT and PV array. Port's system is directly connected to a regional energy system, powered by traditional power stations. Finally, a group of ports traditional loads, and berthed ships, using cold ironing represented as part of the load.

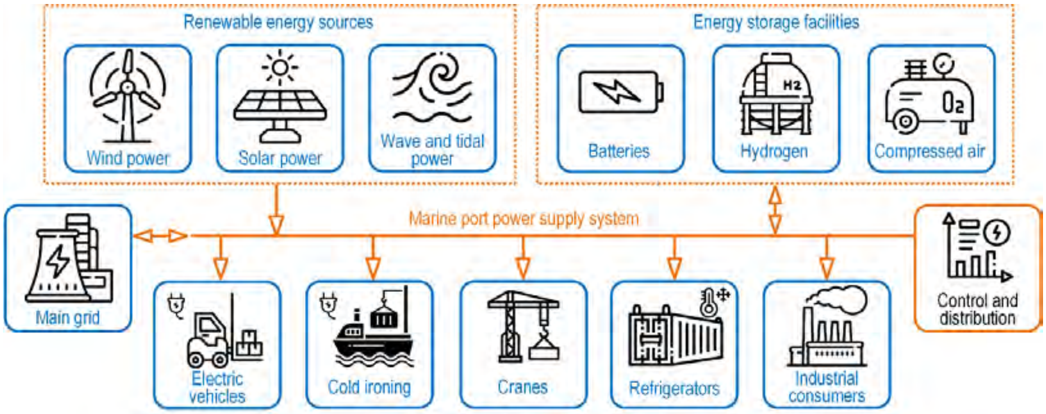


Fig. 20. Simplified diagram of Zero-emission port hybrid renewable energy system model

Let us discuss in more detail the submodules of the system:

Wind power.

The wind speed at the height of the wind turbine (WT) hub is calculated as a power law equation using the wind speed data collected at the height of the anemometer as follows:

$$\mathrm{u}(h) = \mathrm{u}(h_g)\left(\frac{h}{h_g}\right) \tag{3}$$

where $\mathrm{u}(h)$ and $\mathrm{u}(h)$ - wind speeds at hub height (h) and anemometer height (h_g), α - roughness factor.

Wind turbine power output power depends on wind speed:

$$P_W(u) = \begin{cases} 0,\ u < u_c\ or\ u > u_f \\ P_r \frac{u^2 - u_c^2}{u_r^2 - u_c^2},\ u_c \le u \le u_r \\ P_r,\ u_r \le u \le u_f \end{cases} \tag{4}$$

where, P_W is the WT output power, P_r is the rated output power of WT, u_c is the cut-in wind speed, u_r is the rated wind speed, and u_f is the cut-off wind speed.

Weibull parameters and a capacity factor used for WT power production at a certain site:

$$P_{WT,av} = C_p \times P_r \tag{5}$$

$$C_F = \frac{\exp\left[-\left(\frac{u_c}{c}\right)^k\right] - \exp\left[-\left(\frac{u_r}{c}\right)^k\right]}{\left(\frac{u_r}{c}\right)^k - \left(\frac{u_c}{c}\right)^k} - \exp\left[-\left(\frac{u_f}{c}\right)^k\right] \tag{6}$$

where, $P_{WT,av}$ is WT average power, C_F is the WT capacity factor, c, and k are the Weibull parameters of WT, which can be calculated using different statistical analysis methods. The existing series of yearly wind speed data at the point of WT installation also can be used for calculation, if available. Wind series time resolution can affect the speed of calculation, but hourly data are of common use.

PV array.

The solar radiation on the tilted surface (H_t) can be estimated considering the solar insolation, ambient temperature, manufacturer's data of the PV panels, the slope of the PV panels, and latitude and longitude of the site. The output power of the PV array (P_{PV}) is calculated as expressed in the following equation:

$$P_{PV} = H_t \times PVA \times \mu_c(t) \tag{7}$$

where, $\mu_c(t)$ is the instantaneous PV cell efficiency, PVA is the total solar cells area required to supply the load demand and can be calculated from the following equation:

$$\text{PVA} = \frac{1}{24} \sum_{t=1}^{24} \frac{P_{L,av}(t) F_s}{H_t \mu_c(t) \eta_{pc} V_F} \tag{8}$$

where, F_s is the safety factor which includes the possible allowance of insolation data inaccuracy, y_F is the factor of variability which considers the impact of yearly radiation variation, their values are around land 0.95, respectively. η_{pc} is the power conditioning system efficiency.

Energy Storage System.

The battery state of charge (SOC) after a certain time (t) is calculated based on the energy balance between the wind, PV, energy system, and the load:

$$E_B(t+1) = E_B(t)(1-\sigma) + surpluspower \times \eta_{BC} \quad \text{Charging mode} \tag{9}$$

$$E_B(t+1) = E_B(t)(1-\sigma) - deficit\,\text{power}/\eta_{BD} \quad \text{Discharging mode} \tag{10}$$

where, E_B is the energy of the battery, η_{BC} and η_{BD} are the charging and discharging efficiency of the battery, σ is the battery self-discharge rate; usually 0.2% per day.

Other elements.

A regional energy system can be represented as an infinite short circuit source, balancing the ports system.

Port operation loads simply can be presented as time series, provided by the system operator. Berthed ships, connected to the grid and operating as part of cold ironing solution can be presented also as time series dependent on the number and type of ships connected to the system.

3.4.2 Cost estimation of system model elements operation

Cost estimation is created based on the concept of levelized energy cost (LEC). LEC is a standout amongst the most well-known and utilized indicators of economic analysis of HRES and it can be calculated from the following:

$$\text{LEC} = \frac{TPV \times CRF}{LAE} \tag{11}$$

where TPV is the total present cost of the entire system, LAE is the annual load demand, and CRF is the capital recovery factor. CRF and TPV are expressed as shown in the following equations:

$$\mathrm{CRF} = \frac{r(1+r)^T}{(1+r)^T-1} \tag{12}$$

$$\mathrm{TPV} = \mathrm{IC} + \mathrm{OMC} + \mathrm{RC} + \mathrm{ESC} - \mathrm{PSV} \tag{13}$$

where r is the net interest rate, T is the system lifetime in years and IC is the initial capital cost of the HRES components, the latter can be determined from the following equation:

$$\mathrm{IC} = 1.4 \times PV_P \times C_{PV} + 1.2 \times WT_P \times P_R \times \mathrm{NWT} + E_{BR} \times B_P + P_{inv} \times INV_P + P_{ESr} \times \mathrm{ES}_p \tag{14}$$

where PV_P is the PV price per kW ($/kW), C_{PV} is the rated power of the PV system (kW), WT_P is the WT price per kW ($/kW), E_{BR} is the battery capacity (kWh), B_P is the battery bank price per kWh ($/kWh), INV_P is the inverter price per kW ($/kW), and ES_P is the price per kW ($/kW) from the regional energy system.

OMC is the operation and maintenance cost of the HRES segments and can be resolved as this:

$$\mathrm{OMC} = \mathrm{OM}C_0\left(\frac{1+i}{r-i}\right)\left(1-\left(\frac{1+i}{1+r}\right)^T\right),\ \mathrm{r} \neq i \tag{15}$$

$$\mathrm{OMC} = \mathrm{OM}C_0 \times T,\ \mathrm{r} = \mathrm{i} \tag{16}$$

RC is the replacement cost of the HRES components and can be determined as:

$$\mathrm{RC} = \sum_{J=1}^{N_{rep}}\left(C_{RC} \times C_U \times \left(\frac{1+i}{1+r}\right)^{\tau \mathrm{J}/(N_{rep}+1)}\right) \tag{17}$$

where i is the inflation rate of replacement units, C_{RC} is the capacity of the replacement units, C_U is the cost of replacement units, and N_{rep} is the number of unit replacements over the project lifetime T.

ESC is the regional energy system cost and can be calculated as:

$$\mathrm{ESC} = D_f(\mathrm{t})\mathrm{D}G_h P_f \tag{18}$$

where, ES_h is the total operating hours of the DG during T and P_f is the tariff price per kWh ($/kWh).

PSV is the present value of scrap and can be expressed in terms of the value of a scrap of the system components (SV) as:

$$\mathrm{PSV} = \sum_{J=1}^{N_{rep}+1} S\mathrm{V}\left(\frac{1+i}{1+r}\right)^{\tau \mathrm{J}/(N_{rep}+1)} \tag{19}$$

3.4.3 Optimization approach

Hybrid PV/wind/battery/energy system sizing is formulated as an optimization problem and an objective function is formulated as a function of system constraints and performance.

The objective function of the optimization problem is to minimize the overall system cost TPV (X). $TPV(X)$ incorporates capital cost $IC(X)$, operation and maintenance cost $OMC(X)$, the replacement cost $RC(X)$, and the cost of the energy system connection and operation (ESc), throughout the lifetime of the installed system. The system lifetime is assumed to be 25 years. The objective function for optimally designing the HRES must be minimized as:

$$\min_X TPV(X) = \min_X\{IC(X) + OMC(X) + RC(X) + ESc\} \tag{20}$$

where, X is the vector of sizing variables; $X = NWT$, PVA, and E_{BR}.

To solve the optimization problem, a set of constraints must be satisfied with any feasible solution throughout the system operations. Such constraints for example can include the maximum and minimum capacity of WT and PV array, based on analysis of available place for installation in specific port for example, and so on.

A detailed description of the PSO problem-solving algorithm is given in [112, 113], figure 21. Python realization of the minimum viable product of such optimization is given in the appendix to the report.

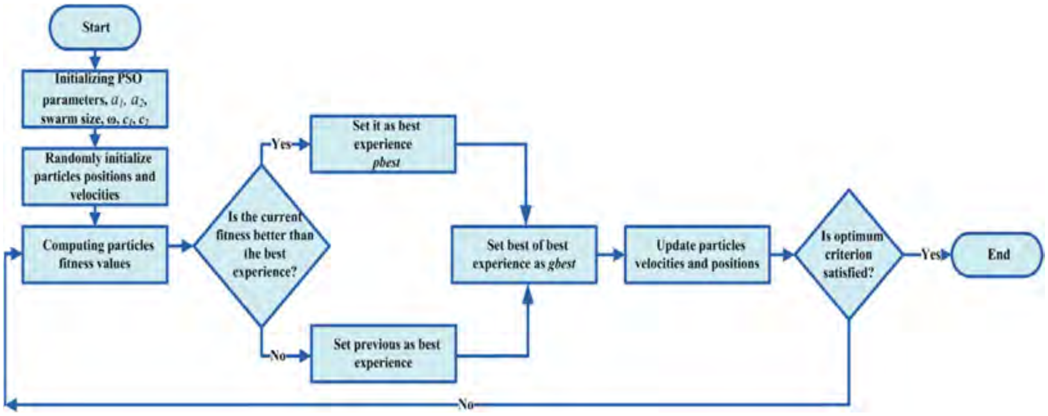


Fig. 21. The process of the PSO algorithm realization

4. Case study calculation

4.1 Justification for selecting a port as case study research

4.1.1 Analysis of port options from the regions of the project participants

Choosing the right object for a case study is an important step in the research. For a port to meet the objectives of the study and allow testing of the approaches being developed within the framework of the zero-emission pore concept, it must meet several criteria:

- the port must be a major maritime center in its region;
- port information should be available for analysis;
- the port should develop dynamically;
- the port should not comply with the concept of zero-emission but should have the potential to develop this concept.

Taking into account the established criteria, as a result of the analysis of ports in the regions of the project participants, three ports were identified that have the potential to be considered within the framework of this project as a case study (Fig. 22):

- port of Kaliningrad, Russian Federation;
- port of Dubrovnik, Croatia;
- port of Dalian, China.

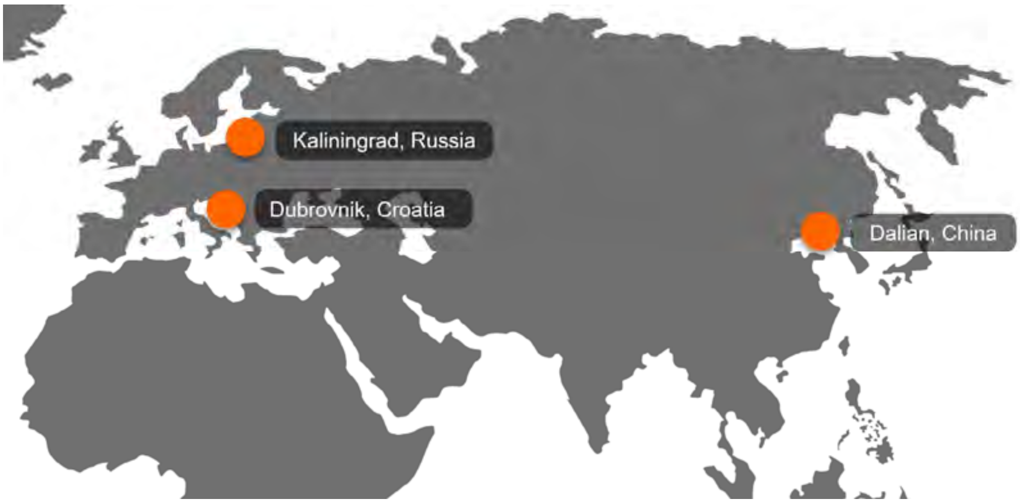


Fig. 22. Geographical location of ports under consideration

The port of Kaliningrad

The port of Kaliningrad (Fig. 23) is a Russian port on the southeastern coast of the Baltic Sea, the only non-freezing port of Russia in the Baltic. The port has an advantageous position. The distance to the capitals of neighboring states - Vilnius, Riga, Minsk, Warsaw, Berlin, Copenhagen, and Stockholm is from 315 to 1460 kilometers, and the largest foreign ports in the Baltic - are from 67 (Gdansk) to 730 (Oulu) nautical miles. The port of Kaliningrad is connected by container lines with the ports of the Netherlands, Great Britain, Germany, Poland, Finland, Latvia, Estonia, Sweden, Denmark, Norway, France, and Lithuania.

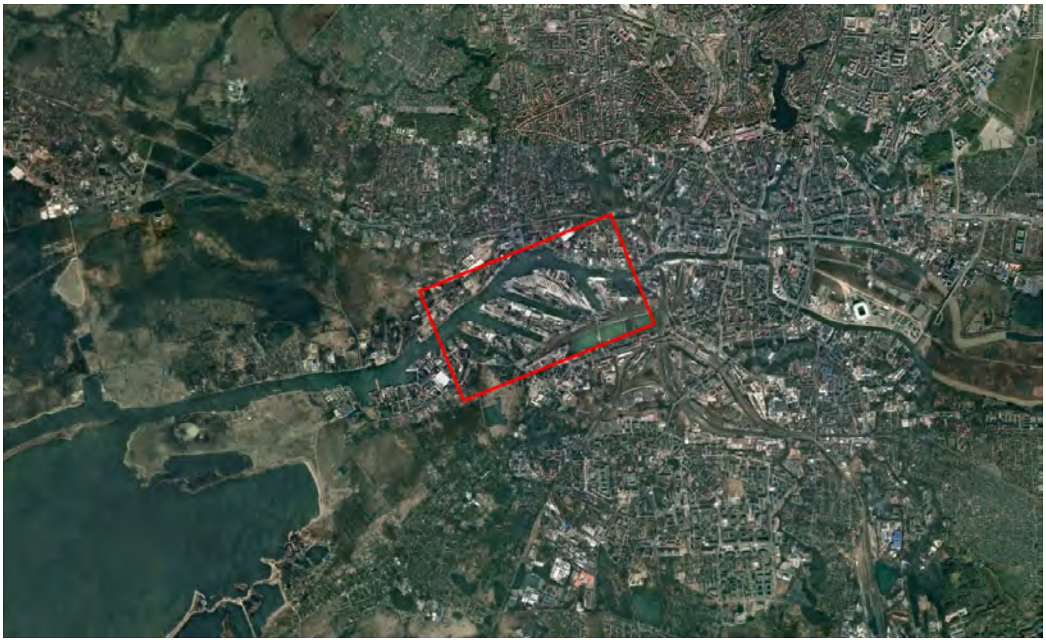


Fig. 23. The port of Kaliningrad location on the satellite map

The port of Kaliningrad is geographically divided into four cargo areas: the Kaliningrad cargo area, the Svetlovsky cargo area, the Baltic cargo area, and the remote Pionersky cargo area. The berths of the port, with a total length of 17 km, are located on the northern side of the Kaliningrad Sea Canal, as well as at the mouth of the Pregolya River with adjacent harbors. 17 different stevedoring companies provide cargo transshipment services: oil products, coal, coke, timber, and timber products (lumber, plywood, pulp, paper), ferrous metals, ferroalloys, mineral fertilizers (liquid, in bulk, and various packages), grain cargoes. The main product exported and imported through the port is rolled metal. Another 5 new terminals are under construction and design development.

The port of Dubrovnik

Dubrovnik is located in the far south of the Republic of Croatia and Dubrovnik-Neretva County. The port of Dubrovnik – Gruž (Fig. 24) is located on the north coast of the gulf and the east coast of the Gulf of Rijeka and has 1629 m of built coast and 829 m of undeveloped coast. Port of Dubrovnik - Gruž is an important transport hub for local, regional, and international maritime passenger traffic of the southern Adriatic. The most significant number of arrivals is the traffic of liner passenger vessels, while the total number of passengers is dominated by the segment of cruise passengers.

The port of Dalian

The Port of Dalian founded in 1899 lies at the southern tip of Liaodong Peninsula in Liaoning province and is the most northern ice-free port in China. It is also the largest multi-purpose port in Northeast China serving the seaports of North Asia, East Asia, and the Pacific Rim. It is the trade gateway to the Pacific. It is the second largest container transshipment hub in mainland China and the city of Dalian is categorized as a Large-Port Metropolis using the Southampton system for port-city classification.

The Port of Dalian (Fig. 25) is located on the Yellow Sea. The port covers a water area of 346 square km and a land area of nearly 15 square km. There are 160 km of specialized railway lines, 300 square km of warehousing, 1,800 square km of stacking yards, and over 1,000 units of different types of loading and discharging machinery and equipment. The port has 80 modern berths in production. Out of these 38 are deep water berths for vessels of over 10,000 tons deadweight.

As an important transportation hub in Northeast Asia, Dalian Port is the Chinese largest loose beam, oil import, and export port and an important foreign trade port. It has modern professional berths for grain, ore, containers, petrochemicals, and bulk cargo. More than 10,000 ships are entering and leaving the port every year, and it has established trade relations with more than 160 countries and regions and more than 300 ports in the world.

Fig. 24. The port of Dubrovnik location on the satellite map

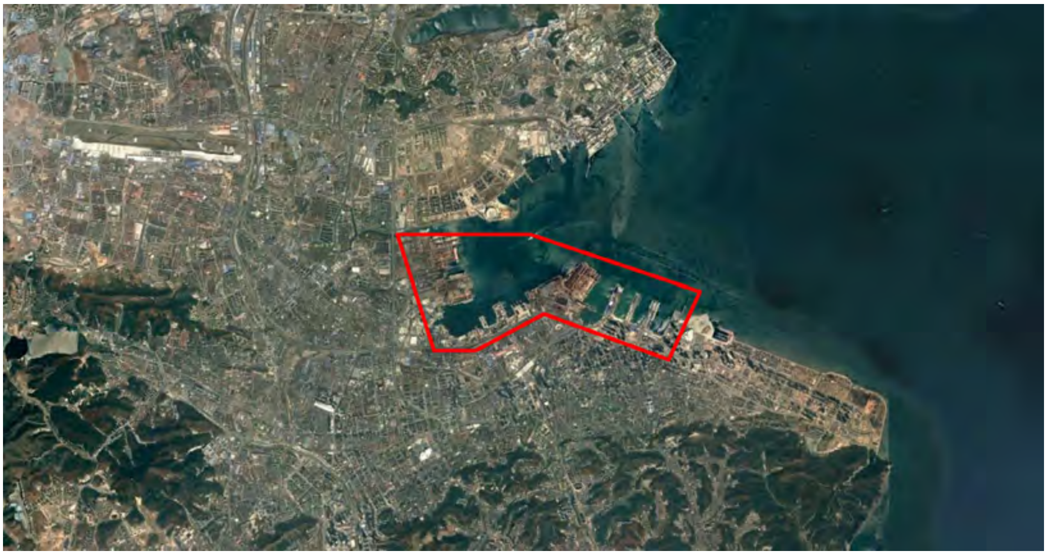


Fig. 25. The port of Dalian location on the satellite map

4.1.2 Analysis of the environmental factors

Climatic conditions in the area of the seaport have a significant impact on the functioning of its power supply system and the prospects for the introduction of renewable energy sources. The most common factors are temperature, wind speed, and insolation in the port area. Temperature changes affect the power consumption of the port, in particular heating systems and refrigeration equipment. Data on wind speeds and insolation make it possible to assess the renewable energy potential available for development. At the same time, it is necessary to take into account both average indicators and the variability of a renewable resource over time, since the construction of a zero-emission port according to the microgrid principle involves continuous learning of the balance of consumption and production of electrical energy.

The port of Kaliningrad. The results of the analysis of data on changes in temperature, wind speed, and insolation for the area of the port of Kaliningrad are shown in Fig. 26-31.

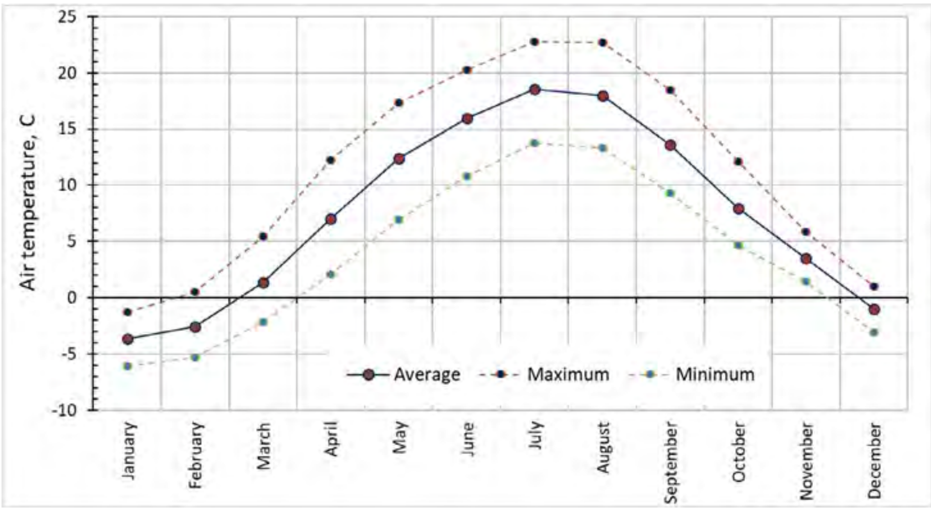


Fig. 26. Air temperature variations in the port of Kaliningrad

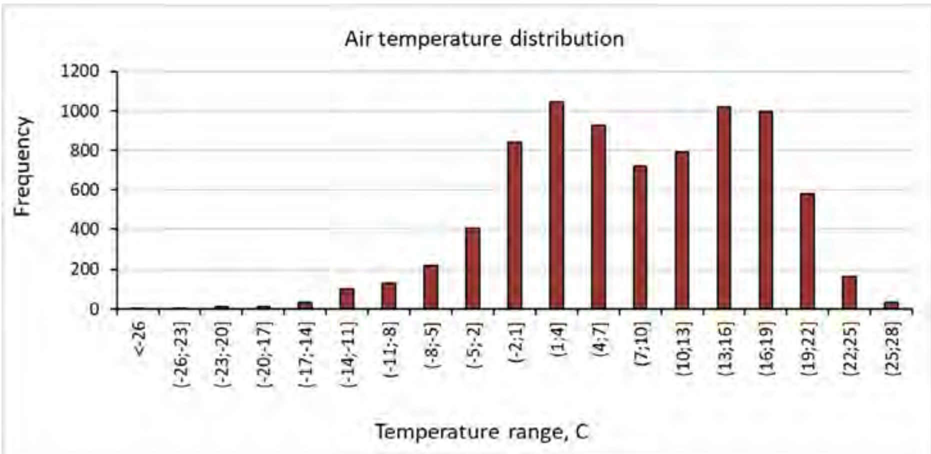


Fig. 27. Analysis of the annual air temperature distribution in the port of Kaliningrad

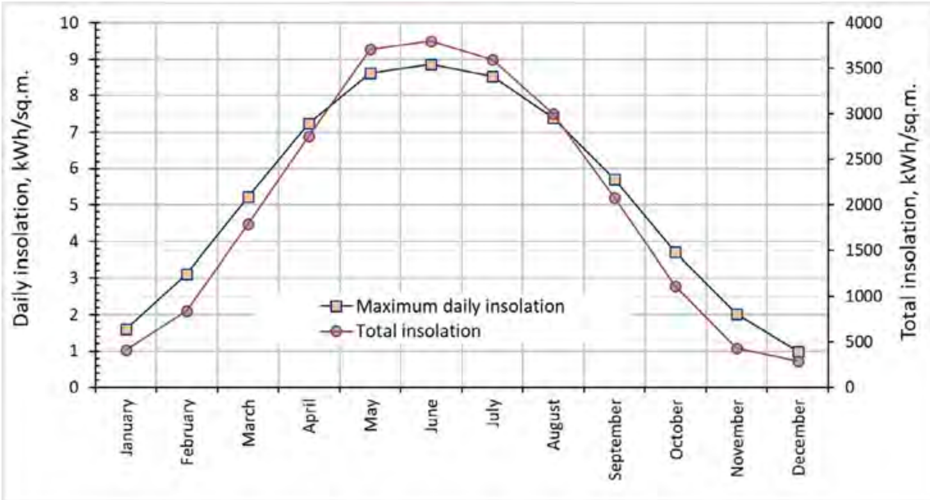


Fig. 28. Insolation variations in the port of Kaliningrad

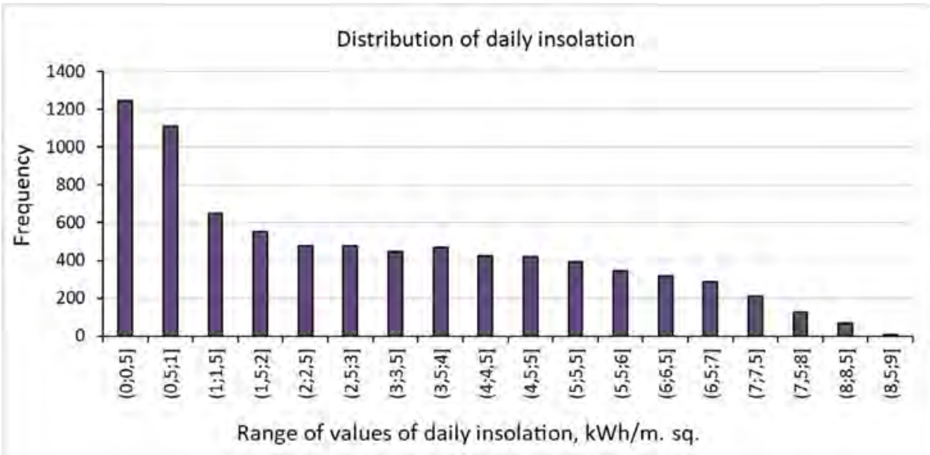


Fig. 29. Analysis of the annual insolation distribution in the port of Kaliningrad

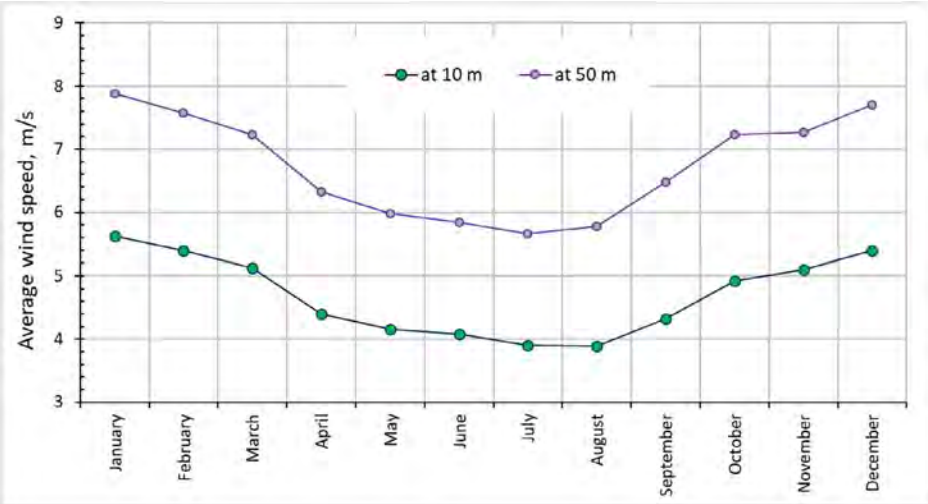


Fig. 30. Wind speed variations in the port of Kaliningrad

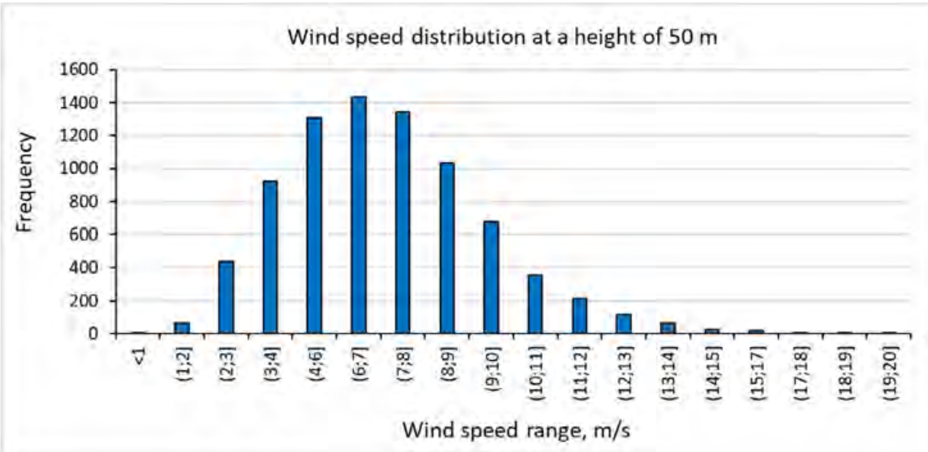


Fig. 31. Analysis of the annual wind speed distribution in the port of Kaliningrad

The port of Dubrovnik. The results of the analysis of data on changes in temperature, wind speed, and insolation for the area of the port of Dubrovnik are shown in Fig. 32-37.

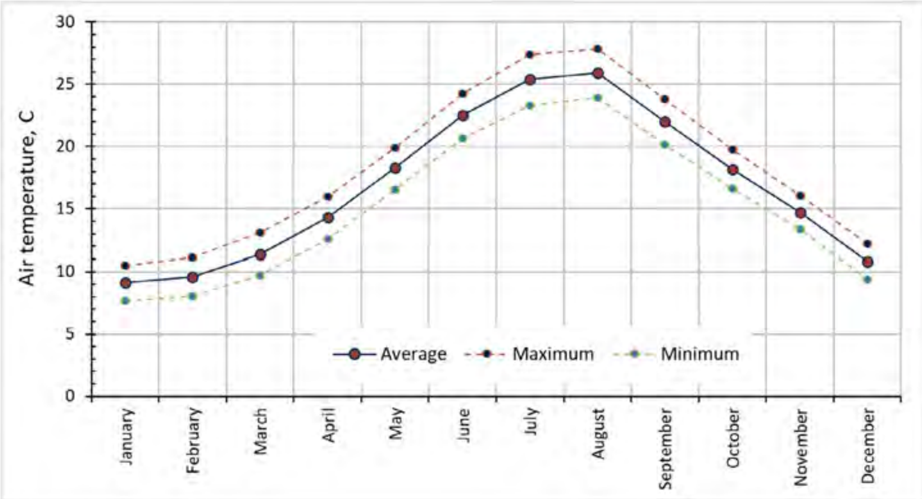


Fig. 32. Air temperature variations in the port of Dubrovnik

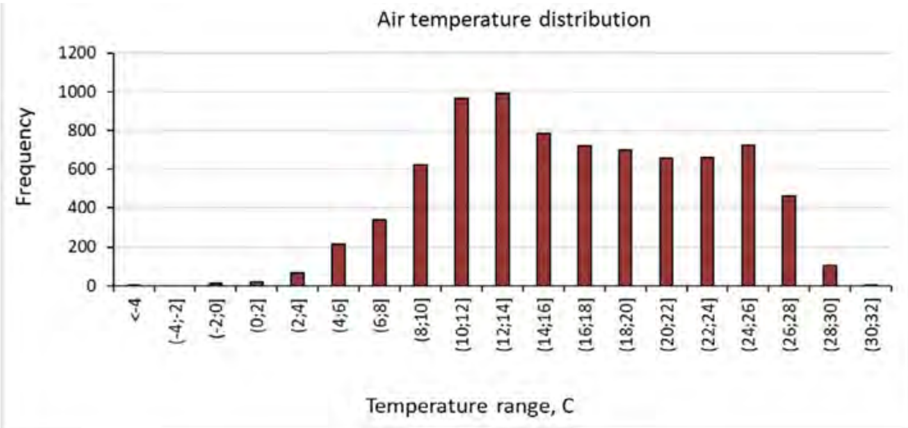


Fig. 33. Analysis of the annual air temperature distribution in the port of Dubrovnik

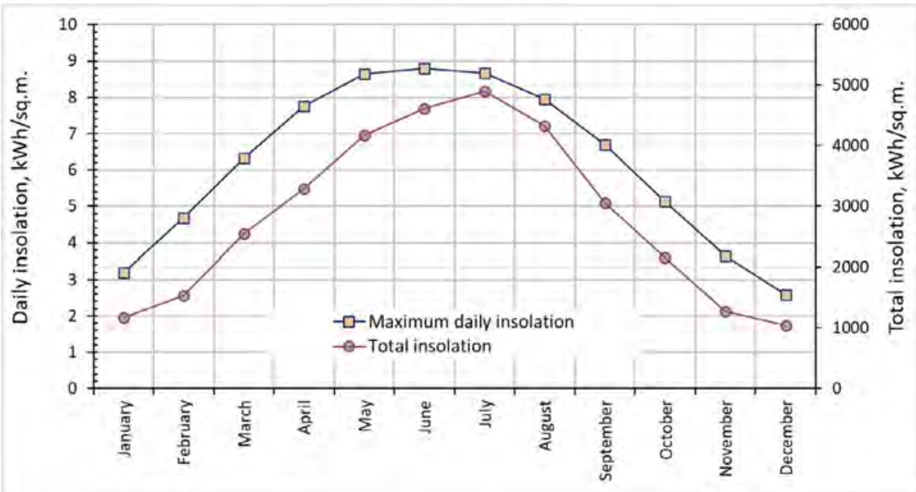


Fig. 34. Insolation variations in the port of Dubrovnik

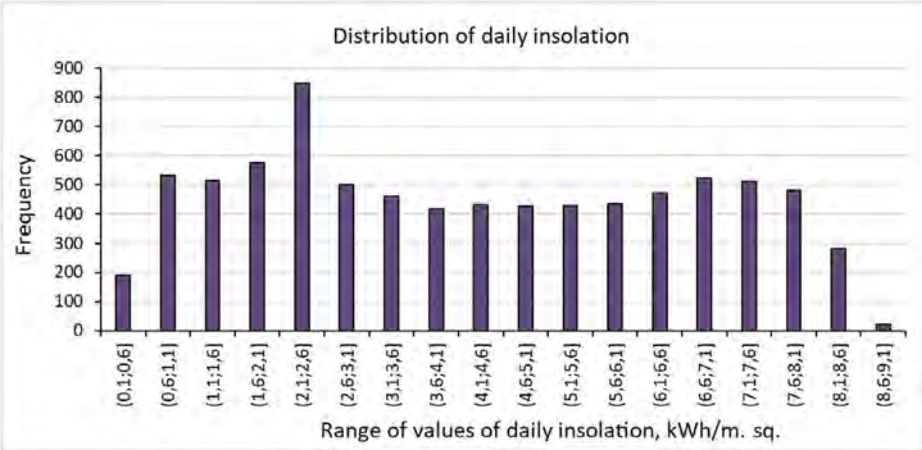


Fig. 35. Analysis of the annual insolation distribution in the port of Dubrovnik

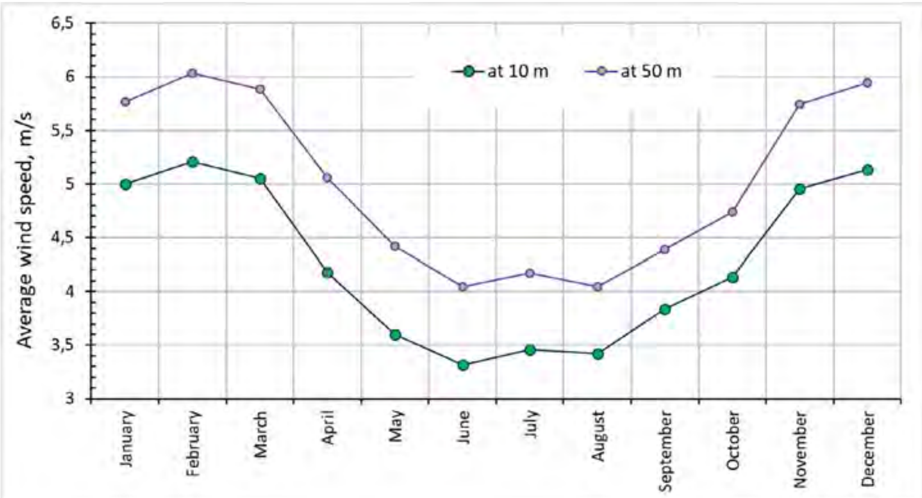


Fig. 36. Wind speed variations in the port of Dubrovnik

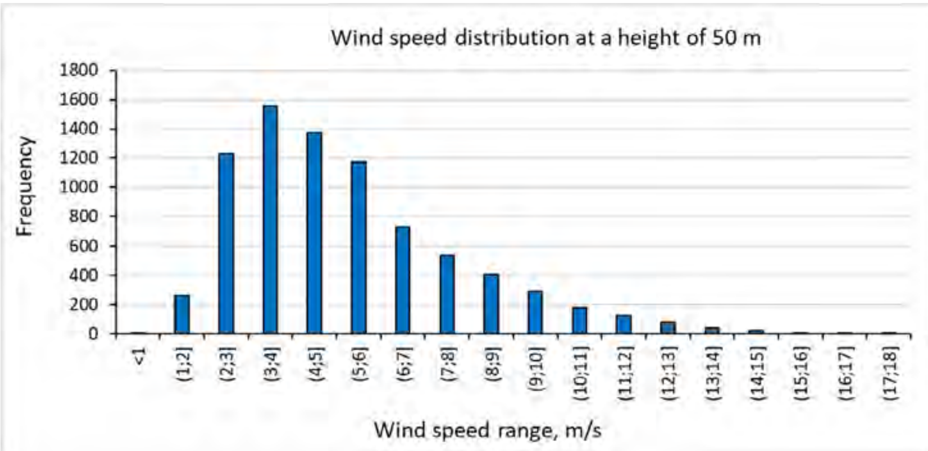


Fig. 37. Analysis of the annual wind speed distribution in the port of Dubrovnik

The port of Dalian. The results of the analysis of data on changes in temperature, wind speed and insolation for the area of the port of Dalian are shown in Fig. 38-43.

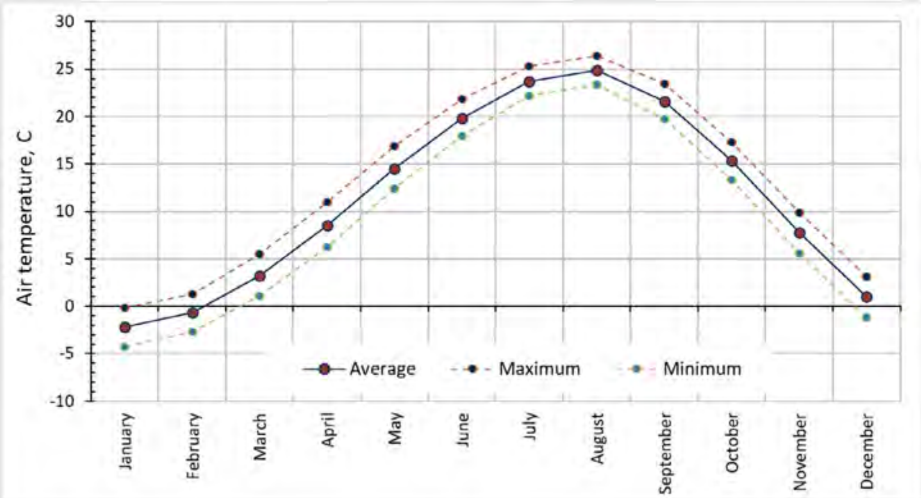


Fig. 38. Air temperature variations in the port of Dalian

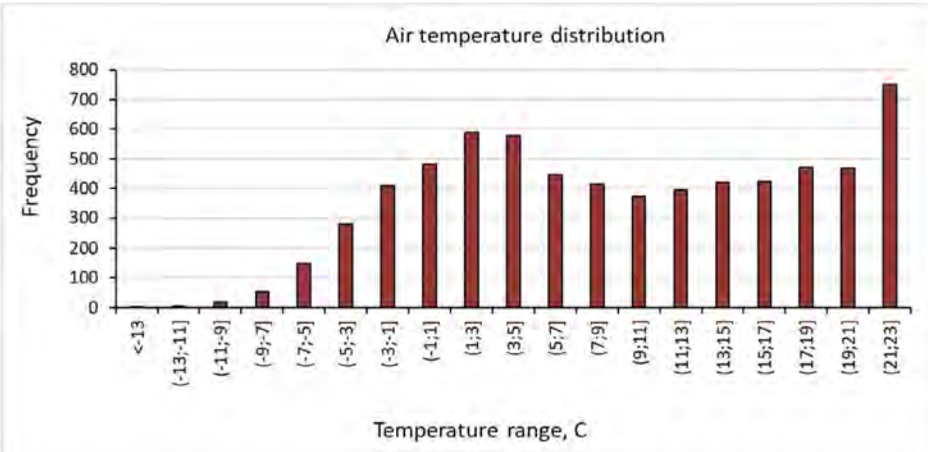


Fig. 39. Analysis of the annual air temperature distribution in the port of Dalian

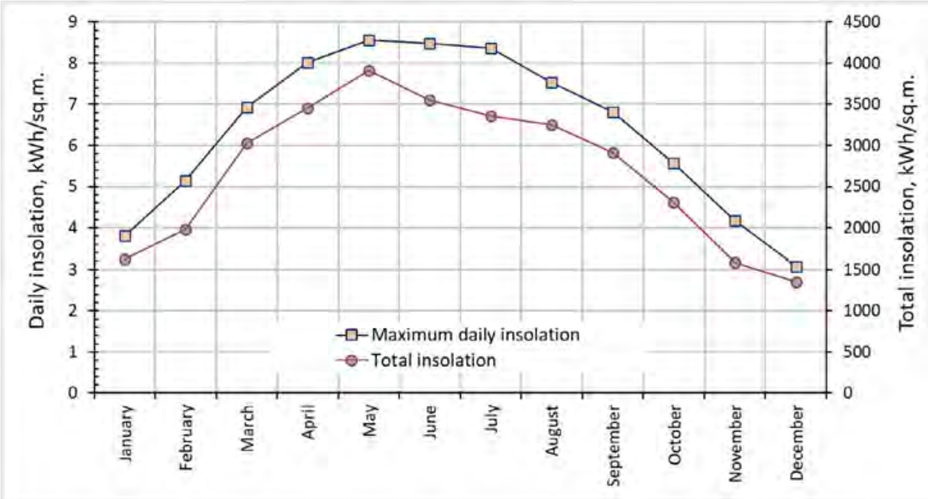


Fig. 40. Insolation variations in the port of Dalian

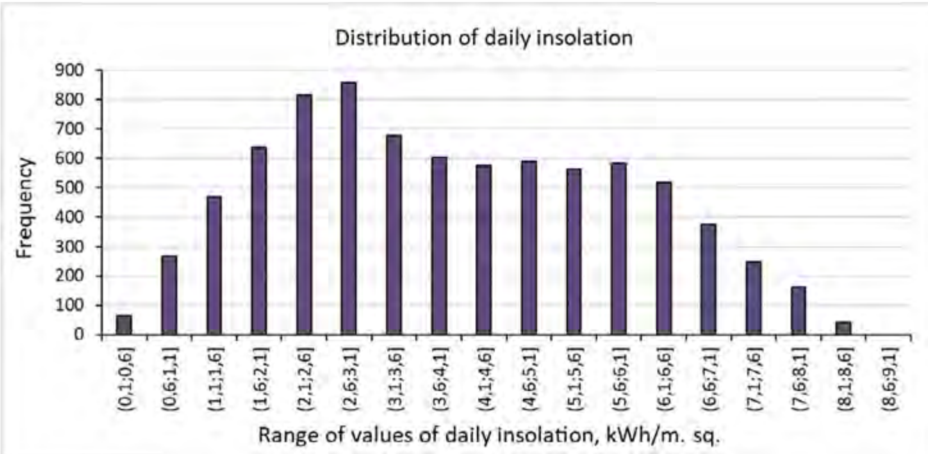


Fig. 41. Analysis of the annual insolation distribution in the port of Dalian

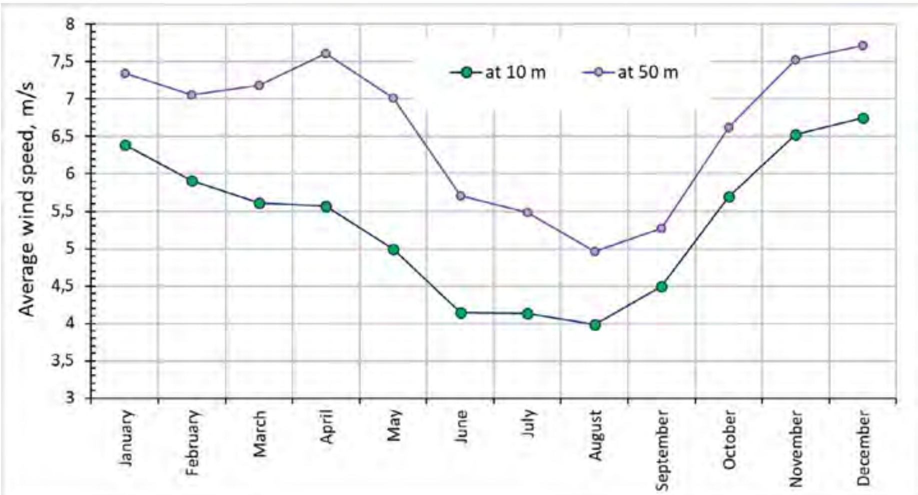


Fig. 42. Wind speed variations in the port of Dalian

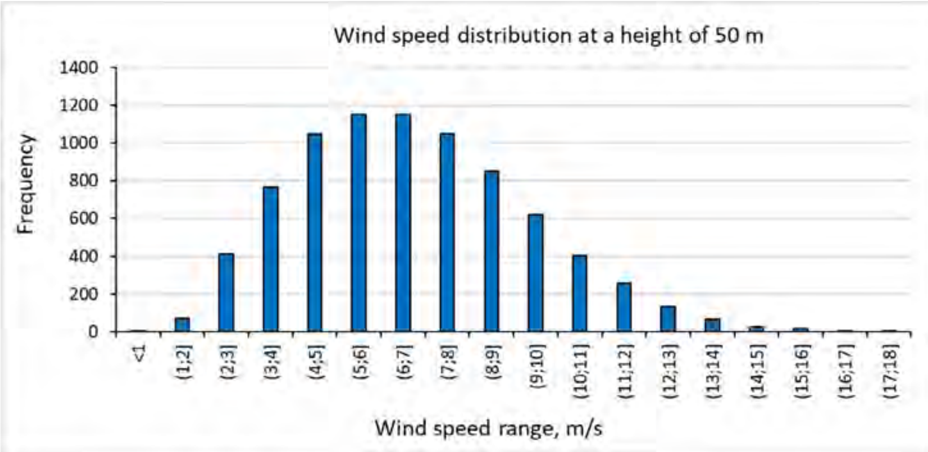


Fig. 43. Analysis of the annual wind speed distribution in the port of Dalian

4.1.3 Results of the study

Based on the analysis of the available data, taking into account the accepted selection criteria, the port of Kaliningrad was chosen as the main case study. From a climatic point of view, the port is in the most difficult conditions, both in terms of temperatures and the availability of renewable energy sources. What makes it particularly relevant in the context of considering the concept of a zero-emission port. In addition, the port of Kaliningrad is characterized by the highest degree of data availability, in particular on electricity consumption. The seaport of Kaliningrad is a major sea hub of the Kaliningrad region of the Russian Federation and is developing dynamically in the context of existing global trends.

From the cold ironing perspective, it is feasible to discuss the port of Dalian possibilities.

4.2 Analysis of case study ports' energy consumption

To analyse the introduction of the zero-emission strategy in the ports of the Baltic Sea region the Kaliningrad seaport was chosen as an example (Fig. 44). The Kaliningrad seaport operates in the port of Kaliningrad – the westernmost port in Russia under the jurisdiction of the North-Western Basin Branch of the "Rosmorport" the infrastructure of which comprises ship terminals located on the coast of the Kaliningrad Sea Canal, as well as in the towns of Baltiysk, Svetly, and Kaliningrad.

Fig. 44. Location of Kaliningrad seaport

4.2.1 Seaport infrastructure analysis

Kaliningrad Sea Port (KSP) is the largest in terms of scope of work and technical equipment among the ports of Kaliningrad, which are the only ice-free ports of Russia in the Baltic. The port is located on the south-eastern coast of the Baltic Sea (Fig. 45).

Fig. 45. Location of the Kaliningrad Sea Port in the Kaliningrad Region

The terminals of KSP are located in the inner harbours (Volnaya and Industrialnaya) of the city of Kaliningrad (Fig. 46) and are connected to the Baltic Sea by a channel, 43 kilometres long, 80 to 150 meters wide, and 9 to 10.5 meters deep. The main activities of the port include loading and unloading operations, storage of goods, customs warehousing services, and mooring operations. It should be noted that KSP invests about 90% of its net profit in the development of its port structure, which confirms the correct choice of the port as a case study.

Fig. 46. Satellite image of the territory of the Kaliningrad Seaport

There are 11 covered warehouses, three elevator buildings, and two refrigerated warehouses for storing refrigerated deep-frozen cargoes, which operate around the clock, on the territory of the port. Data on the infrastructure of the seaport are given in Table 6.

Table 6. Characteristics of the port infrastructure

Characteristics	Units	Value
The territory of the sea terminal	sq. m	663 000
Marine terminal water area	sq. m	460 000
Number of berths	-	15
Berthing front length	m	2 650
Liquid cargo terminal capacity	tons	9 000
Covered warehouse capacity	cub. m	24 000
Open storage area	sq. m	231 400
Number of portal cranes	units	38

4.2.2 Analysis of the seaport power supply system

The connection of the Kaliningrad Sea Port to the power system of the Kaliningrad Region is carried out through a branch substation 110/10 kV O-17 "Rybny Port". The scheme of connecting KSP to the power system is shown in Fig. 47.

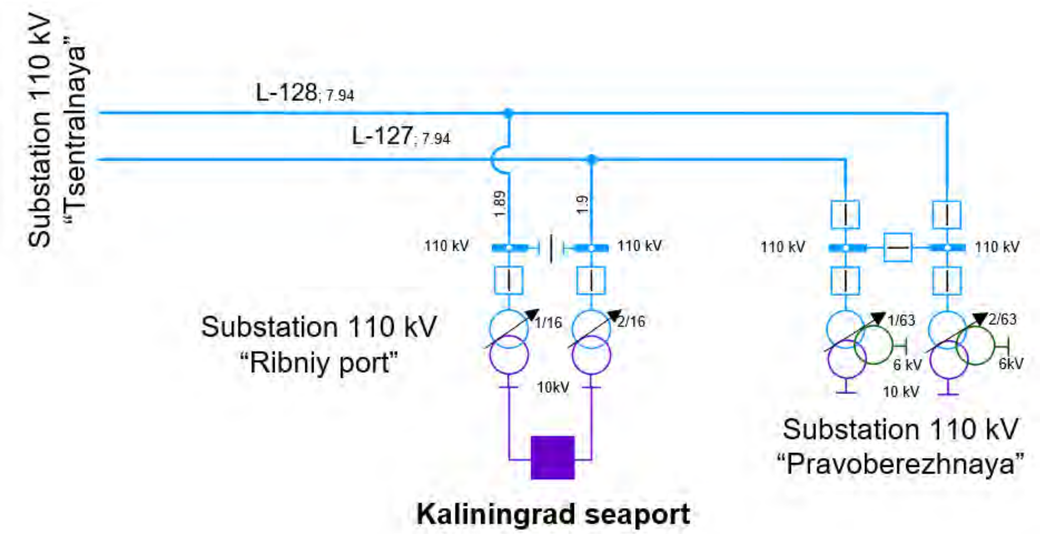


Fig. 47. Fragment of the power system scheme in the area of seaport location

The total capacity of Substation O-17 Rybny Port is 32 MVA. The substation is powered from the O-1 Tsentralnaya substation by two 110 kV lines - taps from L-128 and L-127. The power supply system of the port is connected to Substation O-17 "Rybny Port" through the central distribution point (Fig. 48). Fig. 49 shows the structure of the seaport power supply system, indicating the number of lines connecting transformer substations (TS).

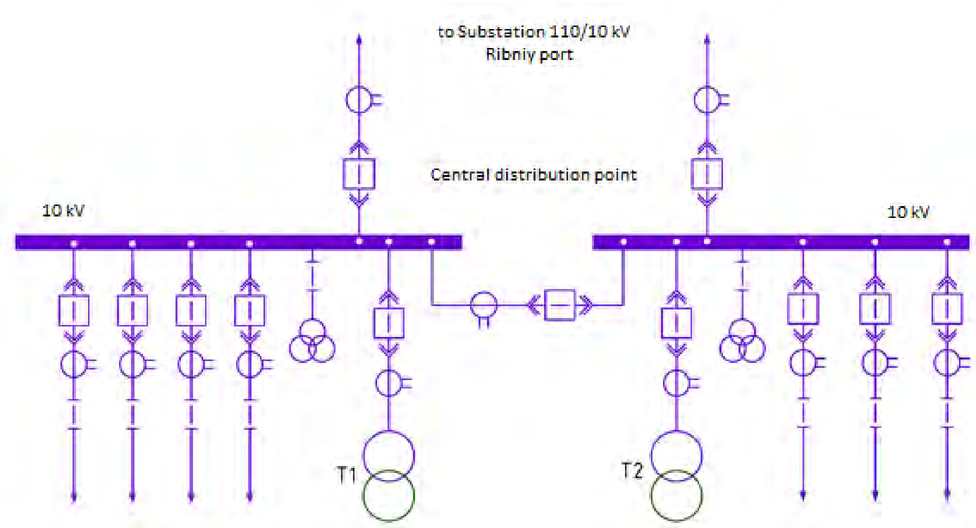


Fig. 48. Electrical diagram of the central distribution point

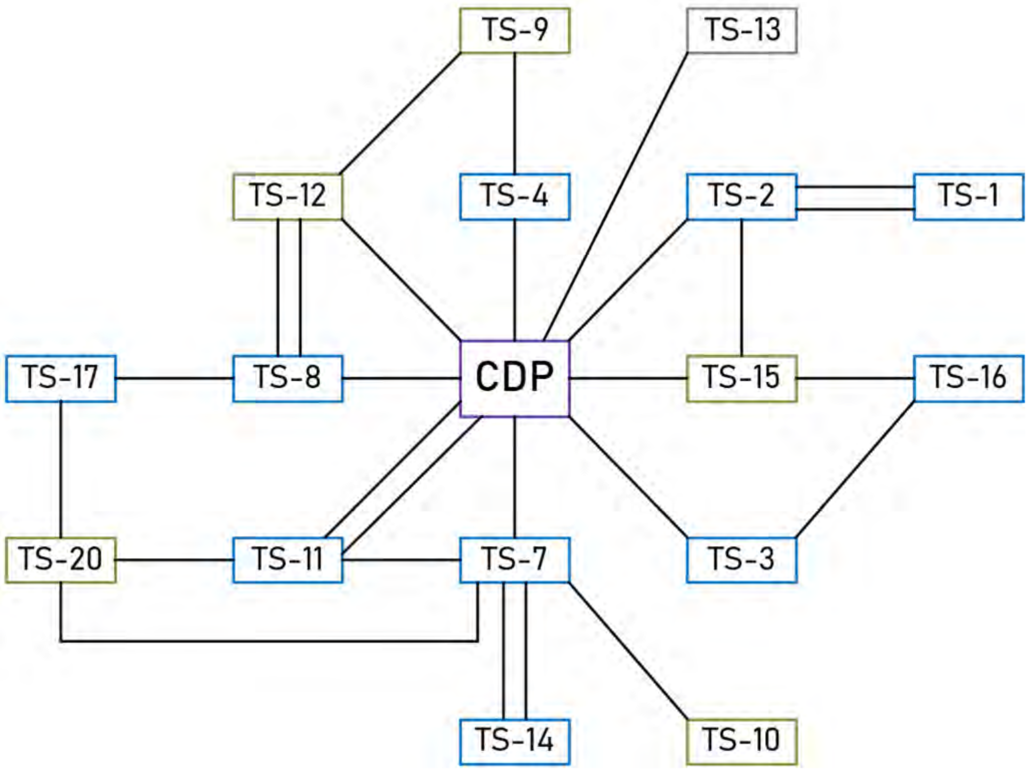


Fig. 49. Structural diagram of the power supply system of the port

The total number of transformers in the power supply system of the Kaliningrad Sea Commercial Port is 28 electrical installations, but not all of them are in operation. The diagram (Fig. 50) shows the rated power of the 10/0.4 kV transformers outgoing from each of the workshop substations of the port power supply system, as well as the total rated power of the transformers in operation.

Fig. 50. Transformers 10/0.4 kV of the seaport substations

4.3 Kaliningrad seaport electrical load charts analysis

Electrical load charts are very important in terms of energy consumption management and optimization. The set of daily schedules of electrical loads in the form of an annual load schedule is the basic tool in the development and application of the programs described in the work. Analysis of the power consumption graph directly determines the choice of approach to integration into the power supply system of the ESS port to optimize power consumption.

4.3.1 Analysis of seaport power consumption

Fig. 51 shows the thermal diagram of the port's power consumption during the year from June 1, 2020, to May 31, 2021. Bright red color indicates power values that are significantly higher than the average annual value, and pale green - power values that are significantly less than the average annual value. Table 7 presents data on the distribution of electricity consumption by characteristic groups of energy consumers. The study of the structure of the electrical loads of the port indicates a significant proportion of handling equipment, the mode of operation of which is linked to the maintenance of ships.

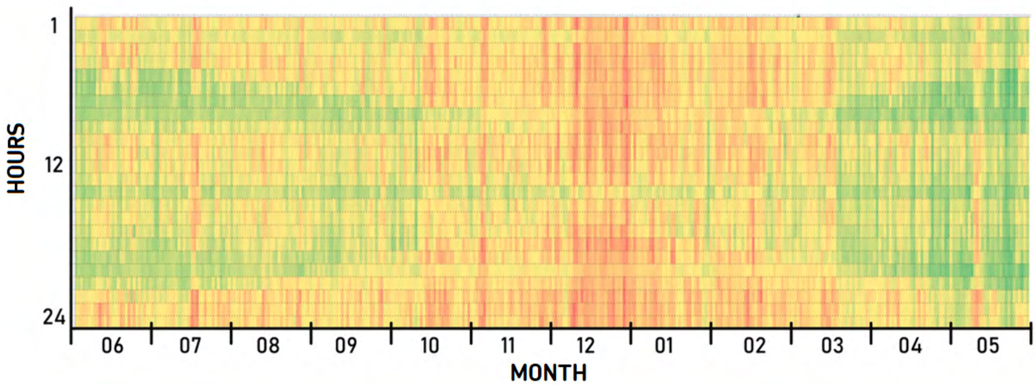


Fig. 51. Annual graph of the port's power consumption in the form of a heat diagram

Table 7. Distribution of electricity consumption by groups of energy consumers

Energy consumers group	Share, %
Gantry cranes	28,27
Lighting systems	9,55
Service premises	2,15
Covered warehouses	0,95
Refrigerated containers	15,22
Mechanization services	1,09
Water and heat supply area	4,34
Wastewater treatment plant	3,88
Port management and access control	1,97
Renters	32,58

Preliminarily, by the nature of the heat map (Fig. 51), it can be stated that the power consumption graph is significantly uneven. High values of power consumption can be observed in any season, but their highest density is reached in winter. The largest load maxima are observed in December. To draw more detailed conclusions, one can refer to the seasonal load profiles (Fig. 52-55).

According to seasonal load profiles, it should be noted that the winter schedule differs most in the form of changes. A daily local minimum typical for all seasons is observed at 14:00 and 2:00 in the morning. Local maxima in autumn, summer, and spring are concentrated in the time intervals of 9:00–11:00 and 21:00–23:00, that is, in the morning and evening.

In many ways, the nature of changes in the spring and summer schedules coincides, and the consumption reaches its lowest value during the day at the 7th and 8th hours.

More clearly, the difference in seasonal profiles can be displayed in a comparative diagram, as shown in fig. 56.

For the convenience of assessing the specific values that make up the seasonal load profiles, Table 8 shows the hourly values of the load power of a typical day for each of the seasons.

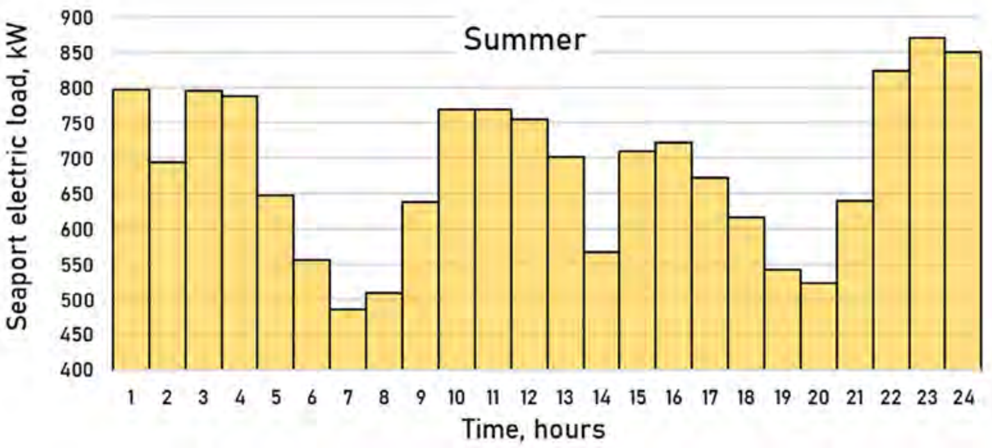


Fig. 52. Summer load profile

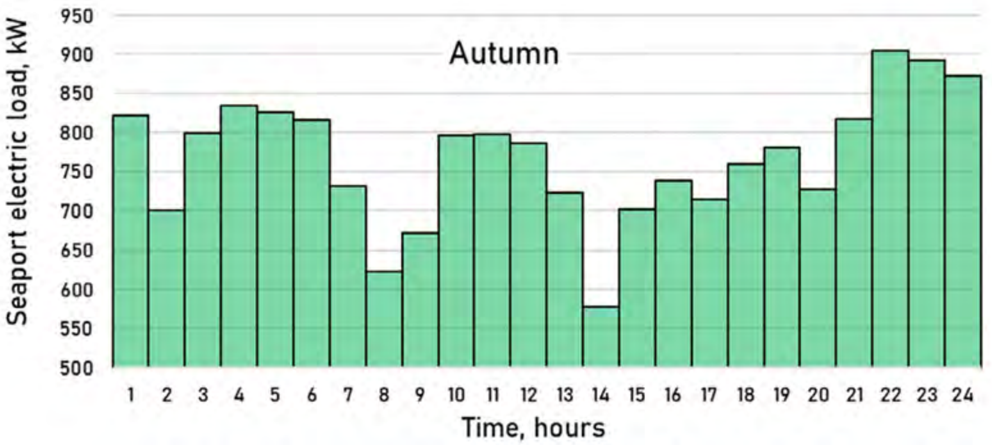


Fig. 53. Autumn load profile

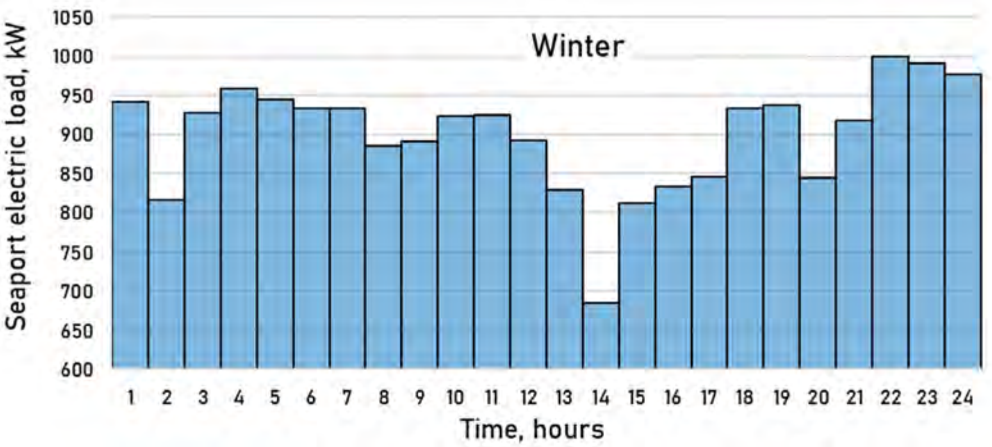


Fig. 54. Winter load profile

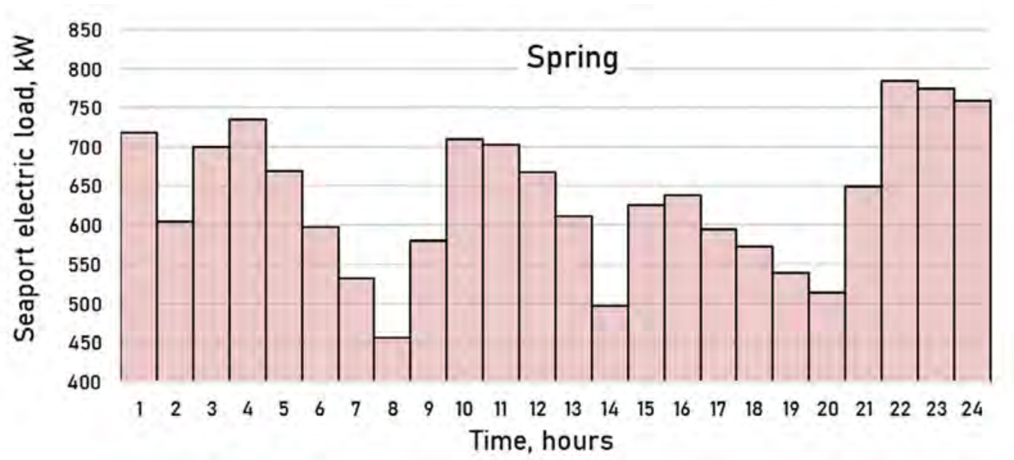


Fig. 55. Spring load profile

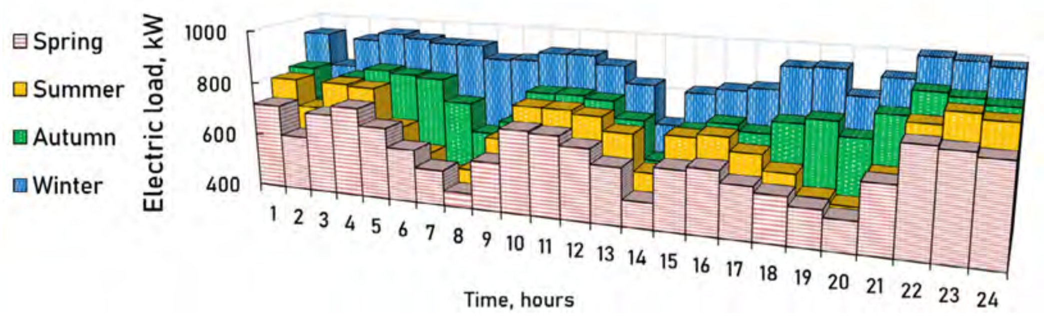


Fig. 56. Chart of power consumption of the port by seasons

Table 8 - Average seasonal load values, kW

Hour	Summer	Autumn	Winter	Spring
1	797.4802	821.6732	941.1128	718.1585
2	693.8525	700.4112	815.9218	603.2566
3	795.6252	798.1495	927.6874	699.9592
4	787.8094	834.4854	958.0355	735.7565
5	646.3592	824.851	944.7171	669.3163
6	555.6639	815.934	932.6021	596.4351
7	484.8584	731.0907	933.3435	531.9234
8	509.2262	622.4962	885.4191	456.1386
9	637.3996	671.9381	890.5185	579.9719
10	768.8292	795.3689	922.7741	709.2065
11	768.5194	796.92	924.4903	702.5453
12	754.5696	786.506	893.0182	667.1503
13	702.0215	722.8051	829.2345	611.5682
14	567.3194	577.8911	685.0783	497.4558
15	709.1152	702.028	812.5208	624.977
16	721.6065	737.5444	832.9074	637.4899
17	671.4654	714.0624	846.4125	593.8548

18	615.749	759.7362	933.0317	572.7782
19	541.5686	779.7571	937.6232	539.3968
20	522.9059	727.3224	845.0347	513.1943
21	639.6107	817.1993	917.3194	648.4228
22	823.8248	904.3421	998.9245	784.3349
23	870.5176	892.262	991.5089	774.7909
24	850.5056	872.2597	976.7842	759.3425

4.3.2 Calculation of load curve coefficients

For the annual load schedule as a set of daily power consumption schedules from 06/01/2020 to 05/31/2021, the coefficients characterizing it were calculated.

The uniformity factor (Fig. 57) is calculated as the ratio of the minimum value of the ordinate of the load graph to the maximum value for the study period (day):

$$k_u = \frac{P_{min}}{P_{max}} \tag{21}$$

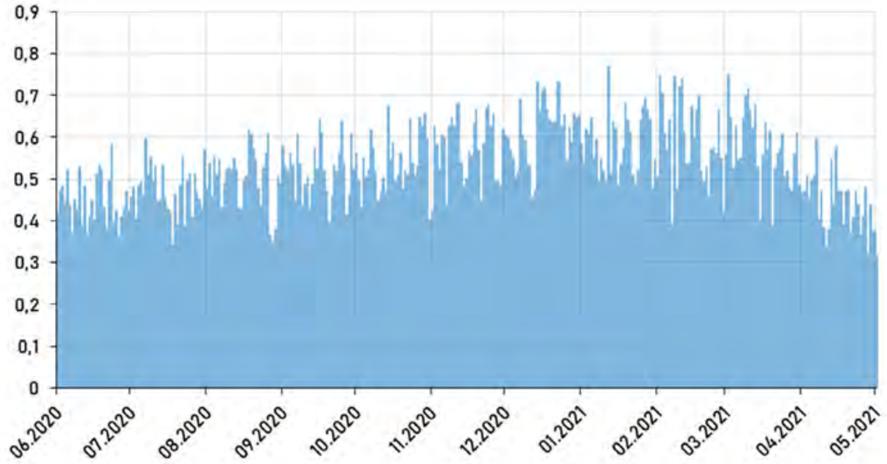


Fig. 57. Daily coefficients of non-uniformity during the study period

The fill factors (Fig. 58) are calculated as the ratio of the average active power to the maximum for the studied period of time (day):

$$k_{fill} = \frac{P_{av}}{P_{max}} \tag{22}$$

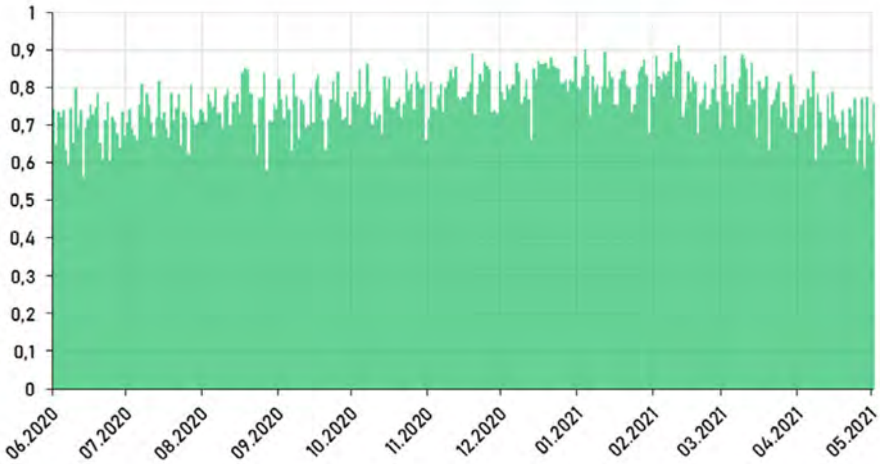


Fig. 58. Daily fill factors during the study period

The energy use factors (Fig. 59) are defined as the ratio of the average daily load to the average annual load:

$$k_{eu} = \frac{P_{av.day}}{P_{av.year}} \tag{23}$$

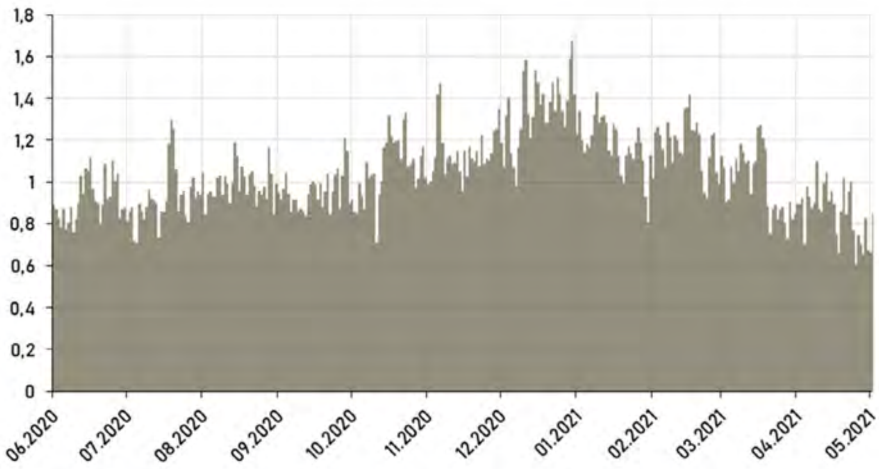


Fig. 59. Daily coefficients of energy use during the study period

Energy use coefficients allow taking into account seasonal load fluctuations and load unevenness across shifts.

The shape factor (Fig. 60) is defined as the ratio of the RMS (effective) power to the average for the study period (day):

$$k_{shape} = \frac{P_{av.square}}{P_{av}} \tag{24}$$

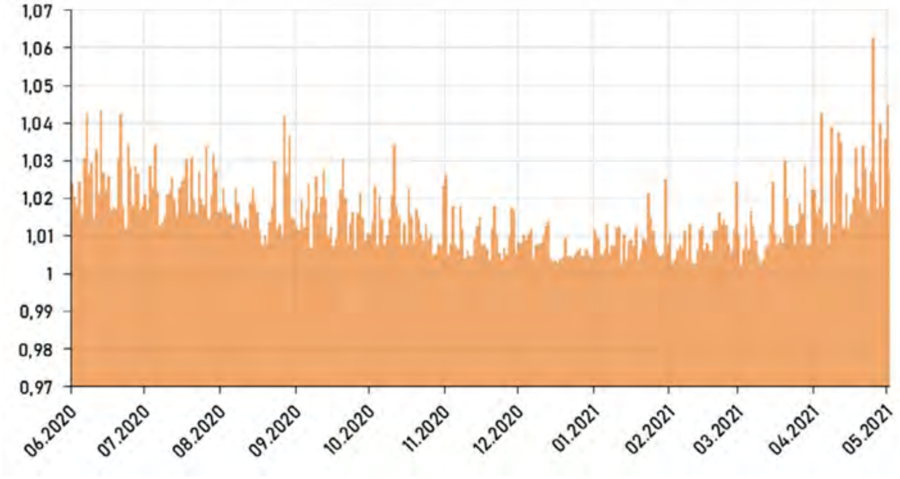
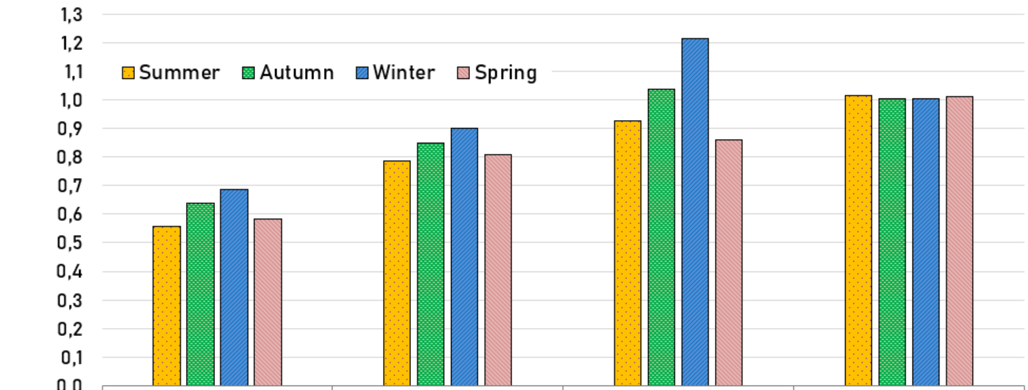


Fig. 60. Daily shape factors during the study period

Also, according to expressions (20-23), the values of the coefficients of non-uniformity, filling, energy use, and shape for the characteristic seasonal load profiles were determined (Fig. 61).



	Uniformity factor	Fill factor	Energy usage factor	Shape factor
Summer	0,557	0,787	0,926	1,013
Autumn	0,639	0,848	1,037	1,005
Winter	0,686	0,900	1,216	1,003
Spring	0,582	0,809	0,858	1,010

Fig. 61. Seasonal values of load curve coefficients

4.3.3 Problems with electricity consumption forecasting

A study of the port's electrical load structure indicates a significant proportion of lifting and handling equipment, the operating mode of which is related to the servicing of ships and does not depend on the time of day, air temperature, or season since the port of Kaliningrad is ice-free.

The revealed dependence of the port's power consumption on the intensity of vessel servicing complicates the prediction of electrical loads for analytical models. This makes it difficult to calculate the required parameters of energy storage units and their operating modes. The active use of cold ironing in combination with the operation of loading equipment leads to an increase in the unevenness of the load schedule, which should also be taken into account when choosing approaches to the development of algorithms for calculating the operating modes of energy storage devices.

The microgrid system makes it possible to simplify the coordination of the processes of production and consumption of electricity through the use of storage devices. However, even for the simplest algorithm for smoothing the load curve (Fig. 62), predictive data on the expected volumes of production and energy consumption are required to set the operating mode of the drive.

Thus, the operation of a port microgrid system is impossible without appropriate predictive models of generation and consumption processes. In its simplest form, such a model could be based on the use of predicted meteorological data, which are widely available and accurate, in particular, air temperature. Fig. 63 provides detailed data and approximating curves for the seaport's daily energy consumption and average daily ambient temperatures over the period under review.

The assessment of the initial hourly data on power consumption and ambient air temperature using the Chi-square criterion does not allow us to reject the null hypothesis that the distribution of these quantities is normal with a p-value of 0.95. For clarity, Fig. 64 shows the quantile-quantile plots of the corresponding distributions of the series of the initial data.

This makes it possible to carry out a correlation analysis of these two series according to Pearson's criterion for different averaging intervals, which were chosen as hourly, daily, weekly and monthly. The results of calculating the corresponding Pearson coefficients are shown in Fig. 65.

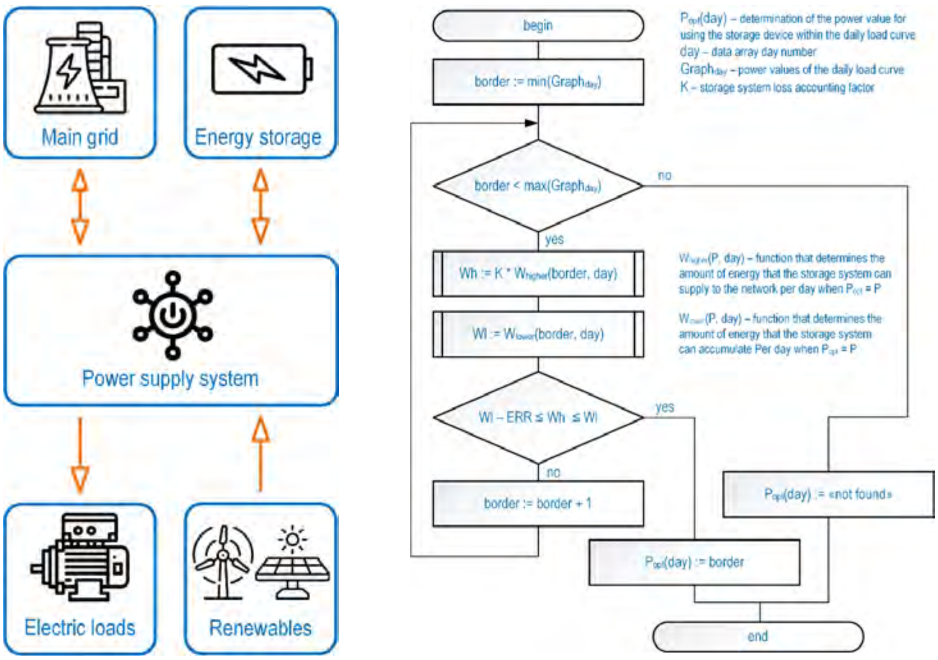


Fig. 62. Energy exchange in the marine port smart grid system and optimization algorithm for storage-based load shifting

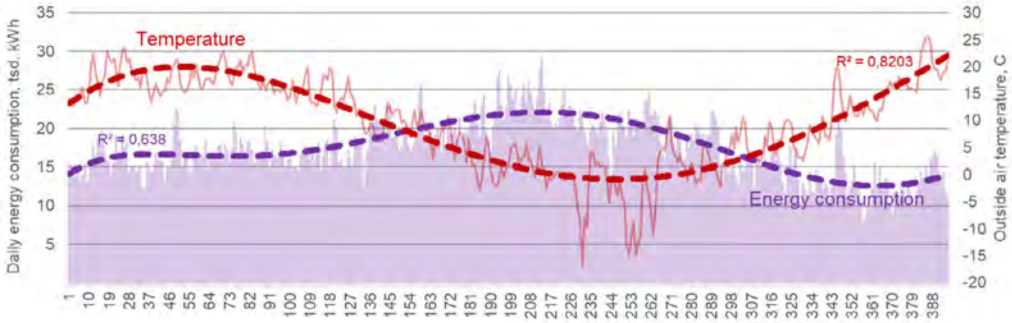


Fig. 63. Daily energy consumption and average temperature data (13-month period)

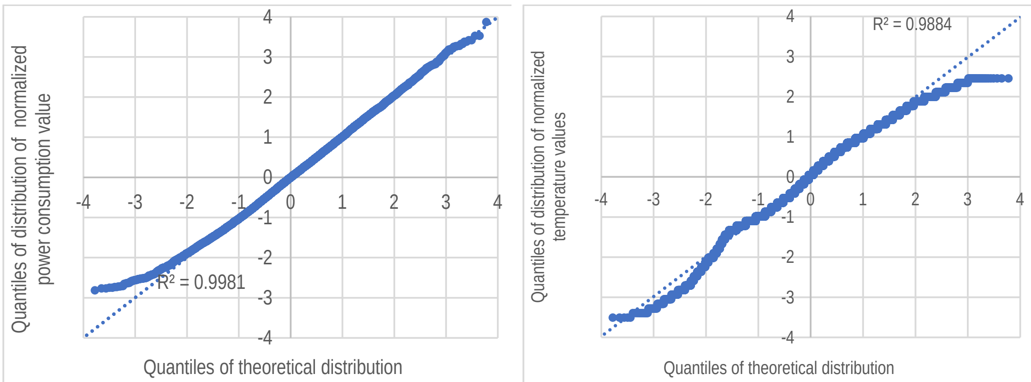


Fig. 64. Quantile-quantile graphs of the distribution of normalized values of hourly series of power consumption and air temperature

Fig. 65. Pearson's correlation coefficient for the series of electricity consumption and temperature data depending on the data averaging interval

Thus, in the case of hourly averaging, there is a weak negative correlation between the level of electricity consumption and the ambient temperature. In other variants of averaging, there is an average negative correlation between these values. Since the requirements for data detailing for the operation of the computational algorithm imply the setting of hourly load values, the obtained correlation level does not allow us to propose an adequate predictive model based only on the use of temperature data. Models of this kind can be obtained using artificial intelligence methods, which requires additional study.

4.4 Analyzing renewable energy source's potential

Wind power potential is mainly determined by the average wind speed at an altitude corresponding to the parameters of the wind turbine. The estimation of the mean wind speed was made for the territory of the port of Kaliningrad based on the analysis of data from the information system [114]. Fig. 66 represents the data on mean wind speeds at the height of 50 and 100 m in the area of port infrastructure facilities (shown as white areas). Summarized data for individual coastal areas are shown in table 9.

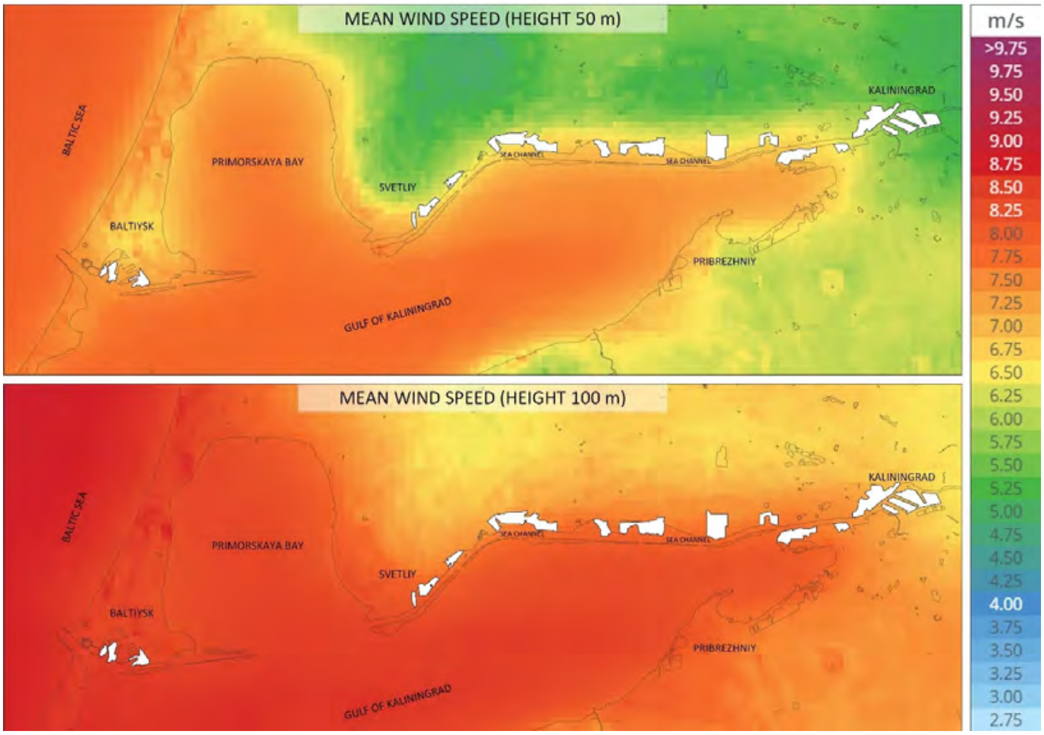


Fig. 66. Map of the mean wind speed in the area of the port of Kaliningrad terminals

Table 9. Data on the mean wind speed in the area of the port of Kaliningrad.

Mean wind speed, m/s	Baltiysk	Svetly	Kaliningrad	Sea channel
at a height of 50 m	7.65	7.18	5.86	7.21
at a height of 50 m	8.57	8.13	7.21	8.06

The analysis of the given data shows that the mean wind speed generalized for the port of Kaliningrad area equals 7 m/s (50 m) and 8 m/s (100 m). The analysis of the performance characteristics of Russian (VDM-technology) [115] and European (Enercon) wind turbines [116] (Fig. 67) provides an assessment of wind turbine operation efficiency in the specified conditions. With the common form of the power curve (Enercon wind turbine) in the speed range of 7-8 m/s, the wind turbine installed capacity utilization factor does not exceed 0.4. In the case of the new Russian technology of the VDM-30 turbine, the usage of installed power in the specified speed range reaches 80%. However, the axis of the hub of this wind turbine is located at a height of 18 m, which corresponds to an average wind speed of 3.2 m/s (Fig. 68).

Thus, it can be concluded that the area of the port of Kaliningrad terminals has potential for the development of wind energy. However, taking into account the characteristics of wind turbines, the complete use of the installed capacity of the generating equipment will not be ensured. At the same time, according to the microgrid and distributed generation concepts, it is promising to use small wind turbines with a lower operating range of wind speeds at the facilities of the port of Kaliningrad.

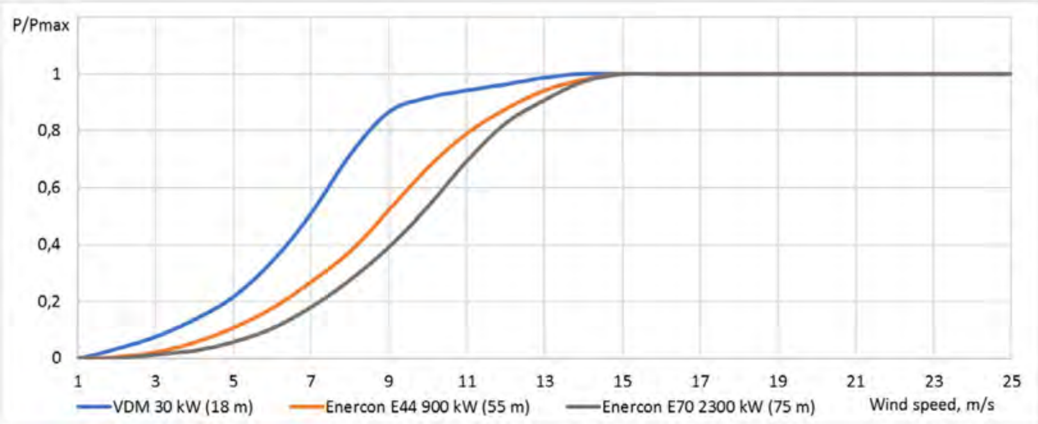


Fig. 67. Comparison of wind turbines performance characteristics

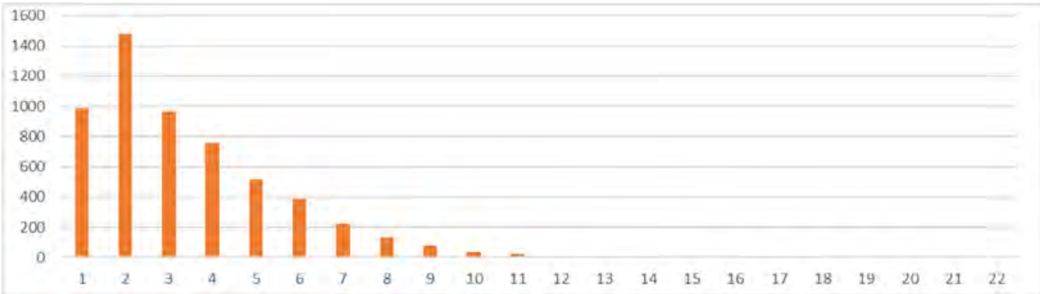


Fig. 68. Annual data on the mean wind speed occurrence frequency at a height of 18 m in the area of the fishing port

The distribution of solar irradiation intensity over the territory of the Kaliningrad region is much more uniform in comparison with the mean wind speed (Fig. 69). For the areas where the port of Kaliningrad infrastructure is located, the average daily amount of direct normal irradiation is 2.8 kWh/m2 [116]. The data on monthly averages on total photovoltaic power output for the area of Kaliningrad seaport location is shown in Fig. 70.

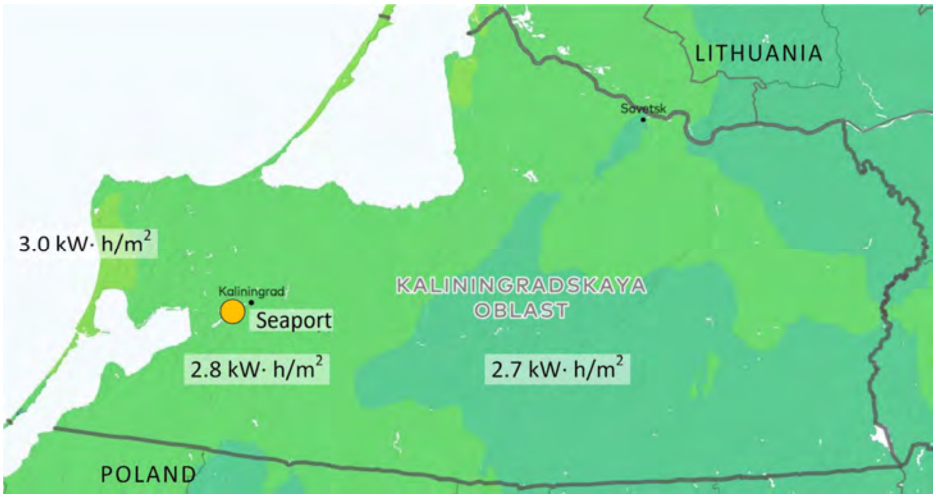


Fig. 69. Average daily direct normal irradiation in the Kaliningrad region

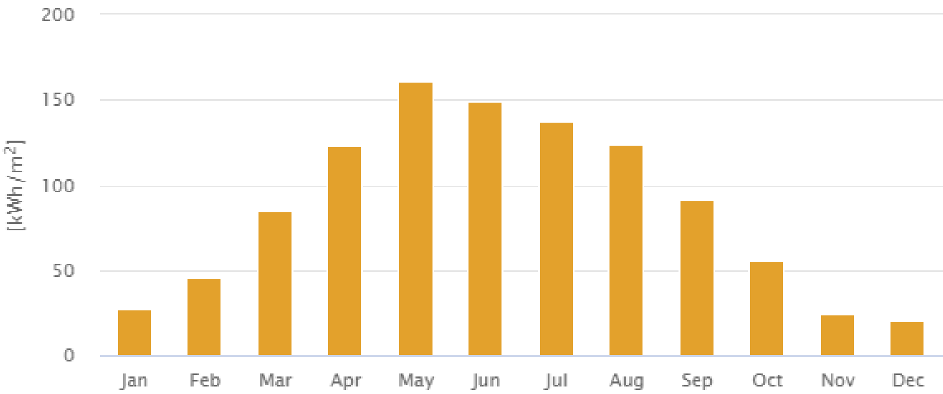


Fig. 70. Monthly averages on total photovoltaic power output [117]

Installation of photovoltaic panels requires a large amount of free space. In the conditions of the marine industry facilities, the roofs of port structures are successfully used as sites for placing panels. The area required for the installation of solar power plants depends on the type, power, and dimensions of the photovoltaic panels and the required tilt angle. The final decision on the appropriateness of using photovoltaic panels should be made taking into account various factors, including the type and efficiency of the photovoltaic panels used.

In addition to the use of wind and solar energy, the concept of a green port often involves the use of ocean energy, in particular wave energy. However, the Kaliningrad seaport is located at the mouth of the river at a considerable distance from the sea coast. Therefore, in the area of the port, the wave energy potential available for development is very small.

4.4.1 Performance score of energy alternatives

Once the ten evaluation criteria of energy alternatives have been identified based on the literature review and expert judgments and weighted through the AHP, the next step is to evaluate the performance of the renewable energy alternatives for each evaluation criterion using a scale of 0-10. The higher the value of the performance scale, the more attractive is the criterion value (Table 10).

Table 10. Performance scores of ten evaluation criteria

Evaluation criteria	Scores	
	0	10
RA	Low and unpredictable	High and predictable
TM	Technology is still relatively new	Technology has been used for a long time
IC	Most expensive	Least expensive
O&M	Most expensive	Least expensive
IOE	Significant impact on the environment	Minor/negligible impact on the environment
SA	Negative public attitude toward specific renewable energy source	Positive public attitude toward specific renewable energy source
LR	No land available/Conflicts with other users	Spacious land available/No conflicts
JC	Few/negligible job opportunities	Substantial job opportunities
K-H	Lack of specialized human resources in the region/country	Availability of specialized human resources in the region/country
CF	Low	High

Experts were asked through interviews to assess the performance of energy alternative X for criterion Y in a city Z (i.e., in the port of Kaliningrad), taking into consideration the hypothetical question "what would be the performance of X for Y if the X option is used in Z" as described in the study by Budak et al. (2019).

The weights in the above methodology step are not geographically dependent. On the contrary, the process of performance score of each energy alternative is site-specific, which means that the involvement of experts, who not only know about renewable energy sources, but also have in-depth knowledge of the techno-economic, spatial, and environmental aspects of a place, is important. The performance matrix [5x10] of the above process is presented in Table 11.

Table 11. Performance scores of renewable energy alternatives for the port of Kaliningrad

Renewable Energy Alternatives	RA	TM	IC	O&M	IOE	SA	LR	JC	K-H	CF
Onshore wind turbines	8	10	10	10	7	7	6	8	9	8
Offshore wind turbines	10	9	7	8	9	10	10	10	9	10
Onshore solar panels	9	10	10	10	9	7	5	8	10	6
Offshore solar panels	8	7	7	8	10	10	10	9	8	5
Wave devices	4	6	8	8	9	9	10	9	7	5

4.4.2 Results of the study

In this last stage of methodology, to determine the weighted total performance score of the five renewable energy alternatives for the case study, the results in Tables 5 and 6 are summed through matrix multiplications (Table 12). At this point, it is important to point out that the five renewable energy sources are not mutually exclusive, but are classified, as one or more technologies that can be chosen for a specific place depending on several parameters (e.g., restrictions, availability of resources, etc.).

Onshore solar panels are ranked as the top choice for the port of Kaliningrad among all energy alternatives, as results from the matrixes multiplications, and aggregations, an expected result, as the port has good resource availability, solar panels are considered a highly mature technology, with low investment and O&M costs, while land requirements can be met with their placement on the roofs of buildings and warehouses, without the need for new space.

Table 12. Total performance scores of the five renewable energy technologies

Evaluation Criteria	Weight Factor (%)	Energy alternatives				
		Onshore wind turbines	Offshore wind turbines	Onshore Solar panels	Offshore Solar panels	Wave devices
RA	27.5	2.2	2.75	2.475	2.2	1.1
TM	19.4	1.94	1.746	1.94	1.358	1.164
IC	13.2	1.32	0.924	1.32	0.924	1.056
O&M	13.2	1.32	1.056	1.32	1.056	1.056
IOE	9	0.63	0.81	0.81	0.9	0.81
SA	6.3	0.441	0.63	0.441	0.63	0.567
LR	4.5	0.27	0.45	0.225	0.45	0.45
JC	3.1	0.248	0.31	0.248	0.279	0.279
K-H	2.2	0.198	0.198	0.22	0.176	0.154
CF	1.6	0.128	0.16	0.096	0.08	0.08
Total score		8.695	9.034	9.095	8.053	6.716

Offshore wind turbines are ranked as a second alternative, as the case study has good resource availability, with stronger offshore winds compared to onshore, the technology has been used for a long time, while due to land restrictions in the port can be placed further offshore, and this one of the main reasons for the lower ranking of onshore wind turbines.

Finally, wave energy is the least preferable option. The low resource availability in the area and the low technological maturity of this type of technology combined with the lack of specialized human resources in the region/country, among others, make this alternative the least acceptable. The scores and classification of energy alternatives resulting from the methodology are in line with previous research studies on the development of alternative energy solutions in light of the zero-emission port.

4.5 Selecting the type of energy storage systems

4.5.1 Energy Storage system for Kaliningrad port

Each type of ESS has its advantages and disadvantages. They differ from each other in capacity, power, discharge and charge time, efficiency, need for maintenance, reliability, degree of environmental impact, cost, and other characteristics. The priority factor in choosing the type of energy storage system is the intended application.

This report discusses the use of an energy storage device to reduce the cost of a seaport for capacity by reducing power consumption (from the power system) during scheduled hours. Taking into account how the processes of accumulation and release of energy into the network are described in the developed methodology, a long-term ESS is needed - capable of consistently accumulating and then delivering large amounts of energy within a day.

Supercapacitors, flywheels, and superconducting magnetic storage are short-term tools. With their help, it is possible to maintain the power system in emergency conditions, improve the quality of electricity and reliability, and use it together with renewable energy sources, especially in isolated areas. However, it is not advisable to use the drives of the listed types to optimize the power consumption mode of the seaport. Hydro storage and compressed air systems as storage technologies are more suitable for large-scale implementation and in the presence of large free areas, which is not relevant for seaports.

A more compact option is the use of hydrogen fuel cells, but this system has low efficiency, which is a consequence of the low efficiency of its elements, from hydrogen production to its use in a fuel cell. When utilizing the heat released by the fuel, the efficiency of the system can be increased up to 80% [104]. The technology of fuel hydrogen cells is currently under development, and the market implementation of the technology has not yet come [105104].

Thus, the question of the possibility of using this accumulation technology in the power supply system of seaports is still open. Based on the foregoing, mainly rechargeable batteries, including flow batteries, meet the requirements for storage devices in the framework of the zero-emission port strategy.

4.5.2 Energy Storage system used in Chinese port

Lianyungang port of Jiangsu Province, China

As the largest seaport in Jiangsu Province, Lianyungang port is one of the three main ports in the Yangtze River Delta port group. The power capacity of the marine high-voltage shore power system built by Lianyungang Power Supply Company and Lianyungang Port Group is 3000 kilowatts, which can supply power to 2 berths at the same time. Function, it can realize continuous monitoring of power quality indicators such as harmonics, flicker, transients and transients. It can achieve 1.2 million kilowatt-hours of electricity replacement each year, reducing emissions of 2110 tons of carbon dioxide, 23 tons of sulfur dioxide, and 34 tons of nitrogen oxides.

The development of shore power has a good foundation. The project plans to build a 5MW (1MW/15s super capacitor + 4MW/4MWh lithium battery) energy storage in the shore power system of the port of Lianyungang port, Jiangsu. The power station meets the shore power access requirements of more than 10MW and a single berth of more than 3MW.

Zhenjiang port of Jiangsu Province, China

Zhenjiang Port is located at the intersection of the Beijing-Hangzhou Grand Canal and the Yangtze River. It is one of the main ports in China and an important trading port opened to the outside in the Yangtze River Delta region. The shore power system can output two voltage systems of 6 kV / 50 Hz and 6.6 kV / 60 Hz. It can provide shore power services for different types of ships, helping ships entering the port achieve "zero fuel consumption and zero emissions. Based on the current operating conditions of the port area, it is estimated that it can replace 671 tons of standard oil and 2174 tons of carbon dioxide annually.

The energy storage project plans to construct a 200MWh energy storage power station in the shore power system of Zhenjiang Port to meet the needs of surface transfer operations and storage and logistics operations.

4.6 Analysis of cold ironing system in the port of Dalian

As an important transportation hub in Northeast Asia, Dalian Port is the Chinese largest loose beam, oil import, and export port and an important foreign trade port. It has modern professional berths for grain, ore, containers, petrochemicals, and bulk cargo. At the same time, Dalian Port Group is the only 3A-level credit enterprise in Liaoning Province, a 500-strong domestic service industry enterprise, and a national 5A-level integrated logistics enterprise. With A+H dual financing platforms, the economic scale exceeds 70 billion. Dalian Port Group has always adhered to the "resource-saving and environment-friendly" green and low-carbon development idea for many years, gave full play to the leading role of technological innovation, actively promoted new management concepts, and provided powerful technology and technology for accelerating the construction of green and low-carbon ports. At the same time, the Dalian Port Group actively responded to the national call to vigorously develop the construction of ship-to-shore power, and completed ahead of schedule the construction target proposed by the Ministry of Transport in the "Port Shore Power Layout Plan".

4.6.1 Overview of the shore-to-ship power situation in Dalian Port

The Dalian Municipal Government issued the "Implementation Plan of Dalian Air Pollution Prevention and Control Action Plan in 2014 and proposed that the proportion of shore power used by port container terminals should not be less than 50% by 2017. The target is that the use ratio of shore power to shipyards should not be less than 90%. The "Key Work Opinions of the 2016 Atmospheric Action Plan" was issued again in 2016, which clearly stated the goal that "the proportion of shore power installations in port container terminals should not be less than 40% in 2017".

With the great attention and efforts of Dalian Port Group, during the "Twelfth Five-Year Plan" period, Dalian Port Group took the lead in launching shore power technology project transformation for port-operated ships and berths for small and medium-sized ships. After entering the "Thirteenth Five-Year" plan, the construction and development of Dalian Port's ship-to-shore power project reached a new level. By 2017 several systems were put into operation in the port of Dalian:

- two sets of high-voltage variable frequency shore power systems at the container terminal:
- three sets of high-voltage power frequency ship shore power systems at the berths of Dalian Bay Ro-Ro Passenger Terminal:
- two sets of dual-frequency ship shore power systems at the bulk grain terminal;
- the high-voltage frequency conversion shore power supply at Dayao Bay Ore Wharf has also been completed;
- a set of mobile low-voltage variable frequency shore power facilities at the general cargo terminal in Dalian Bay.

At present, Dalian Port Group has completed the construction of a total of 18 sets of shore power projects, which can meet the requirements of 32 berths for docking ships to connect shore power. The port's specialized berths for ore, bulk grain, and Dalian Bay passenger rolls have a shore-based power supply. More than half of the specialized container berths have completed the installation and transformation of shore power equipment. Two mobile low-voltage shore power systems can be used in multiple berths at the Dalian Bay General Cargo Terminal. The construction target of the "Port Shore Power Layout Plan" proposed by the Ministry of Transport has been completed. In the future, Dalian Port Group will also carry out shore power project renovations to three specialized container berths and two specialized berths for the dry bulk cargo of 50,000 tons or more. The specific construction of ship-to-shore power in Dalian Port is shown in the following Table 13.

Table 13. Construction of shore-to-ship power in Dalian Port

Name of Wharf	Shore power construction berth	Finish Time	Shore power quantity	Power supply capacity and power supply system	Available power parking spaces
Dayaowan container terminal	9# - 12#, 15#, 16#	2012	6 set	50kKA 380V/50Hz	6
	15#	2016	1 set	3MVA 6.6kV/60Hz	
	18#	2016	1 set	2MVA 6.6kV/60Hz	1
Dayaowan Ore Wharf	40#, 15#	2017	1 set	3MVA 6.6kV/60Hz	2
Dayaowan bulk grain wharf	0#, 1#, 2#	2017	2 set	500kVA 0.45kV/60HZ	3
Dalian ro-ro ferry terminal	18#	2016	1 set	1MVA 6kV/50Hz	1
Dalian Bay general cargo wharf	17#, 19#, 20#	2017	3 set	800kVA 6kV/50Hz	3
Changxing Island Hengli Petrochemical bulk cargo wharf	One set of mobile frequency conversion types and one set of mobile power frequency	2017	2set	400kVA 0.45kV/60Hz 400kVA 0.4kV/50Hz	13

	1# - 3#	2016	1 set	5000kVA0.4kV/50Hz	3
SUM			18 set		32

4.6.2 The necessity of shore-to-ship power construction in Dalian Port

In recent years, China has successively introduced a series of policy requirements and incentive measures. Encourage port companies to build shore power facilities, to have the ability to provide shore power services to ships calling at the port, to achieve the purpose of energy saving, emission reduction, and improvement of the ecological environment.

(1) The policy necessity of shore power for ports and ships.

The State Council’s "Thirteenth Five-Year Plan for Energy Conservation and Emission Reduction" and the Ministry of Transport’s "Special Action Plan for Ship and Port Pollution Prevention and Control (2015-2020)" proposed that "by 2020, 90% of the country’s major ports will be used for ships, Official ships use shore power when calling at ports, and 50% of specialized terminals for the container, ro-ro passenger and post ships can supply shore power to ships. In July 2017, the Ministry of Transport issued the "Port and Shore Power Layout Plan" and proposed that by 2020, the country’s major ports and emission control zones should have 493 specialized berths capable of supplying shore power to ships, including 366 coastal ports. There are 127 inland river ports. The promulgation of a series of policies and programs has provided rare opportunities and broad development space for the construction of my country's port shore power greatly increased the enthusiasm for its construction and enhanced the core competitiveness of port enterprises.

(2) The environmental benefits of shore power for ports and ships.

When ships use auxiliary diesel engines to generate electricity during their berths, they will inevitably produce a large number of harmful substances, including nitrogen oxides, sulfur oxides, carbon monoxide, carbon dioxide, hydrocarbons, and suspended particulate matter. The production of these pollutants can cause extreme damage to the environment. Great pollution and destruction. The application of shore power technology enables ships to stop marine generators during berthing and switch to the power supply provided by the wharf, which can greatly reduce pollution emissions during berthing and eliminate the ship’s power generation. The noise pollution caused by the work of the generator set improves the ecological environment of the port area and creates a good living and working environment for the residents and ship workers in the port area. Its environmental benefit advantage is very significant.

(3) Advantages of economic benefits of port shore power.

Replacing the ship’s fuel generators with power supply from the port’s power grid can greatly reduce the cost of power supply during the ship’s docking period, reduce energy consumption, extend the service life of auxiliary generators, and reduce electricity costs and equipment maintenance costs. Port enterprises can purchase electricity at an agreed price and sell it to shipping companies to earn a certain service fee by signing a power purchase agreement with a power supply company to supplement the maintenance and maintenance costs of shore power equipment, thereby promoting the availability of port shore power construction and use. Continuous development. In addition, from the perspective of the development of the port shore power industry, with the country’s vigorous advocacy and encouragement, the demand for shore power equipment from port terminals across the country has greatly increased, which is bound to promote the innovation of shore power technology and promote the formation of the shore power industry chain. And development, which will bring hundreds of billions of industrial added values.

4.6.3 Data analysis of environmental benefits of shore-to-ship power in Dalian Port

Environmental benefits generally refer to the contribution of human production, construction, and business activities to the promotion of environmental improvement. The term environment includes two aspects. The first aspect is the natural environment such as air, soil, water, animal and plant systems, etc.; the second aspect refers to the human environment. Ship shore power technology replaces the current situation of using auxiliary engine fuel oil to generate electricity after ships dock, thereby reducing the emission of pollutants into the air. Therefore, the analysis of the environmental benefits of ship shore power in Dalian Port in this research was carried out mainly from the perspective of air pollutant emissions.

Composition and hazards of pollutants

Before the application of shore power technology, the electricity used by ships during berthing operations was mainly obtained from their auxiliary engines, while the auxiliary engines needed to burn a large amount of heavy oil or diesel at the same time. The main components were hydrogen sulfide, mercaptans, and Benzene series hydrocarbons, during the combustion process, ships will emit a large number of pollutants into the air, which will cause varying degrees of harm to the atmospheric environment and human health. The main components of the pollutant emissions include nitrogen oxides (NOx), sulfur oxides (SOx), carbon oxides (CO2), and suspended particles. The composition of these compounds and the hazards are shown in the following Table 14.

Table 14. Composition and harm of pollutants discharged from ships

Contaminants	Constitute	Hazard
NO_X	$NO.NO_2$	Formed by chemical smoke, which damages human health and causes asthma, emphysema, bronchitis, pharyngitis, rhinitis, and other diseases. If inhaled in excess, it will lead to pulmonary failure.
SO_X	$SO_2.SO_3$	This kind of pollutant is the main source of acid rain and causes strong irritation to human eyes and respiratory mucosa. In severe cases, it will cause pulmonary edema, laryngeal edema, and even ventricular death.
Volatile organic compounds	$CO.CO_2$	It is an important component of greenhouse gases and causes serious damage to the atmospheric ozone layer. At the same time, it will stimulate the human eyes and respiratory tract, resulting in dizziness, visual impairment, and other diseases, memory loss.
Diesel particulate	PM	Can enter the lungs, blood vessels, heart, and other key organs of the body through the respiratory tract, causing asthma, lung cancer, heart, and other diseases.

Control of emission pollution

(1) Control of sulfur and oxygen compounds

The "International Convention for the Prevention of Pollution from Ships" puts forward a clear requirement for the control of sulfur oxygen compounds: the mass percentage of any fuel oil used by ships shall not exceed 4.5% by mass. Ships can use the exhaust gas purification system approved by the competent authority by the guidelines formulated by the IMO to reduce the ship's sulfur oxide emissions to 6.0 g/(kWh).

From a technical point of view, the main methods for controlling the emission of sulfur oxygen compounds from ships include: using low-sulfur fuel and desulfurizing the exhausted flue gas. Fuels with low sulfur content are expensive because they need to be desulfurized, and they are not widely used. One of the main methods of desulfurization technology for flue gas is water washing, and the flue gas is treated in a scrubber to desulfurize oxygen compounds. The wastewater produced by the washing water after dissolving the sulfur oxygen compounds is relatively acidic and cannot be discharged at will. Therefore, the key technical problem in this method is how to treat the washing water to avoid secondary pollution. At present, the main treatment methods of washing water in the world are the wet lime method and chemical neutralization method, but these methods are relatively complicated in the process of treatment, and the requirements for the equipment and costs involved are high not been widely adopted.

(2) Control of nitrogen and oxygen compounds

The current control of nitrogen oxide emissions mainly includes internal one-time measures and external secondary measures. One-time internal measures are mainly used to reduce the combustion temperature and the concentration of oxygen during combustion during the working process of the oil recovery unit to achieve the purpose of optimizing and reducing the emission of nitrogen oxides. Internal secondary measures refer to the treatment of exhaust gas to reduce nitrogen oxide emissions. At present, urea is mainly used as a catalyst to selectively reduce the emitted nitrogen oxides, which can reduce the emission of nitrogen oxides by more than 90%. However, due to factors such as equipment investment and high transportation costs, the widespread use of this method is limited.

(3) Control of volatile organic compounds

The main components of volatile organic compounds are carbon monoxide and carbon dioxide. The control of carbon monoxide is mainly through the modification of diesel engines to make the fuel burn more fully and achieve the purpose of reducing emissions. Carbon dioxide has strong chemical stability and is expensive to control, so it is relatively difficult to control its emissions.

Calculation method of pollutants discharged by ships calling at the port

At present, there are two calculation methods for calculating pollutant emissions from ships. One is to use the top-down fuel method to calculate based on the amount of fuel consumed by the ship or the volume of cargo turnover. The other is to use the automatic identification system to collect real-time data such as ship speed and sailing time and use the bottom-up dynamic method for calculation. According to the requirements for the content of nitrogen oxides and sulfur oxides in marine fuels, this study selects the bottom-up dynamic method to measure the emissions of pollutants during the operation of ships calling at Dalian Port. The formula for calculating the power of auxiliary machinery during the docking period:

$$P = MCR \times LF \tag{25}$$

Among them:

P is the power of the auxiliary machinery during the docking period of the ship;

MCR is the rated power of the ship's auxiliary machinery;

LF is the load factor of auxiliary machinery during the ship's berth.

The calculation formula for the pollutant emission of auxiliary machinery during the docking period of the ship:

$$E = P \times T \times EF \times FCF \times CF \times 10^{-6} \tag{26}$$

Among them:

E is the amount of pollutants discharged;

T is the docking time of the ship;

EF is a pollutant emission benchmark factor, based on the emission factor of heavy oil with a sulfur content of 2.7%;

FCF is the fuel oil correction factor - when the sulfur content of the fuel used by the ship is different from 2.7% of heavy fuel oil, the emission volume must be multiplied by the fuel oil correction factor to determine the final emissions;

CF is an emission control factor.

Calculation of pollutant emissions from ships calling at Dalian Port

Taking the 400,000-ton super-sized vessel “Minghui” that docked at Dalian Port after 18 years of continuous power supply for two hours, the rated power of the “Minghui” main engine is 45,000 horsepower, which is approximately equivalent to 33,000 kW, the ship mainly relies on auxiliary machinery to generate electricity during the docking period. The power ratio coefficient of the main engine and the auxiliary engine is shown in Table 15:

Table 15. Power ratio coefficient of main engine and auxiliary engine

Ship type	Oil tanker	Bulk cargo	Chemical ship	Container ship	Liquefied gas ship	Roro ship	General cargo
Ratio coefficient	0.211	0.222	0.211	0.22	0.211	0.278	0.191

The calculations performed in this study are based on the data on the air pollution emission factors produced and published by the Port of Los Angeles in the United States (Tables 16-18).

Table 16. Emission factors of pollutants from auxiliary equipment of ocean-going ships

PM_{10}	$PM_{2.5}$	DPM	NO_X	SO_X	CO	HC	CO_2	N_2O	CH_4
1.5	1.2	1.5	13.0	12.3	1.1	0.4	683	0.031	0.005

Table 17. Fuel correction factors

Fuel type	Sulfur content	PM	NO_X	SO_X	CO	HC	CO_2	N_2O	CH_4
Heavy oil	3.5%	0.82	1	0.56	1	1	1	1	1
Diesel oil	1.5%	0.47	0.9	0.56	1	1	1	0.9	1
Diesel / light oil	0.5%	0.25	0.94	0.18	1	1	1	0.94	1
Diesel / light oil	0.2%	0.19	0.94	0.07	1	1	1	0.94	1
Diesel / light oil	0.1%	0.17	0.94	0.04	1	1	1	0.94	1

Table 18. Load factor of the auxiliary engine during ship docking

Ship type	Container ship	Bulk cargo	liner	LNG	Roro ship	Chemical ship	General cargo
Load factor	0.4	0.4	0.7	0.7	0.7	0.4	0.4

The results of performed calculations show that the use of shore-to-ship power supply during the docking period of the "Minghui" vessel can reduce pollutant emissions as shown in Table 19:

Table 19 Pollutant discharge of "Minghui" cargo vessel

Contaminants	Emissions(t)	Contaminants	Emissions(t)
PM_{10}	0.0022	CO	0.0065
$PM_{2.5}$	0.0018	HC	0.0023
DPM	0.0022	CO_2	4
NO_X	0.0617	N_2O	0.0002
SO_X	0.0130	CH_4	0.00003

4.6.4 Data analysis of economic benefits of shore-to-ship power in Dalian Port

Data analysis of economic benefits of the shipowner

Taking the 400,000-ton "Minghui" vessel and the "COSCO France" 1.5ETU container ship docking in Dalian Port as an example, if auxiliary engines are used to generate electricity during the docking period, according to the specific requirements of China's current ship air pollutant emission control zone berthing ships need to use light oil with a sulfur content of not more than 0.5% during the docking period. The actual fuel consumption calculation formula is as follows:

$$E = P \times T \times \eta \times 10^{-3} \tag{27}$$

Among them:
P is the auxiliary engine power during the docking period of the ship, see formula 3.1 for details;
T is the stop time;
η is the average fuel consumption of auxiliary engine power generation
The average fuel consumption of ship auxiliary engine power generation is 0.215kg/kWh according to the calculation rules of the International Maritime Organization's Ship Energy Efficiency Design Index (EEDI). According to described calculation method, the actual fuel consumption of the “Minghui” placer ship during the docking period is 1.26 tons, and the sulfur content should not exceed 0.5% of light oil. The reference price is about 3,000 yuan/ton, and the fuel price costs 3780 yuan.
If the “Minghui” uses a shore-based power supply during its docking period, according to the “Diesel Truck Pollution Control Action Plan” it is proposed that terminals and other shore power operators are allowed to charge ships for electricity according to the current electricity price policy. Port shore-based power supply Implement the policy of “large industrial electricity prices, free of storage (required) costs”. The tariff conditions used for calculations are: 0.433 yuan/kWh, and time according to Fenggu’s time-of-use tariff requirements (peak hours: 8:00-11: 00 and 17: 00-22: 00 total) for 8 hours, the electricity price will rise by 50%, and during the trough period from 22: 00 to 5: 00 the next day, the electricity price will fall by 50% for a total of 7 hours, and the electricity price will remain unchanged for a total of 9 hours in other periods), and the average electricity price of the two periods is taken as 0.441 yuan/kWh. The formula for calculating the electricity bill during the docking period of the "Minghui" vessel is as follows:

$$W = P \times T \times \mu \tag{28}$$

where W is the total cost of electricity used during the parking period; P is the power of auxiliary machinery during the docking period of the ship; T is the stop time; μ is the price of electricity;
According to performed calculations, the electricity cost of the "Minghui" placer ship during docking is 2,561 yuan, which can save 1,219 yuan in fuel costs compared to the use of auxiliary engines for power generation during docking operations in the past.
Data analysis of economic benefits of the port
At this stage, for the port side, the investment in the early construction and renovation of shore power is relatively large. Take the cruise berth in the Dalian port area under construction as an example. According to the calculation of Dalian Port, without considering related issues such as power capacity increase in Zhongshan District, the construction of 16 MW shore power facilities requires an investment of about 57 million yuan, and the power unit needs to invest more than 10 million yuan. Although the state has issued subsidies for shore power construction in recent years, in 2018, Dalian Port’s general cargo terminal, ore terminal, bulk grain terminal, Dalian Bay passenger terminal, and other shore power projects received a total of 8.15 million yuan in rewards from the Ministry of Transport. The shore power project in the circular low-carbon port theme project has received nearly 3 million yuan in funding from the Ministry of Communications, but these awards are a drop in the amount of early construction costs. In addition, most of the ships arriving at the port do not have power receiving devices and do not have the conditions to apply shore power. Shipping companies are not very enthusiastic about transforming ships to connect shore power, and the demand for shore power connection is not obvious, which in turn results in the very low utilization rate of shore power facilities in Dalian Port. Combining the above analysis, it should be suggested that the country should introduce a policy system for electricity tariffs on the issue of shore power charging, set reasonable electricity prices, and allow shore power operators to charge corresponding service fees, to ensure the sustainable development of the economic benefits of shore power at the port.

4.6.5 Results of the study

Through the analysis of the environmental and economic benefits of shore power in this study, it is not difficult to see that shore power can help ships calling at Dalian Port to reduce emissions during docking, and at the same time, it can save energy consumption and reduce operating costs. It has a good environment for ships. And economic benefits. For the port side, although shore power projects can reduce pollution emissions in the port area and improve the living and working environment of the port area, it is easy to bear the construction and operating costs of shore power, and the corresponding profits are not appreciable. Causes the loss of shore power at the operating stage, so for the port side, the shore environmental benefits are significant but the economic benefits are not obvious.

5. Discussion of calculation results

Using the proposed MVP of optimization tool a few calculation scenarios for a different rate of renewable energy sources penetration were calculated. The results and discussion of the calculation are described in this section.

The basic approach for the calculation consisted of some simplifications, such as:

- power losses in the external and internal grid were not taken into account;
- only one-year load series were used as input parameter, the reason is the unavailability of longer period data, because of security reasons, introduced by the Russian government;
- only Russian port electrical load series were used, the reason is the inability to provide the meeting with port authorities in other countries, because of the COVID-19 pandemic.
- solar irradiation and wind speed data were achieved from the closest meteorologic station, but not exactly in the place installation, the reason is insufficient funds and time for project realization to install proper meteorological equipment on site.

5.1 Port consumption optimization scenarios with one renewable source

Taking into account the different installed capacities of the solar power plant that provides power to the Kaliningrad port, the values of electricity generation for the study period - from June 1, 2020, to May 31, 2021 are analyzed. The average annual generation profile of a solar power plant is shown in Fig. 71.

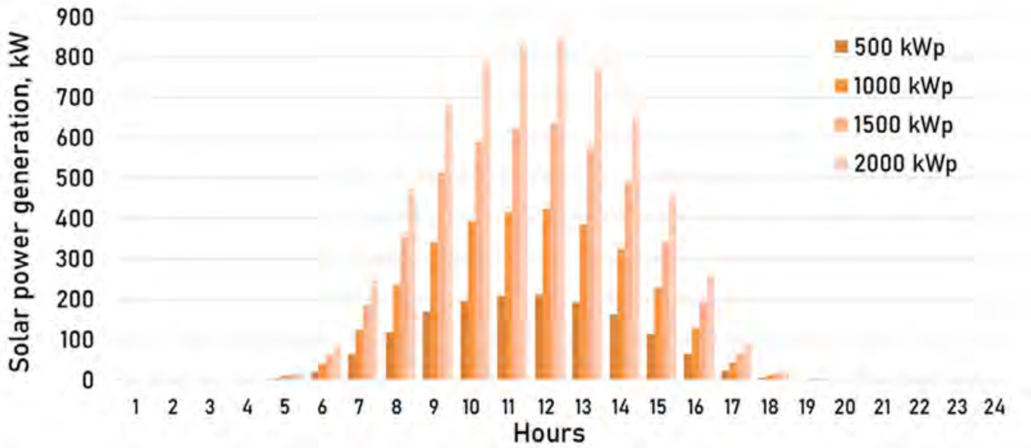


Fig. 71. Average hourly values of solar generation

The influence of a solar generation of various installed capacities on the port's power consumption from the power system during the year under study is reflected by thermal load diagrams (Fig. 72). The presence of generation significantly reduces the power consumption of the port from the power system in the “spring-summer” zone during the daytime from 8 a.m. to 5 p.m.

In more detail, the impact of solar generation on the power consumption graph of the seaport is shown in a bar chart built based on average annual power values (Fig. 73). Thus, the generation of electricity by a solar power plant covers the load curve of the seaport from the power system in the region from the 8 a.m. to 2 p.m. of a typical day.

Using the developed optimization technique, annual load curves were analyzed taking into account solar generation. The result of the analysis is the dependence of the possible value of the seaport's savings on power on the value of the specified capacity of the electric power storage (Fig. 74). It can be seen from the graph that the presence of generation shifts the savings curve above the savings curve of the initial electricity consumption without renewables.

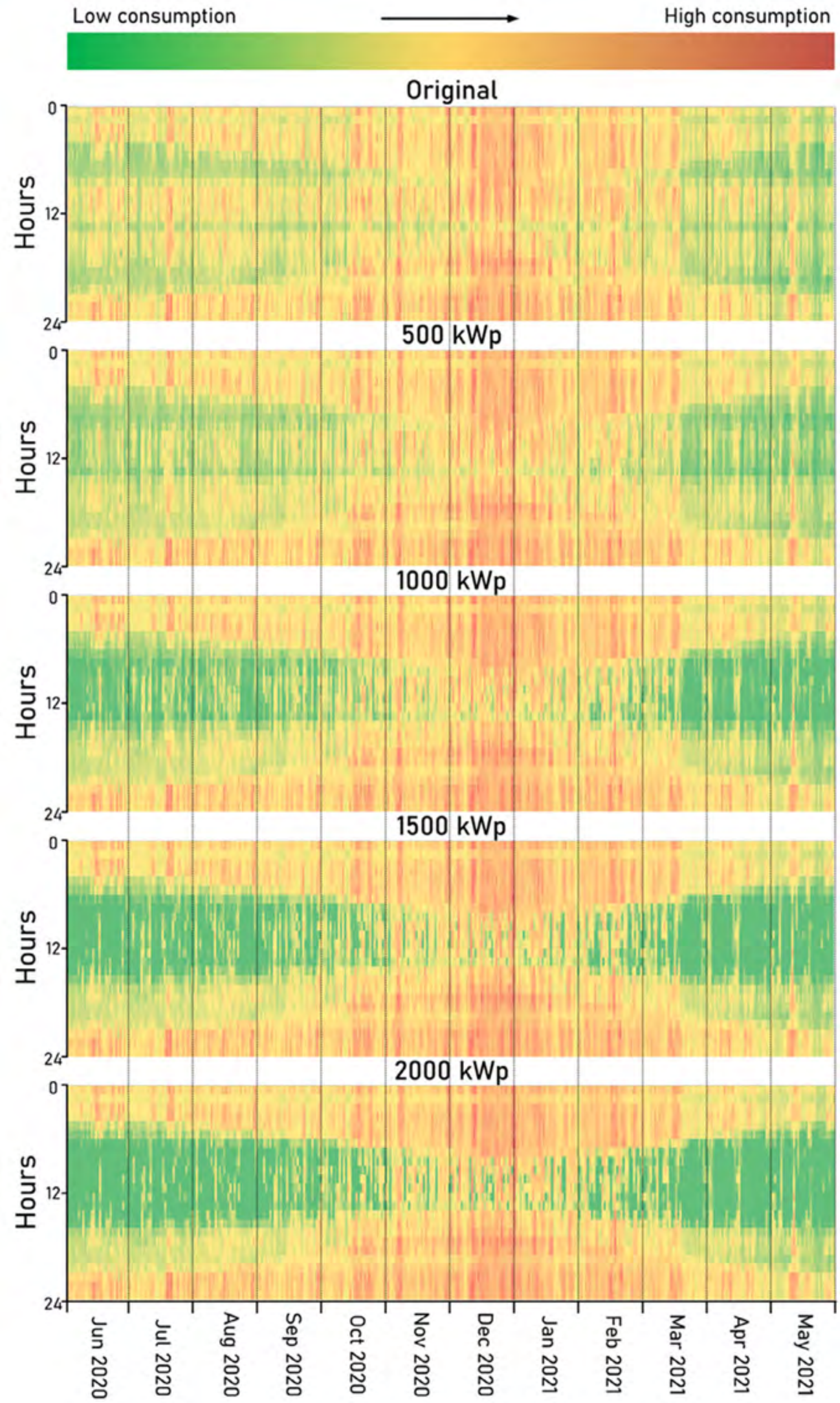


Fig. 72. Heat maps of the port's power consumption from the power system, taking into account solar generation

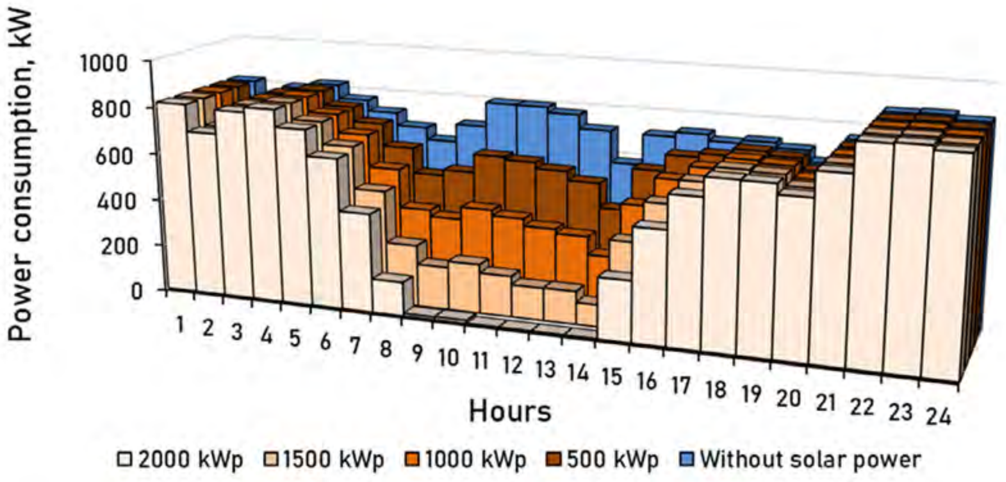


Fig. 73. Daily load chart of port's power consumption from the power system, taking into account solar generation

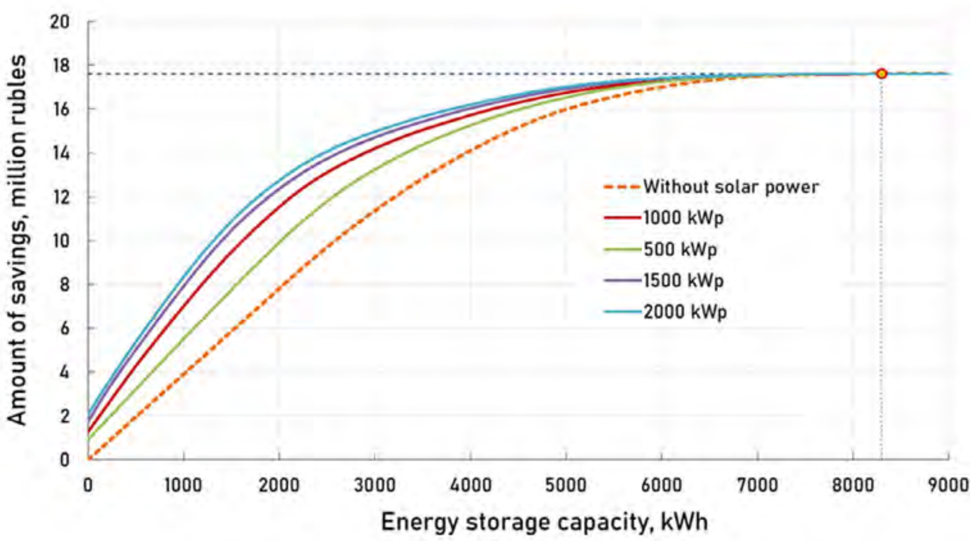


Fig. 74. Dependence of the amount of port saving on power on the capacity of the electric power storage

At the same time, the value of the maximum savings is the same for all the cases presented and amounts to 17.6 million rubles, due to the achievement of the maximum coverage of the port's power consumption during scheduled hours.

The value of sufficient capacity of the energy storage device to achieve the corresponding savings can also be represented in the form of the dependence shown in Fig. 75.

For the point of maximum savings corresponding to the value of the storage capacity of 8298 kWh for the initial power consumption of the port, software optimization was carried out using the described methodology. The results of optimizing the port's power consumption by minimizing power costs are reflected in the average annual load profile of the port from the power system (Fig. 76).

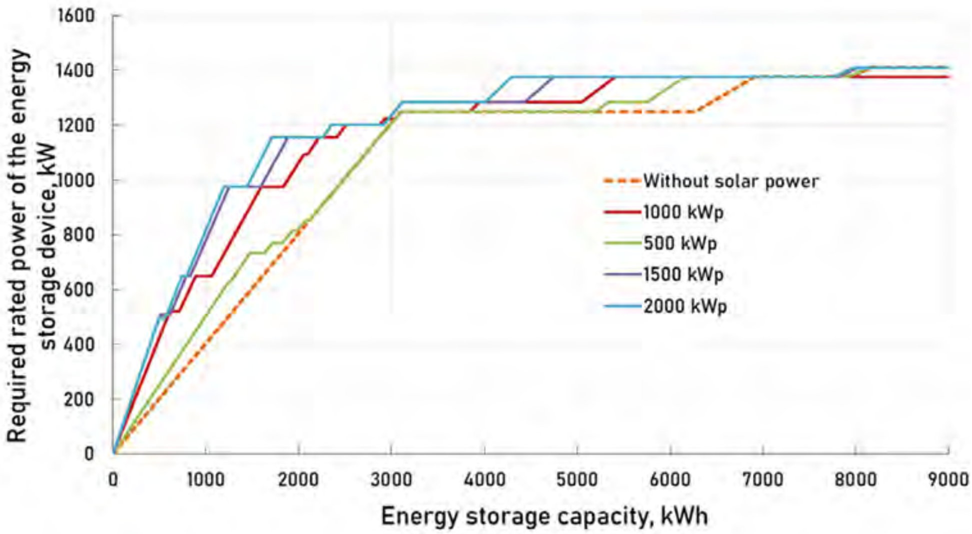


Fig. 75. Dependence of the maximum sufficient power of the energy storage device on its capacity

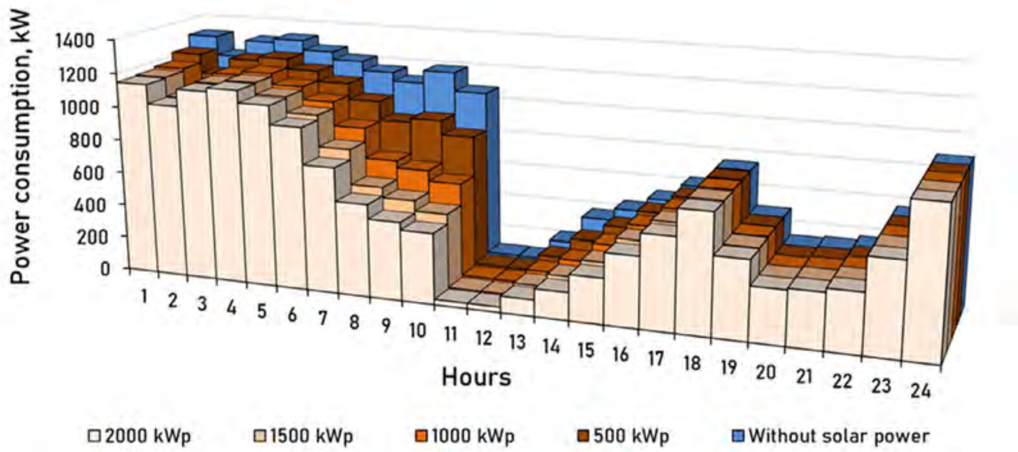


Fig. 76. Port power consumption dependence with solar generation and ESS optimization

Based on the presented data, it can be concluded that the presence of renewable energy in the port with the simultaneous use of optimization of power consumption by the storage device allows reducing the cost of power by covering the power consumption of the seaport from the power system during the scheduled peak load hours.

5.2 Port consumption optimization scenarios with renewable sources combination and ESS

The conclusion made about the significant impact of solar generation on reducing the power consumption of the seaport from the power system can be extended to wind energy.

An analysis of the wind potential of the territory of the Kaliningrad Seaport was carried out to determine the values of electricity generation by a wind farm located in the port at a height of 30 m. The values were determined for various installed capacities of the wind farm within the study period. The average annual generation profile of wind farms is shown in Fig. 77.

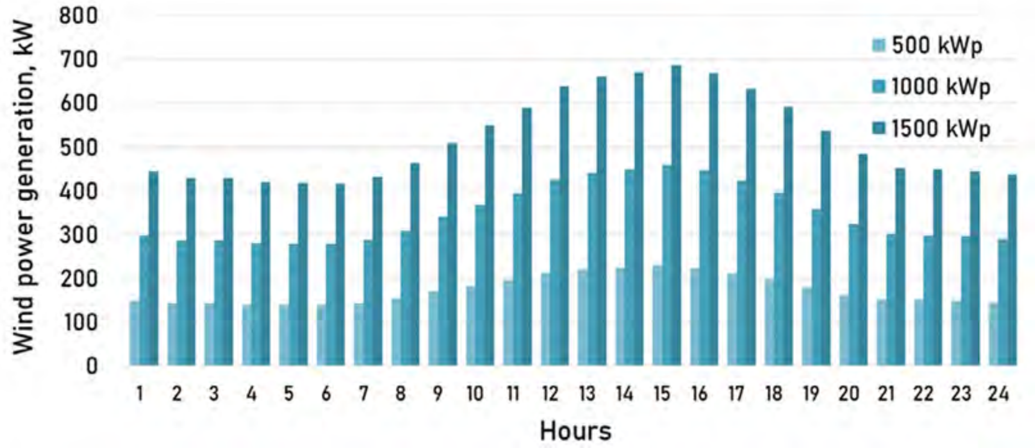


Fig. 77. Average hourly values of wind farm generation per day

To evaluate the results of optimizing the schedule of electrical loads with renewable generation, various combinations of wind and solar generation of various installed capacities were formed in the form of scenarios. Thermal diagrams in Fig. 78 reflect the annual load curve of the seaport from the energy system after the program optimization for various scenarios.

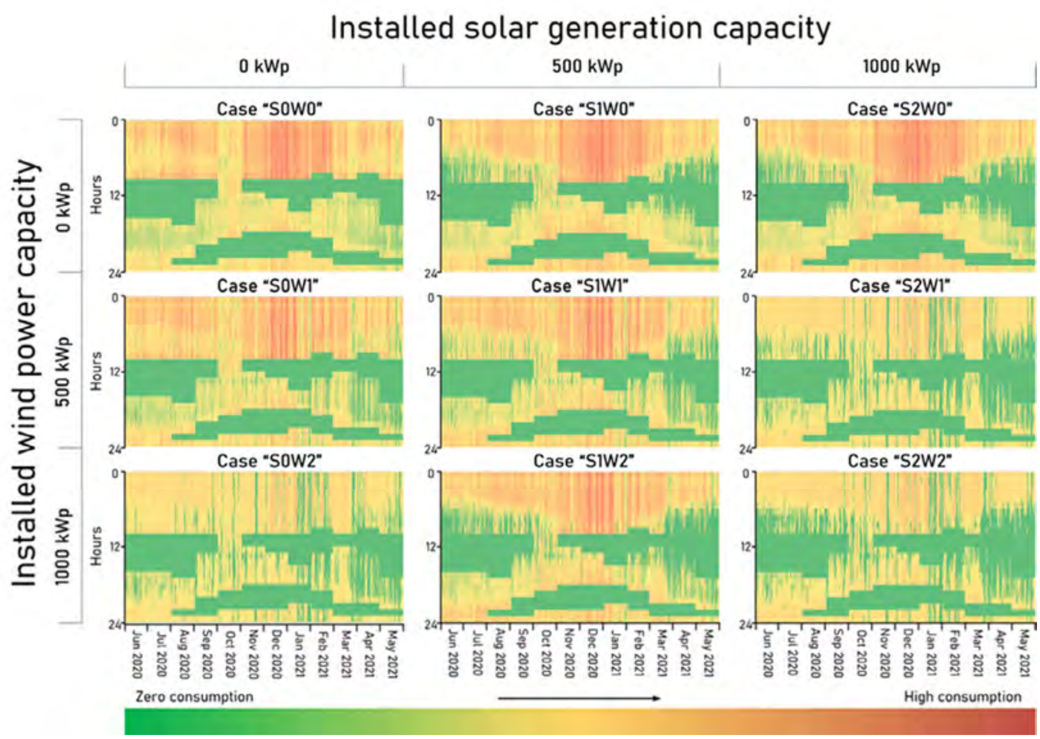


Fig. 78. Heat maps of the port's power consumption from the power system side, taking into account renewable generation scenarios after optimization

The values of the annual power consumption of the seaport from the power system under various scenarios are expressed in the form of histograms in Fig. 79. The analysis of the diagrams shows that the largest decrease in annual power consumption is manifested by the combination of solar and wind generation at installed values of 1000 kW and 1000 kW, respectively - scenario “S2W2”.

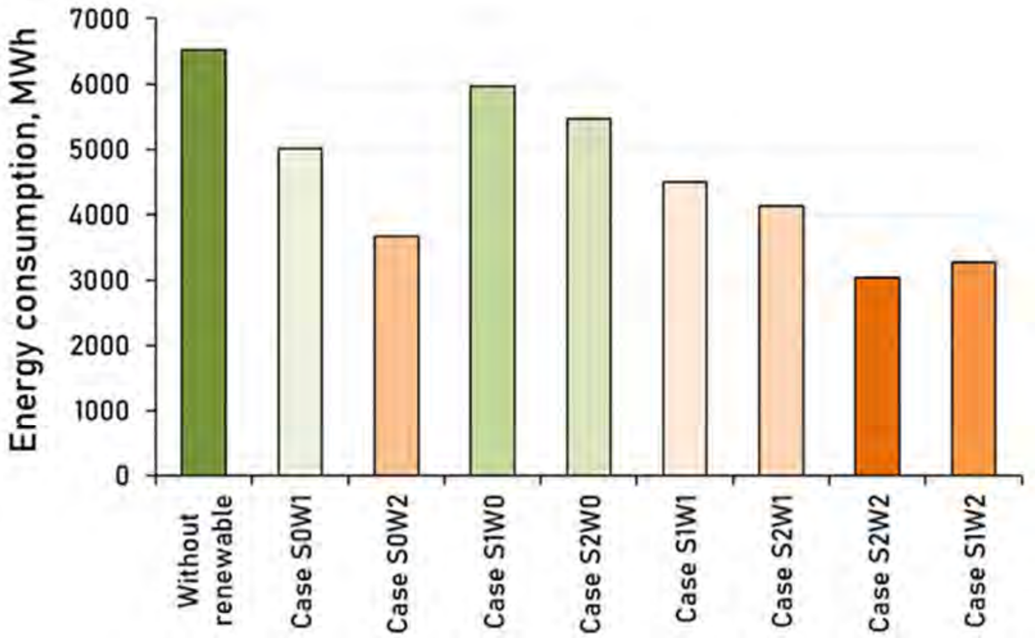


Fig. 79. Volumes of annual energy consumption for renewable energy scenarios

At the same time, the presence of solar generation does not make such a significant contribution to reducing electricity consumption as wind generation. The difference in electricity consumption of the “S1W2” scenario relative to the “S2W2” scenario is about 230 MWh, due to the lack of 500 kW of installed capacity of the solar power plant.

Reducing the consumption of electricity from the system through the use of wind energy is 2.8 times higher than that of solar generation, which shows the feasibility of installing wind turbines in the port rather than solar panels.

Based on the results of the software optimization of power consumption for each of the cases under study, the dependence of the amount of saving on power on the capacity of the energy storage device was obtained. The dependence is shown in the graph in Fig. 80. Using the “S2W2” scenario provides a reduction of the storage capacity, at which the maximum amount of money saved on power is achieved, to 6550 kWh. For the “S0W2” scenario, this value is about 7050 kWh. Whereas in the absence of renewable energy generation in the port, it will be 8298 kWh.

The use of complex generating plants based on renewable energy in the port can significantly reduce the capacity of the energy storage system used to optimize the power consumption of the port from the power system to reduce power costs.

The results of optimizing the port's power consumption by minimizing power costs are also expressed in the form of an average annual load profile, shown in Fig. 81.

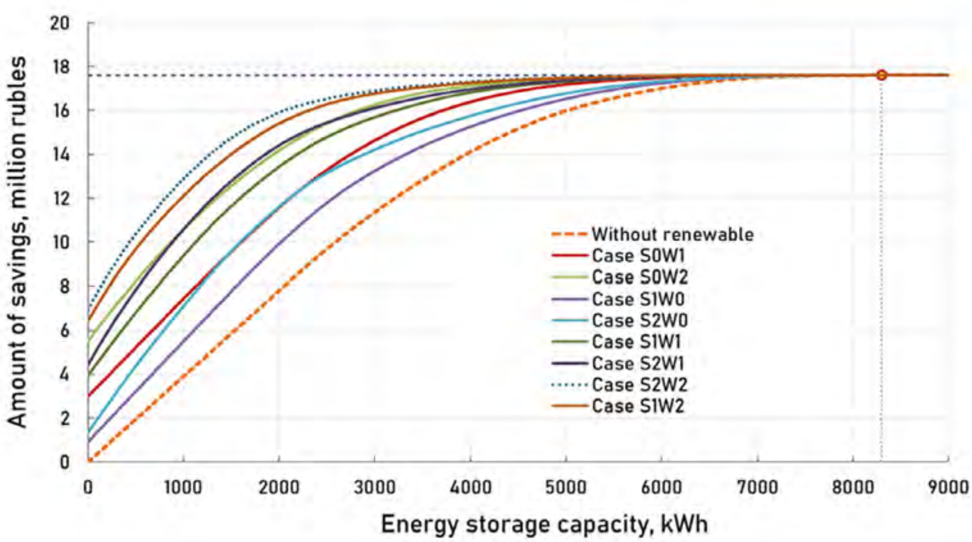


Fig. 80. Dependence of the port savings on the capacity of the energy storage for various scenarios of renewable generation

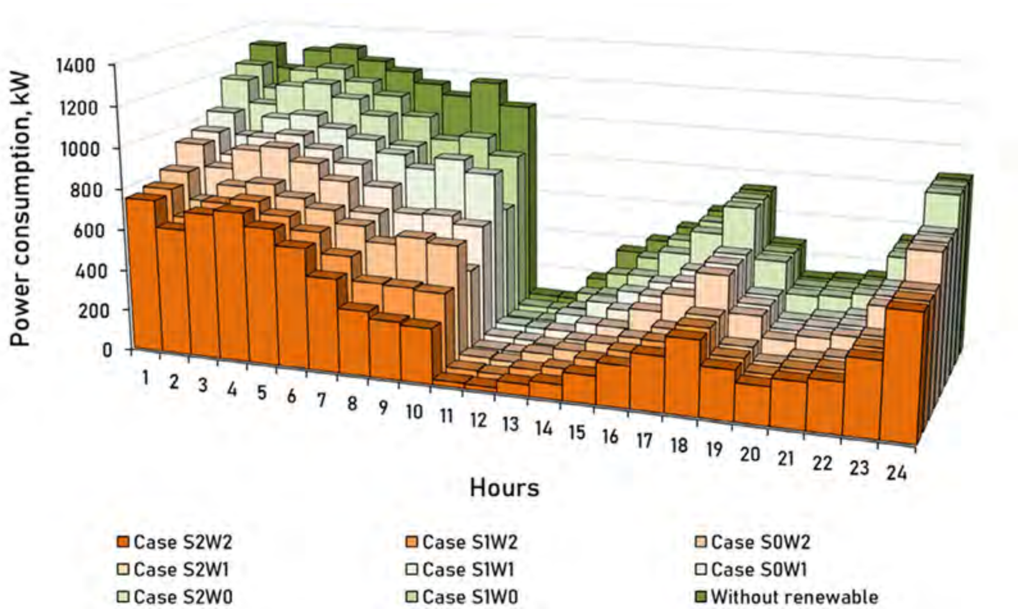


Fig. 81. Graphs of port energy consumption from the grid side under various renewable energy scenarios and storage use

5.3 Main findings of the case study research

Case study gives the results of calculations of port consumption optimization scenarios with one or multiple renewable sources, with and without energy storage system justified by the use of developed energy management framework for Kalininrad Region conditions. Preliminary calculations shows, that existing consumption of the port could be covered with renewables. Non conventional renewables, such as tidal or wave energy, bio-energy or geothermal energy were excluded from research on the 1st step, because of poor technological development at the moment, low economical feasibility and small potential on place of installation in Kaliningrad region. Only wind and solar energy were taken into scenario calculation as the most perspective. Also, all developing ESS technologies were excluded from the research, but they could be added into framework as soon as necessary.

- The presence of renewable generation shifts the savings curve above the savings curve of the initial electricity consumption without renewables.
- The presence of generation significantly reduces the power consumption of the port from the power system in the “spring-summer” zone
- Still, the presence of solar generation does not make such a significant contribution to reducing electricity consumption as wind generation.
- The use of complex generating plants based on renewable energy in the port can significantly reduce the capacity of the energy storage system used to optimize the power consumption of the port from the power system to reduce power costs.

5.4 Conclusions

Zero-emission port is a concept to be overtaken soon. Without a proper management framework for the operation control of the elements of the concept such as renewables, electrical storage system, cold-ironing system, and external electrical grid this concept is not sustainable and even not achievable.
According to the project schedule, the 1st part of the work was devoted to the refinement of the research aim and objectives based on the importance of the research. Because of COVID-19 pandemic conditions resulting in the inability to provide necessary stakeholders meetings, constraints were applied to initial data such as meteorological and port loads databases. As a result, the minimum viable product of optimization software was stated as delivery of the project.
Systematic literature review with the identification of the zero-emission port concept provided ground for methodology justification for necessary calculations. The results of the review are presented in section 2 of the report.
Describes the approach and the basic methodology for zero-emission port energy management framework development were developed and discussed in the 3rd part of the project. For the optimization procedure, the PSO algorithm was chosen. Solar and wind production were chosen for scenario calculations. Calculation methods to define actual production by these sources were justified for later calculations.
The selection of a port as the case study research was justified in the next section based on the analysis of geographical and meteorological information and the availability of initial data, provided for calculation. As mentioned before some limits arose during the project such as pandemic flight restrictions and the Russian Government's increased sensibility to providing international partners with information concerning port infrastructure. This results in a hasty change of the cold-ironing case scenario to Dalian.
In the next part of the project port consumption optimization scenarios with one and multiple renewable sources, and calculations were developed and presented.
In the last section of the project report, additional information on project dissemination results is given.

6. Dissemination of project results

6.1 Publications of project results

The results of the study were published during the project in Russian and International magazines.

[1] Kovalishin, P., Nikitakos, N., Svilicic, B., Zhang, J., Nikishin, A., & Kharitonov, M. (2021). USING ARTIFICIAL INTELLIGENCE (AI) METHODS TO COMBAT CLIMATE CHANGE at MARINE PORTS. Paper presented at the 21st Annual General Assembly, IAMU AGA 2021 - Proceedings of the International Association of Maritime Universities, IAMU Conference, 717-729.

[2] The paper "Using Artificial Intelligence (AI) Methods to Combat Climate Change at Marine Ports" (submitted, JOMA-D-21-00129, under review);

[3] Conference report "Conceptual framework for integration on renewable energy sources for marine port electrification by Profs. Nikitakos, Stefanakou, Nikishin, Kharitonov, Gordeeva, Popov, Kovalishin at the International Maritime Transport and Logistics Conference 11, session 7 "Blue Economy: Renewable Energy Perspective". Proceedings. Acknowledgements to the Nippon Foundation and IAMU. Alexandria, Egypt, March, 20-22.

[4] Nikishin A. Modernization of marine ports electrical power supply systems in the framework of zero-emission strategy / Nikishin A., Kharitonov M. // IOP Conference Series: Earth and Environmental Science, Kaliningrad, 05–10 October 2020. – Kaliningrad, 2021. – P. 012018. – DOI 5.1088/1755-1315/689/1/012018. – EDN GLQVLH.

[5] Nikishin A., Prospects for the use of renewable energy within the framework of the zero-emission concept of the port of Kaliningrad / Nikishin A., Kharitonov M., Nikitakos N. // Baltic Maritime Forum: materials of the VIII International Baltic Maritime Forum: in 6 volumes., Kaliningrad, October 05–10, 2020. - Kaliningrad: Kaliningrad State Technical University, 2020. - pp. 110-118. – EDN YIQBPZ.

[6] Kharitonov M., Nikishin A., Kazhekin, I. Problems of integrating renewable energy sources into power supply systems of sea mouth ports // Marine Intelligent Technologies. – 2020. – No. 4-2(50). - pp. 32-38. – DOI 10.37220/MIT.2020.50.4.069. – EDN LIJZTE.

[7] Prospects for the use of artificial intelligence in seaports to combat climate change / N. Nikitakos, P. Kovalishin P., Nikishin A., Kharitonov M. // Baltic Maritime Forum: materials of the IX International Baltic Maritime Forum: in 6 tons., Kaliningrad, 04–09 October 2021. - Kaliningrad: Separate structural unit "Baltic Fishing Fleet State Academy" of the Federal State Budgetary Educational Institution of Higher Education "Kaliningrad State Technical University", 2021. - P. 190-196. – EDN YPURZU.

[8] Nikishin A., Prospects for load schedule control technology to reduce seaport costs / Nikishin, M. S. Kharitonov M., Zubavichyus R.// Baltic Maritime Forum: materials of the IX International Baltic Maritime Forum: in 6 Vol., Kaliningrad, 04–09 October 2021. - Kaliningrad: Separate structural unit " Baltic Fishing Fleet State Academy " of the Federal State Budgetary Educational Institution of Higher Professional Education "Kaliningrad State Technical University", 2021. - pp. 196-202. – EDN GFTHUD.

[9] Nikishin A., Kharitonov M., Zubavichyus R. Electricity storage as a means of regulation of seaport power consumption // Marine Intelligent Technologies. - 2021. - No. 4-4 (54). – pp. 87-93. – DOI 10.37220/MIT.2021.54.4.012. – EDN KRWAIA.

[10] Osyka, M. Calculation of the efficiency of solar panels in the conditions of the Kaliningrad sea fishing port / M. Osyka, Nikishin A. // Bulletin of youth science. - 2021. - No. 1 (28). – pp. 12. – DOI 10.46845/2541-8254-2021-1(28)-17-17. – EDN OMAZYA.

[11] Logistics 4.0 in maritime sector / V. Petsini, D. Papachristos, N. Nikitakos [et al.] // Operation of maritime transport. – 2022. – No 1(102). – pp. 74-83. – DOI 10.34046/aumsuomtl02/16. – EDN VKGDYM.

6.2 Participation in national and international conferences

The results and some aspects of the study were presented at National and International conferences. IAMU AGA conference slides are included into appendix B of the report.

1. 21st Annual General Assembly, IAMU AGA 2021 Alexandria, Egypt. Presenter: Andrey Nikishin.
2. The International Maritime Transport and Logistics Conference 11, session 7 “Blue Economy: Renewable Energy Perspective”. Proceedings. Acknowledgements to the Nippon Foundation and IAMU. Alexandria, Egypt, March, 20-22. Presenter: Nikitas Nikitakos.
3. BUP Symposium 2021/ Perspectives of demand response technology as one of the options for sustainable operation of Kaliningrad region energy system. Presenter: Andrey Nikishin.

6.3 Stakeholders’ meetings

During the project four main stakeholders’ meetings were organized by the manager of the project Pavel Kovalishin.

1. Preliminary meeting with the local stakeholders - the representatives of federal state unitary enterprise (ROSMORPORT) in charge of operation and development of Kaliningrad Marine Port to discuss and investigate the statement of facts and the case – existing practices in terms of RES use, potential for further development of the sector, analysis of the data required.

Participants: ROSMORPORT, head of commercial department : Nikolay Mamenko, Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Andrey Nikishin, the chief coordinator of the project Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Maxim Haritonov, the deputy chief coordinator of the project

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Pavel Kovalishin, project manager.

2.The 1st ZOOM «Kick-off» international Meeting of the «FRONTER» project consortium of the projects partners. Wednesday, April,1 2020. Via Zoom application.

Participants:

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Andrey Nikishin, the chief coordinator of the project

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Maxim Haritonov, the deputy chief coordinator of the project

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof.Pavel Kovalishin, project manager

University of the Aegean(UA)(Greece): Prof. Nikitas Nikitakos, deputy project coordinator for science

University of Rijeka: Prof. Boris Svilicic

Dalian Maritime University: Prof. Zhang Jinnan

Results: the roles for further activities have been assigned.

The initial step of our joint work - to present the state of the art review of the research problem as well as to gain empirical/practical evidence of the relevance of the research issue and the national cases.

3. Visiting the largest Russian Black Sea Port of Novorossiysk, DELO(container terminal),TRANSNEFT(oil/coal/timber terminal), ROSMORPORT (1st workshop).

Meeting with the stakeholders owning and operating the facilities, responsible for energy supply and efficiency. July,18-23 2021

Participants: ROSMORPORT, head of commercial department : Nikolay Mamenko, Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Andrey Nikishin, the chief coordinator of the project Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Maxim Haritonov, the deputy chief coordinator of the project ,Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Pavel Kovalishin, project manager.

The KSTU research team carried out the analysis/interviewed on the situation connected with the presence and introduction of the use of renewable energy sources.

For this purpose, the team investigated 3 marine ports in one region dealing with the officials.

We selected the ports due to the leading position of cargo operation and throughput.

4. Meeting in Kaliningrad (full time).

Kaliningrad State Technical University. October,4-9 2021

Summing up the state of the art reviews from the partners using 'Prisma" and the data gained in terms of the project national cases concerned with the ports energy management and possible measures to increase its efficiency thus lowering the negative impact on the environment….

Participants: Andrey Nikishin, the chief coordinator of the project

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof. Maxim Haritonov, the deputy chief coordinator of the project

Baltic Fishing Fleet State Academy(BFFSA) of Kaliningrad State Technical University (KSTU): Prof.Pavel Kovalishin, project manager

University of the Aegean(UA)(Greece): Prof. Nikitas Nikitakos, deputy project coordinator for science

University of Rijeka: Prof. Boris Svilicic

Dalian Maritime University: Prof. Zhang Jinnan

Reports presented- «Demand analysis of shore power capacity of Tianjin Port Wharf Dalian Port in Liaoning Province and Lianyungang Port in Jiangsu Province». Comprehensive analysis of the cold ironing use and its environmental and economic benefits has been presented by Prof. Zhang Jinnan (Dalian Maritime University)

"Analysis of the experimental data gained from the climatic station of the Port of Dubrovnik" by Prof. Boris Svilicic (University of Rijeka)

References

[1] Asariotis R *et al* 2019 *Review of Maritime Transport* UNCTAD/RMT/2019. Available at: https://www.unece.org/fileadmin/DAM/cefact/cf_forums/2019_UK/PPT_L_L-UNCTAD-RMT.pdf

[2] D.O. Akinyele, R.K. Rayudu. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments, **8,** 74-91.

[3] Lindstad H E, Eskeland G S 2016 *Transportation Research Part D: Transport and Environment* **47** 67–76

[4] GreenPort 2018 IMO sets first industry wide emissions strategy. Available at: https://www.greenport.com/news101/Regulation-and-Policy/imo-sets-firstindustry-wide-emissions-strategy

[5] Carpenter A, Lozano R, Sammalisto K, Astner L 2018 *Marine pollution bulletin* **128** 539–547

[6] A. Nikishin, M. Kharitonov. Modernization of marine ports electrical power supply systems in the framework of zero-emission strategy. IOP Conf Ser: Earth Environ Sci. **689**(1), 012018, (2021 Mar 1).

[7] X. Luo, J. Wang, M. Dooner, J. Clarke. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied energy. **137**, 511-36, (2015 Jan 1)

[8] A. Martín-Martín, M. Thelwall, E. Orduna-Malea, E.D. López-Cózar. Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science, and OpenCitations' COCI: a multidisciplinary comparison of coverage via citations. Scientometrics 126(1), 871-906, (2021 Jan).

[9] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, D. Moher. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. Journal of Clinical Epidemiology 134, 103-12, (2021 Jun 1).

[10] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Prisma Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS medicine 6(7), e1000097, (2009 Jul 21).

[11] https://www.eurelectric.org/ports-green-gateways-to-europe

[12] Binti Ahamad, N.B., Guerrero, J.M., Su, C.-L., Vasquez, J.C., Zhaoxia, X., "Microgrids technologies in future seaports". In: 2018 IEEE Int. Conf. Environ. Electr. Eng. 2018 IEEE Ind. Commer. Power Syst. Eur. (EEEIC/I&CPS Eur. IEEE), (2018), pp. 1-6. https://doi.org/10.1109/EEEIC.2018.8494428.

[13] Rødseth, K.L., Schøyen, H., Wangsness, P.B., "Decomposing growth in Norwegian seaport container throughput and associated air pollution". Transport.Res. Transport Environ. 85,(2020), 102391https://doi.org/10.1016/j.trd.2020.102391

[14] Ahamad, N.B., Othman, M., Vasquez, J.C., Guerrero, J.M., Su, C.L.,"Optimal sizing and performance evaluation of a renewable energy based microgrid in future seaports". Proc IEEE Int Conf Ind Technol,(2018). https://doi.org/10.1109/ICIT.2018.8352322. Febru:1043e8.

[15] Osterman, C., Hult, C., Praetorius, G., "Occupational safety and health for service crew on passenger ships". Saf. Sci. 121, (2020), pp. 403-413. https://doi.org/10.1016/ j. ssci.2019.09.024.

[16] Lindstad, H.E., Eskeland, G.S., "Environmental regulations in shipping: policies leaning towards globalization of scrubbers deserve scrutiny". Transport. Res.Transport Environ. 47, (2016), pp. 67-76. https://doi.org/10.1016/j.trd.2016.05.004.

[17] Asad Tariq., Onshore power supply in Europe –an overview. 2021

[18] OJL 307, 28. 10.2014, p.1.

[19] Council Directive 2003/96/EC.

[20] European Commission, 2015. Launching the Public Consultation Process on a New Energy

Market Design.
[21] Gonzalez Aregall, M., Bergqvist, R., Monios, J., “A global review of the hinterland dimension of green port strategies.” Transport. Res. Transport Environ. 59, (2018), pp 23-34. https://doi.org/10.1016/j.trd.2017.12.013
[22] He, J., Huang, Y., Yan,W., “Yard crane scheduling in a container terminal for the trade-off between efficiency and energy consumption.” Adv. Eng. Inf. 29, (2015), pp 59-75. https://doi.org/10.1016/j.aei.2014.09.003.
[23] Defeuilley, C., “Energy transition and the future(s) of the electricity sector”, Util. Pol. 57, (2019), pp 97-105. https://doi.org/10.1016/j.jup.2019.03.002
[24] Winnes, H., Styhre, L., Fridell, E., “Reducing GHG emissions from ships in port areas.” Res Transp Bus Manag 17, (2015), pp 73-82. https://doi.org/10.1016/ j.rtbm.2015.10.008
[25] Fenton, P., “The role of port cities and transnational municipal networks in efforts to reduce greenhouse gas emissions on land and at sea from shipping- an assessment of the World Ports Climate Initiative. Mar. Pol. 75, (2017), pp 271-277. https://doi.org/10.1016/j.marpol.2015.12.012.
[26] Parola, F., Maugeri, S., “Origin and taxonomy of conflicts in seaports: towards a research agenda”. Res Transp Bus Manag 8, (2013), pp 114-122. https://doi.org/10.1016/ j.rtbm.2013.07.005
[27] Dinwoodie, J., Tuck, S., Knowles, H., Benhin, J., Sansom, M, “Sustainable development of maritime operations in ports”. Bus. Strat. Environ. 21, (2012), pp 111-126. https://doi.org/10.1002/bse.718
[28] Almutairi, A., Collier, Z.A., Hendrickson, D., Palma-Oliveira, J.M., Polmateer, T.L., Lambert, J.H., “Stakeholder mapping and disruption scenarios with application to resilience of a container port”. Reliab. Eng. Syst. Saf. 182, (2019), pp 219-232. https://doi.org/10.1016/j.ress.2018.10.010.
[29] Buckwell, A., Fleming, C., Muurmans, M., Smart, J.C.R., Ware, D., Mackey, B., “Revealing the dominant discourses of stakeholders towards natural resource management in Port Resolution”. Vanuatu, using Q-method. Ecol. Econ, (2020), p 177. 106781. https://doi.org/10.1016/j.ecolecon.2020.106781.
[30] Ha, M.-H., Yang, Z., Lam, J.S.L., “Port performance in container transport logistics: a multi-stakeholder perspective”. Transport Pol. 73, (2019), pp 25-40.
[31] Buckwell, A., Fleming, C., Muurmans, M., Smart, J.C.R., Ware, D., Mackey, B., “Revealing the dominant discourses of stakeholders towards natural resource management in Port Resolution”. Vanuatu, using Q-method. Ecol. Econ, (2020), p 177. 106781. https://doi.org/10.1016/j.ecolecon.2020.106781
[32] Dooms, M.,“Stakeholder Management for Port Sustainability”. Green Ports, Elsevier, (2019), pp 63-84.
[33] Van den Berg, R., De Langen, P.W., “Environmental sustainability in container transport: the attitudes of shippers and forwarders”. Int J Logist Res Appl 20, (2017), pp 146-162. https://doi.org/10.1080/13675567.2016.1164838
[34] Tovar, B.,Wall, A., “Environmental efficiency for a cross-section of Spanish port Authorities”. Transport. Res. Transport Environ. 75, (2019), pp 170-178. https://doi.org/ 10.1016/j.trd.2019.08.024.
[35] Aveta, C., Romano, C., “A port planning study case: the freight strategy of the new Central Tyrrhenian Sea Port Authority 2017-2020”. Transp Res Procedia 45, (2020), pp 127-134. https://doi.org/10.1016/j.trpro.2020.02.098
[36] Hollen, R.M.A., Van Den Bosch, F.A.J., Volberda, H.W., “Strategic levers of port authorities for industrial ecosystem development”. Marit. Econ. Logist. 17, (2015), pp 79-96. https://doi.org/10.1057/mel.2014.28.
[37] Venturini, G., Iris, Ç., Kontovas, C.A., Larsen, A., “The multi-port berth allocation problem with

speed optimization and emission considerations". Transport. Res. Transport Environ. 54, (2017), pp 142-159. https://doi.org/10.1016/j.trd.2017.05.002.

[38] Fossile, D.K., Frej, E.A., Gouvea da Costa, S.E., Pinheiro de Lima, E., Teixeira de Almeida, A., "Selecting the most viable renewable energy source for Brazilian ports using the FITradeoff method". J. Clean. Prod. 260, (2020), 121107. https:// doi.org/10.1016/j.jclepro.2020.121107

[39] Van den Berg, R., De Langen, P.W., "Environmental sustainability in container transport: the attitudes of shippers and forwarders". Int J Logist Res Appl 20, (2017), pp 146-162. https://doi.org/10.1080/13675567.2016.1164838

[40] Sdoukopoulos, E., Boile, M., Tromaras, A., Anastasiadis, N., "Energy efficiency in European ports: state-of-practice and insights on the way forward". Sustainability 11, (2019),4952. https://doi.org/10.3390/su11184952.

[41] Yang, Y.-C., Ge, Y.-E., "Adaptation strategies for port infrastructure and facilities under climate change at the Kaohsiung port". Transport Pol. 97, (2020), pp 232-244. https://doi.org/10.1016/j.tranpol.2020.06.019.

[42] García-Olivares, A., Sole, J., Osychenko, O., "Transportation in a 100% renewable energy system". Energy Convers. Manag. 158, (2018), pp 266-285. https://doi.org/10.1016/ j.enconman.2017.12.053.

[43] Fenton, P., "The role of port cities and transnational municipal networks in efforts to reduce greenhouse gas emissions on land and at sea from shipping- an assessment of the World Ports Climate Initiative. Mar. Pol. 75, (2017), pp 271-277. https://doi.org/10.1016/j.marpol.2015.12.012.

[44] Zhu, S., Sun, J., Liu, Y., Lu, M., Liu, X., "The air quality index trend forecasting based on improved error correction model and data preprocessing for 17 port cities in China". Chemosphere 252, (2020), p 126474. https://doi.org/10.1016/ j.chemosphere (2020).

[45] Wiacek, A., Li, L., Tobin, K., Mitchell, M., "Characterization of trace gas emissions at an intermediate port". Atmos. Chem. Phys. 18, (2018), pp 13787-13812. https:// doi.org/10.5194/acp-18-13787-2018.

[46] Kang, D., Kim, S., "Conceptual model development of sustainability practices: the case of port operations for collaboration and governance". Sustainability 9, (2017), p 2333. https://doi.org/10.3390/su9122333.

[47] Tichavska, M., Tovar, B., "External costs from vessel emissions at port: a review of the methodological and empirical state of the art". Transport Rev. 37, (2017), pp 383-402. https://doi.org/10.1080/01441647.2017.1279694

[48] Van Duin, J.H.R., Geerlings, H., Froese, J., Negenborn, R.R., "Towards a method for benchmarking energy consumption at terminals: in search of performance improvement in yard lighting". Int J Transp Dev Integr 1, (2017), pp 212-224. https:// doi.org/10.2495/TDI-V1-N2-212-224.

[49] Tseng, P.-H., Pilcher, N., "A study of the potential of shore power for the port of Kaohsiung, Taiwan: to introduce or not to introduce?". Res Transp Bus Manag 17 (2015), pp 83-91. https://doi.org/10.1016/j.rtbm.2015.09.001

[50] Kampelis, N., Sifakis, N., Kolokotsa, D., Gobakis, K., Kalaitzakis, K., Isidori, D., et al., "HVAC optimization genetic Algorithm for industrial near-zero-energy building demand response". Energies 12, (2019), p 2177. https://doi.org/10.3390/ en12112177

[51] Hall, W.J., "Assessment of CO2 and priority pollutant reduction by installation of shoreside power". Resour. Conserv. Recycl. 54, (2010a.), pp 462-467. https://doi.org/ 10.1016/j.resconrec.2009.10.002

[52] Mertikas, P., Dallas, S.E., Spathis, D., Kourmpelis, T., Georgakopoulos, I.P., Prousalidis, J.M., et al., "Furthering the electricity to ships and ports: the ELEMED project". In: Proc - 2018 23rd

Int Conf Electr Mach ICEM (2018). https:// doi.org/10.1109/ICELMACH.2018.8506729, 2542e8.
[53] Kumar, J., Palizban, O., Kauhaniemi, K., “Designing and analysis of innovative solutions for harbour area smart grid”. In: 2017 IEEE Manchester PowerTech. IEEE (2017), pp. 1-6. https://doi.org/10.1109/PTC.2017.7980870
[54] Hall,W.J., “Assessment of CO2 and priority pollutant reduction by installation of shoreside power”. Resour. Conserv. Recycl. 54, (2010b), pp 462-467. https://doi.org/ 10.1016/j.resconrec.2009.10.002
[55] Coppola, T., Fantauzzi, M., Lauria, D., Pisani, C., Quaranta, F., “A sustainable electrical interface to mitigate emissions due to power supply in ports”. Renew. Sustain. Energy Rev. 54, (2016), pp 816-823. https://doi.org/10.1016/j.rser.2015.10.107.
[56] Sifakis N., Tsoutsos T., “Planning zero-emission ports through the nearly zero energy port concept”, Journal of Cleaner Production, Iss.286, (2021), p 8.
[57] Ihle, N., Runge, S., Grundmeier, N., Meyer-Barlag, C., Appelrath, H.-J.,“An ITarchitecture to support energy efficiency and the usage of flexible loads at a container terminal”. Enviro (2014)
[58] Van Duin, J.H.R., Geerlings, H., Froese, J., Negenborn, R.R., “Towards a method for benchmarking energy consumption at terminals: in search of performance improvement in yard lighting”. Int J Transp Dev Integr 1, (2017), pp 212-224. https:// doi.org/10.2495/TDI-V1-N2-212-224.
[59] Schmidt, J., Meyer-Barlag, C., Eisel, M., Kolbe, L.M., Appelrath, H.-J., “Using battery-electric AGVs in container terminals d assessing the potential and optimizing the economic viability”. Res Transp Bus Manag 17, (2015b), pp 99-111. https:// doi.org/10.1016/j.rtbm.2015.09.002
[60] Liu, W., Li, N., Jiang, Z., Chen, Z., Wang, S., Han, J., et al., “Smart micro-grid system with wind/PV/battery”. Energy Procedia 152, (2018), pp 1212-1217. https://doi.org/10.1016/j.egypro.2018.09.171.
[61] Kuipers, B., Zuidwijk, R., Smart, E., Rotterdam, P., “Smart Port Perspectives Essays in Honour of Hans Smits”. Erasmus University Rotterdam, Rotterdam, (2013).
[62] Tournaki, S., Frangou, M., Tsoutsos, T., Morell, R., “Nearly Zero Energy Hotels-From European Policy to Real Life Examples: the neZEH Pilot Hotels”. NezehEu. (2014).
[63] Tsoutsos, T., Tournaki, S., Urosevic, Z., Derjanecz, A., “Nearly Zero Energy Hotels the European Project Nezeh”. AivcOrg (2016).
[64] Dhupia, J., Adnanes, A., Lee, K., Kennedy, L.,“Electrification of Port and Port Operations” (2011).
[65] Yang, Y.-C.C., Lin, C.-L.L., “Performance analysis of cargo-handling equipment from a green container terminal perspective”. Transport. Res. Transport Environ. 23, (2013), pp 9-11 https://doi.org/10.1016/j.trd.2013.03.009.
[66] Gutierrez-Romero, J.E., Esteve-Perez, J., Zamora, B., “Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth”. Appl. Energy 255, (2019), 113883. https://doi.org/10.1016/ j.apenergy.2019.113883.
[67] Heras-Saizarbitoria, I., Zamanillo, I., Laskurain, I., “Social acceptance of ocean wave energy: a case study of an OWC shoreline plant”. Renew. Sustain. Energy Rev. 27, (2013), pp 515-524. https://doi.org/10.1016/j.rser.2013.07.032.
[68] Akbari, N., Irawan, C.A., Jones, D.F., Menachof, D., “A multi-criteria port suitability assessment for developments in the offshore wind industry”. Renew. Energy 102, (2017), pp 118-133. https://doi.org/10.1016/j.renene.2016.10.035.
[69] Deep, S., Sarkar, A., Ghawat, M., Rajak, M.K., “Estimation of the wind energy potential for coastal locations in India using the Weibull model. Renew”. Energy 161 (2020), pp 319-339. https://doi.org/10.1016/j.renene.2020.07.054.
[70] Yarova, N., Vorkunova, O., Khoteyeva, N., “Economic assessment of the alternative energy

sources implementation for port enterprises". Econ. Ann. 166, (2017), pp 46-50. https://doi.org/10.21003/ea.V166-09.
[71] El-Amary, N.H., Balbaa, A., Swief, R., Abdel-Salam, T., "A reconfigured whale optimization technique (RWOT) for renewable electrical energy optimal scheduling impact on sustainable development applied to damietta seaport, Egypt". Energies 11, (2018), p 535. https://doi.org/10.3390/en11030535.
[72] Ramos, V., Carballo, R., Alvarez, M., Sanchez, M., Iglesias, G., "A port towards energy self sufficiency using tidal stream power". Energy 71, (2014), pp 432-444. https://doi.org/10.1016/j.energy.2014.04.098.
[73] Hadadpour, S., Etemad-Shahidi, A., Jabbari, E., Kamranzad, B., "Wave energy and hot spot in Anzali port". Energy 74 (2014), pp 529-536. https://doi.org/10.1016/j.energy.2014.07.018.
[74] Naty, S., Viviano, A., Foti, E., "Wave energy exploitation system integrated in the coastal structure of a mediterranean port". Sustainability 8, (2016), p 1342. https://doi.org/10.3390/su8121342.
[75] Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., Giuliano, G., et al., "Environmental sustainability in seaports: a framework for successful Innovation". Marit. Pol. Manag.41, (2014), pp 480-500. https://doi.org/10.1080/ 03088839.2014.932926.
[76] Tichavska M et al 2019 Transport Policy 75 128–140
[77] WG150 'Sustainable Ports' A Guidance for Port Authorities. The World Association for Waterborne Transport Infrastructure Revision 7. Available at: https://sustainableworldports.org/wp-content/uploads/EnviCom-WG-150-FINAL-VERSION.pdf
[78] Beley, V., Nikishin, A., & Gorbatov, D. (2018, September). Strategy of Metropolis Electrical Energy Supply. In International Conference on Advanced Engineering Theory and Applications (pp. 870-879). Springer, Cham.
[79] Kalambe S, Agnihotri G 2014 Renewable and sustainable energy reviews 29 184–200
[80] Antmann P. Reducing technical and non-technical losses in the power sector. – 2009.
[81] Momoh, J.: Smart Grid: Fundamentals of Design and Analysis, IEEE Press, 2012.
[82] Nikishin, A. J., & Kharitonov, M. S. (2021, March). Modernization of marine ports electrical power supply systems in the framework of zero-emission strategy. In IOP Conference Series: Earth and Environmental Science (Vol. 689, No. 1, p. 012018). IOP Publishing.
[83] Anthony Roy , François Auger , Jean-Christophe Olivier , Emmanuel Schaeer and Bruno Auvity 'Design, Sizing, and Energy Management of Microgrids in Harbor Areas: A Review' Energies 2020, 13, 5314; doi:10.3390/en13205314
[84] Nikitas Nikitakos' Green logistics: The concept of zero emissions port' FME Transactions, 2012, pp. 201-206
[85] Tzannatos, E. Cost assessment of ship emission reduction methods at berth: the case of the Port of Piraeus, Greece, Maritime Policy & Management, Vol. 37, No. 4, pp. 427-445, 2010.
[86] N. Nikitakos I. G. Dagkinis, P. Kofinas D. Papachristos Green Logistics - The concept of Zero Emissions Port based on PSO' Proceedings of the Maritime and Port Logistics of the XXIII International Conference MHCL 2019 pp. 38-42
[87] Stolz, B. & Held, Maximilian & Georges, G. & Boulouchos, K.. (2021). The CO2 reduction potential of shore-side electricity in Europe. Applied Energy, Volume 285, 2021.
[88] Tarigan P., Hasan M., Wahab M., Dogheche E. and Djamaludin A., "Renewable Energy Source Selection for a Green Port with AHP", IOP Conference Series: Earth and Environmental Science, Vol. 753, (2020), pp. 012001.
[89] C. Budak, X. Chen, S. Celik and B. Ozturk, "A Systematic Approach for Assessment of Renewable Energy Using Analytic Hierarchy Process", Energy Sustainability and Society, Vol.

37, No. 9, (2019), pp. 1-14.
[90] N. Shatnawi, H. Abu-Qdais and F. Abu Qdais, “Selecting Renewable Energy Options: An Application of Multi-Criteria Decision Making for Jordan”, Sustainability: Science, Practice and Policy, Vol. 17, (2021), pp. 209-219.
[91] M. Faizal Bin, A. Zaidi, S. Binti Mohd Shafie and M. K. Irwan Bin Abdul Rahim, “AHP Model for Selection Sustainable Energy: A Focus on Power Generation and Supplying for End-Users”, International Journal of Supply Chain Management, Vol. 9, No. 2, (2020), pp. 227-233.
[92] M. Ammer and T.U. Daim, “Selection of Renewable Energy Technologies for a Developing Country: A Case of Pakistan”, Energy for Sustainable Development, Vol. 15, (2011), pp. 420-435.
[93] B. Pavlovic, D. Ivezic and M. Zivkovic, “A Multi-Criteria Approach for Assessing the Potential of Renewable Energy Sources for Electricity Generation: Case Serbia”, Energy Reports, Vol. 7, (2021), pp. 8624-8632.
[94] K. Y. Bjerkan and H. Seter, “Reviewing Tools and Technologies for Sustainable Ports: Does Research Enable Decision Making in Ports?”, Transportation Research Part D, Vol. 72, (2019), pp. 243-260.
[95] N. Asgari, A. Hassani, D. Jones and H.H. Nguye, “Sustainability Ranking of the UK Major Ports: Methodology and Case Study”, Transportation Research Part E, Vol. 78, (2015), pp. 19-39.
[96] McLarnon F. R. and Cairns E. J., “Energy storage Annual review of energy”, Vol. 17, No. 1, (2001), pp 241-271.
[97] Mohamad F. et al., “Development of energy storage systems for power network reliability: A review”, Energies, Vol. 11, No. 9, (2018), pp. 2278.
[98] Eckroad S. and Gyuk I., “EPRI-DOE handbook of energy storage for transmission & distribution applications”, Electric Power Research Institute, (2003).
[99] Kousksou T. et al., “Energy storage: Applications and challenges”, Solar Energy Materials and Solar Cells, Vol. 120, (2014), pp. 59-80.
[100] Farrokhabadi M. et al., “Energy storage in microgrids: Compensating for generation and demand fluctuations while providing ancillary services”, IEEE power and energy magazine, Vol. 15, No. 5, (2017), pp. 81-91.
[101] Faias S. et al., “An overview on short and long-term response energy storage devices for power systems applications system”, Vol. 5, (2008), pp. 6.
[102] Ibrahim H., Ilinca A. and Perron J., “Energy storage systems—Characteristics and comparisons”, Renewable and sustainable energy reviews, Vol. 12, No. 5, (2008), pp. 1221-1250.
[103] Gupta R., Nigam N. and Gupta A., “Application of energy storage devices in power systems”, International Journal of Engineering, Science and Technology, Vol. 3, No. 1, (2011), pp. 289-297.
[104] Kozlov S., Kindryashov A. and Solomin E., “Analysis of the efficiency of energy storage systems”, AEE, Vol. 166, No. 2, (2015), pp. 29-34.
[105] Filippov S., Golodnitsky A. and Kashin A., “Fuel cells and hydrogen energy”, Energy policy, Vol. 153, No. 11, (2020), pp. 28-39.
[106] Weitemeyer S., KIeinhans D., Vogt T., Agert C. lntegration of renewable energy sources in future power systems: the role of storage. Renewable Energy2015; 75: 14-20.
[107] Mohamed, M. A., EItamaly, A. M., Farh, H. M., AIolah, A. I. Energy management and renewable energy integration in smart grid system. In IEEE International Conference on Smart Energy Grid Engineering (SEGE) August, 2015; 1−6.
[108] Fadaee M., Radzi M. A. M. Multi-objective optimization of a stand-alone hybrid renewable energy sys- tem by using evolutionary algorithms: a review. Renewable and Sustainable Energy Reviews 2012; 16 (5): 3364-3369.
[109] Bai O. Analysis of particle swarm optimization algorithm. Computer and information

science2010; 3 (1): 180-184.
[110] Du W. B., Gao y., Liu C., Zheng Z., Wang Z. Adequate is better: particle swarm optimization with limited information. Applied Mathematics and Computation 2015; 268: 832-838.
[111] Gao Y., Du W., Yan G. Selectively-informed particle swarm optimization. Scientific reports 2015; 5: 9295. doi: 10.1038/srep09295 PMID: 25787315
[112] Marini, F., & Walczak, B. (2015). Particle swarm optimization (PSO). A tutorial. Chemometrics and Intelligent Laboratory Systems, 149, 153-165.
[113] Mohamed, M. A., Eltamaly, A. M., & Alolah, A. I. (2016). PSO-based smart grid application for sizing and optimization of hybrid renewable energy systems. PloS one, 11(8), e0159702.
[114] Global Wind Atlas. https://globalwindatlas.info/. Accessed online 2022-05-25.
[115] Brief technical description of the 30 kW wind turbine. http://vdmtech.ru/ru/node/7. Accessed online 2022-05-25.
[116] Overview of ENERCON platform. https://www.enercon.de/en/products/. Accessed online 2022-05-25.
[117] Global Solar Atlas. https://globalsolaratlas.info/. Accessed online 2022-05-25.

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