Modernization of marine ports electrical power supply systems in the framework of zero-emission strategy

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Abstract. The article describes some approaches to the modernization of the power supply system of marine ports in the framework of zero-emission strategy. A case study of the Kaliningrad sea fishery port given as an example. The authors analyze the electrical power supply system of the enterprise and its power balance, proposing several solutions to improve energy efficiency, reliability and energy loss reduction using distributed renewable energy sources such as wind and solar generation.

1. Introduction
Maritime transport industry handles more than 85% of the global trade volume [1]. Because of the significance of its impact on the climate and environment, this sector is under increasing pressure.

Global emissions from the maritime sector is responsible for 10–15% of anthropogenic sulfur (SOx) and nitrogen oxide (NOx) emissions, as well as approximately 3% of the carbon dioxide (CO2) emissions [2]. As a response, in 2018 the International Maritime Organization (IMO) member states set an absolute target of greenhouse gases emissions to 50% reduction by 2050 compared to 2008, called “Paris Agreement for shipping” [3]. Adapting the maritime sector towards zero-emission will require tremendous effort in terms of new technologies and other measures. The problem is, that emission reduction efforts should not hamper economic growth and international trade [4]. Emission classification is given in [5] (Figure 1).

![Figure 1. Maritime air emission classification [5].](image-url)
Analysis shows, that the main contributor of pollution comes from shipping traffic within a port and port operations [6] (Figure 1). It results in a paradigm shift of the key players of sustainability in maritime transport from shipping companies to port authorities and operators [7]. As a response to that, so called “Green ports” framework represent an important direction in 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;
• implementation of smart microgrid concept;
• implementation of cold ironing.

A short introduction into modern technics to reach zero-emission marine port electrical energy supply system is given in this paper. After the introduction the power loss reduction measures are presented. Next, the concept port microgrid with renewable power supply, storage systems and power management are given. As a possible example for future concept development, Kaliningrad fishery port is discussed with preliminary calculation of mentioned above measures application. Finally, the conclusions and recommendations are outlined.

2. Overview of power supply system modernization measures for port emissions reduction

Normally, the marine port power supply system is a traditional distribution system with well-developed infrastructure and similar to metropolis energy supply system in terms of complexity [8]. It’s 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.

Marine port electrical supply system has some specific features. Distribution grid is mainly made of cable lines, which are widely used due to the impossibility of usage of overhead lines on the port territory. Substations are one- and two-transformers. 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 of power supply system operation efficiency has the biggest potential and mainly associated with the decrease of energy and power losses in port distribution grid.

2.1. Potential strategies to increase marine ports electrical power supply system efficiency

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

The analysis in [9] shows that more than 75% of network losses are associated with low voltage networks, middle voltage networks and distribution transformers which are the main components of marine port distribution system. Overall: up to 47% of the total losses are in low voltage networks; up to 13% of losses are load losses in distribution transformers; up to 10% of losses are no-load losses in distribution transformers; up to 27% are in middle voltage networks; up to 24% of total losses are in primary and grid transformers, and high voltage networks (110 kV and higher). Taking into account mentioned above specifics for marine ports power supply system, it is possible to say, that reduction of power losses and optimization of power supply has a big potential in such systems.

Classification of the power losses in distribution grids is given in [10]. Same classification could be used for marine ports electrical distribution system (Table 1).

Traditional measures for reduction of power losses in distribution networks are shown on Figure 2. All of them can be implemented in marine ports. Their total contribution to the reduction of emissions, as mention above, is not great, nevertheless, the efficient operation of the power supply system without implementation of such measures is impossible.
Table 1. Classification of the power losses in marine ports distribution grids.

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

Electrical grids power losses reduction methods

Figure 2. Measures to reduce energy losses in power supply system.

Management and metering system measures need a development of digital metering infrastructure and deep consumption data analysis. In the last decade this approach became a part of modern smart microgrid concept. To implement this concept for marine port distribution grid a complex upgrade of the system should be provided.
2.2. New technologies for reliable and sustainable power supply

Electricity usage in ports is rising significantly for the last decade and will continue to increase due to operational, regulatory and environmental factors. Control and optimization of such systems become more and more complicated. To reach zero-emission aims and meet challenges regarding sustainability and environmental friendliness of the marine ports, new technologies are coming.

One of the possible solutions is use of promising type of power system - so called Smart Microgrid. U.S. Department of Energy (DOE) defines a microgrid as interconnected loads and distributed energy resources (DER), including renewables, such as wind and solar, which acts as a single controllable entity with respect to the grid, capable of operating in both grid-connected and “islanded” mode. To do that DER should be integrated with storage devices and controllable loads. The scheme of such system is presented on Figure 3.

Port areas under appropriate control could adjust their demand to support local energy system and also profit from lower electricity prices. To fully realize such control there is a need for appropriate smart load management system. Its effective operation needs use of storage systems of different types.

As for DERs, research shows, that Kaliningrad region itself, including marine ports areas, has a viable wind energy potential [11]. Optimization of siting and use of distributed generation in microgrids could significantly decrease power losses in the supply system because of consumption and production centers bonding [12]. Those calculations are possible to provide only with adequate mathematical optimization models [13].

2.3. Cold ironing

Emissions from ships auxiliary engines at the berth to supply power to vessel consumers are estimated to be ten times higher than emissions from port operations [14]. Possibilities for their reduction is also much more significant.

Cold ironing, refers to ship connection to port electric power supply mains, is a viable solution to use this potential. In this case the operation of the onboard generators can be minimized such that the power requirement is met by land-based generation, supplying the electrical energy from a centralized source [15]. To support the effort for greenhouse gases emissions limitation the port should provide the infrastructure and the ‘green’ energy (e.g. renewables). This gives a locally emission-free solution, though the resultant overall airborne emissions will be a function of the generation mix employed on land [16,17].

EU recommendation 2006/336/EC highlights shore connection technology as the optimal solution in terms of both cost savings and pollution control. Green ships e.g. ships with onshore connection equipment can enjoy fees rebate up to 10%. First time technology was implemented in the port of Gothenburg in 2000. Vessels is partially supplied by wind power generated electricity. Nowadays one
out of three vessels consumption at this port can be completely covered by cold ironing system. Until today only a few ports in the Baltic Sea are using cold ironing, but the interest is growing. Currently the plans for implementing shore-based power supply for vessels are being globalized [14]. The technical details of the connection depend on many factors, such as available energy source mixture, connection of the port infrastructure to local energy grid and so on, but generic concept of cold ironing system could be described as represented on Figure 4.

![Figure 4. Generic concept of cold ironing system [15].](image)

3. The case study of Kaliningrad fishery port

To analyze introduction of zero-emission strategy in the ports of the Baltic sea region the Kaliningrad sea fishery port was chosen as an example (Figure 5). Fishery port 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.

![Figure 5. Location of Kaliningrad sea fishery port.](image)

Fishery port provides a range of services including anchorage of the vessels, loading and unloading operations, storage of frozen fish and meat products, storage of general, bulk, liquid, chemical and other types of cargo, technological accumulation of cargo, cold ironing and shore power supply. The cargo complex of the port is located on the Pregolya river in the town of Kaliningrad. The key parameters and data on port infrastructure are listed in the Table 2.
Table 2. Infrastructure overview of Kaliningrad fishery port.

| Characteristics                     | Units     | Value     |
|-------------------------------------|-----------|-----------|
| Number of ship terminals            | -         | 17        |
| Liquid cargo terminal capacity      | cub. m    | 31 400    |
| Bulk cargo terminal capacity        | tons      | 18 000    |
| Covered warehouse capacity          | cub. m    | 24 000    |
| Open storage area                   | sq. m     | 65 000    |
| Refrigerator capacity              | tons      | 6 000     |
| Number of portal cranes            | units     | 7         |
| Length of crane runways             | m         | 2 100     |
| Lifting capacity of cranes          | tons      | 5         |
| Number of fork and bucket loaders   | units     | 14        |

4. Analysing renewable energy potential

Increase of port electrical supply system efficiency reduce amount of consumed energy, power losses and correspondent port facilities emissions. Cold ironing reduces ships’ emission. Still electrical energy is coming from local energy system, mainly from fossil fuel’s sources. As a result, total contribution of discussed measures to air emission is limited. In the framework of “zero emissions port” with smart grid technology approach the main sources should be renewables, such as wind solar, geothermal and tidal and wave energy. Although there are so many, the difficult task is the conversion to electricity and the efficiency of the converting systems [18].

At present, solar energy is one of the most widely used renewable energies in the world. Photovoltaic have now reached a high technological level, with many technologies available on the market for different kinds of application [19]. Marine port facilities could have potential for optimal siting of solar panels.

Among all existing energies, along with solar energy wind is one of the most developed renewable energy technologies in the world. Different designs od wind turbines available on the market [19].

To discuss the abilities to use wind and solar as primary electricity production, first, the potential of those renewables in the marine port area should be assessed.

4.1. Wind power 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 [20]. The Figure 6 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 is shown in Table 3.

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) [21] and European (Enercon) wind turbines [22] (Figure 7) provides an assessment of wind turbines operation efficiency in the specified conditions. With the common form of 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 (Figure 8).
Table 3. 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        |

Figure 6. Map of the mean wind speed in the area of the port of Kaliningrad terminals.

Figure 7. Comparison of wind turbines performance characteristics.
Thus, it can be concluded that the area of the port of Kaliningrad terminals has a potential for 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.

4.2. Solar power potential
Distribution of solar irradiation intensity over the territory of the Kaliningrad region is much more uniform in comparison with the mean wind speed (Figure 9). For the areas where the port of Kaliningrad infrastructure is located, the average daily amount of direct normal irradiation is 2.8 kWh/m² [23].

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. As an example, the option of placing solar power plants on the territory of the Kaliningrad Sea Fishery Port is considered (Figure 10).
The area required for installation of solar power plants depends on the type, power and dimensions of the photovoltaic panels and the required tilt angle. As an example the calculation was made for Hevel HVL-380/HJT panels with a power of 380 W, produced in Russia by the Hevel group of companies (Table 4) [24]. The installation angle of the panels is taken equal to 38°.

### Table 4. Hevel HVL-380/HJT photovoltaic panel specifications.

| Rated power, W | Efficiency, % | Open circuit voltage, V | Operating point voltage, V | Dimensions, mm | Weight, kg |
|---------------|---------------|------------------------|----------------------------|----------------|------------|
| 380           | 19            | 52.78                  | 44.37                      | 1996 × 1002 × 30 | 32         |

The capacity of the solar power plant was assessed based on the data on port warehouses with flat roofs of a relatively large area and load bearing capacity. The calculation was made for the ten largest warehouses on the territory of the fishery port (Table 5, Figure 11).

### Table 5. Calculation of the parameters for placing photovoltaic panels on the roofs of warehouses.

| Warehouse number | Surface area, sq. m | Surface dimensions, m | Number of panels | Installed capacity, kWp |
|------------------|---------------------|-----------------------|-----------------|-------------------------|
| 1                | 2 875               | 115 × 25              | 958             | 364.2                   |
| 2                | 2 000               | 100 × 20              | 667             | 253.3                   |
| 3                | 4 690               | 70 × 67               | 1563            | 594.1                   |
| 4                | 8 700               | 145 × 60              | 2900            | 1 102.0                 |
| 5                | 2 125               | 85 × 25               | 708             | 269.2                   |
| 6                | 3 600               | 60 × 60               | 1200            | 456.0                   |
| 7                | 9 600               | 160 × 60              | 3200            | 1 216.0                 |
| 8                | 3 888               | 108 × 36              | 1296            | 492.5                   |
| 9                | 4 520               | 113 × 40              | 1507            | 572.5                   |
| 10               | 2 592               | 108 × 24              | 864             | 328.3                   |
| Total            | 44 590              | –                     | 14 863          | 5 648.1                 |
According to the results of estimated calculations with a total roof area of 44.59 thousand sq. m it is possible to install about 14.86 thousand HVL-380/HJT photovoltaic panels with a total installed capacity of more than 5 600 kWp. However, taking into account the seasonal change in the amount of daily solar irradiation, the volumes of electricity produced by the solar power plant will also change (Figure 11). The calculations showed that under cleared conditions, the maximum annual production of electricity by the solar power plant can reach 5.8 million kWh.

5. Analysing energy efficiency improvement potential

The transformer substations of the fishing port are supplied with electrical power from the 110/10 kV substation. There are 16 10/0.4 kV substations on the territory of the port, 12 of which are in operation. Substations have overaged oil transformers with a capacity from 250 to 1000 kVA and oil circuit breakers. The total length of cable lines is 6 km for 10 kV and 40 km for 0.4 kV. The total capacity of the transformers installed at the port's substations is more than 10 MW with the currently authorized capacity of 2.5 MW. The port's actual load is 0.7 MW in summer and 1.2 MW in winter periods.

The analysis of the nomenclature and the characteristics of electric loads has made it possible to form a number of general groups of consumers. The following Table 6 gives a data on the installed capacity and the actual load in the summer and winter periods for these general groups. The most energy-consuming facility of the fishing port is the refrigerating warehouse used to store frozen products.

| Type of consumer    | Installed capacity | Consumption in summer period | Consumption in winter period |
|---------------------|--------------------|------------------------------|-----------------------------|
|                     | P, kW              | Q, kvar                      | P, kW                      | Q, kvar                      |
| Portal cranes       | 666.7              | 500.0                        | 41.7                       | 31.3                        |
| Pumps               | 270                | 202.5                        | 155.3                      | 116.6                       |
| Electrical heating  | 164.3              | 33.3                         | 0.3                        | 0.1                         |
| Shore power         | 150.0              | 112.5                        | 41.7                       | 31.3                        |
| Office block        | 88.9               | 66.7                         | 22.2                       | 16.7                        |
| Outdoor lighting    | 85.2               | 52.8                         | 5.4                        | 3.3                         |
| Pumps               | 88.9               | 66.7                         | 60.0                       | 45.0                        |
| Compressors         | 416.7              | 312.5                        | 187.5                      | 140.6                       |
| Floor heating       | 320.0              | 240.0                        | 156.8                      | 117.6                       |
| Lighting            | 49.1               | 30.4                         | 22.1                       | 13.7                        |
| **Total**           | **2299**           | **1617.4**                   | **692.9**                  | **516.2**                   |

The crane equipment of the port is the second consumer by the energy consumption and is represented by ten portal cranes with a lifting capacity of up to five tons (Table 7). Crane electric drives
have induction electric motors with a phase rotor. Currently portal cranes have no devices for reactive power compensation.

Table 7. List of electrical equipment of portal crane

| Type of consumer       | Number of drives | Nominal capacity, kW | Total capacity, kW |
|------------------------|------------------|----------------------|--------------------|
| Lift winch drive       | 2                | 65                   | 130                |
| Boom swing drive       | 1                | 11                   | 11                 |
| Movement drive         | 2                | 7                    | 14                 |
| Derrick drive          | 1                | 7                    | 7                  |
| Total                  | 6                | -                    | 162                |

The following Figures 12 and 13 represent the results of the real and reactive power balance calculation. Despite the considerable installed capacity of crane equipment, its contribution to the energy balance is currently relatively small due to low load factor.

Figure 12. The real and reactive power balance of the fishing port power system.

Figure 13. The contribution of consumers groups in the energy balance of the fishing port.
5.1. Estimation of energy losses in the power supply system

The need to control energy losses derives from the possibility of reducing the cost of losses (economic reasons) and the requirements of legislation in the field of energy saving and improvement of energy efficiency (legal reasons) [25].

Calculation of electrical power losses is usually based on the values of electrical loads. However, because of the lack of electricity metering systems on outdated transformer substations, it is often difficult to obtain data on actual loads for fishery enterprises. In such a case, it is advisable to use analytical calculation methods. The evaluation of the flow distribution in the power supply system of the enterprise can be done with the software for mathematical modeling of power systems. In this paper, the calculation of the fishing port power supply system was made with the Neplan software (Figure 14).

\[
\Delta P_{NL} = (\Delta P_{NL, nom} + K \cdot \Delta Q_L) \cdot \left(\frac{U_{av}}{U_{nom}}\right)^2
\]

\[
\Delta P_L = (\Delta P_{L, nom} + K \cdot \Delta Q_L) \cdot \left(\frac{S_{av}}{S_{nom}}\right)^2
\]

\[
\Delta P_{CL} = \sum 0,003 \cdot K^2 \cdot I_i^2 \cdot R \cdot L
\]

\(\Delta P_{NL, nom}\), \(\Delta P_{L, nom}\) – nominal no load and load losses; \(K\) – coefficient of change in active power loss; \(U_{av}\) – average voltage value in electrical grid; \(U_{nom}\), \(S_{nom}\) – nominal voltage and apparent power; \(\Delta Q_L\) – constant component of losses of no load and load reactive power losses; \(S_{av}\) – average apparent power; \(K_f\) – form factor of daily load graph; \(I_i\) – the value of the current at each half-hour interval; \(R\) – direct-current resistance of conductors; \(L\) – length of cable line.

The Table 8 gives the summary on electrical energy loss calculation at the transmission and distribution stage for the existing power supply system of the fishing port during winter period Analysis of the data shows that, due to the low load factor of transformers, no load losses are predominant.
Table 8. Electrical energy loss in the existing power supply system.

| Power losses, kW | Energy losses, th. kWh/year |
|-----------------|-----------------------------|
| ΔP<sub>NL</sub> | ΔW<sub>NL</sub> | ΔP<sub>L</sub> | ΔW<sub>L</sub> | ΔP<sub>CL</sub> | ΔW<sub>CL</sub> | Total |
| 27.3            | 138.2                     | 2.3             | 11.8          | 0.7             | 3.3    | 153.9    |

5.2. Proposing solutions to improve energy efficiency

Since the major part of electrical energy loss during transmission and distribution in the power supply system of the fishing port occurs in transformers, modernization of the power supply system must include optimization of the transformer substations load factor. Taking into account the technical condition of the transformer substations electrical equipment and cable lines, the complete reconstruction of 10 kV network is desirable. New transformer substations should be located in the load centers to minimize the length of the cable lines.

The choice of the number and capacity of transformers for industrial enterprises should be made taking into account the existing electrical loads in summer and winter periods, the maximum permissible capacity, the prospects for expansion and the possibility to optimize the load factor. Nowadays 10/0.4 kV transformers up to 1000 kVA are manufactured with oil immersed and molded insulation, as well as with magnetic cores from amorphous alloys. These alloys provide significant reduction of no load losses and increase in the efficiency of lightly loaded transformers (Figure 15) [27].

![Figure 15. The form of the hysteresis loop and efficiency to load factor curve for transformers with a core made of silicon and amorphous steel.](image-url)

Comparative analysis of the characteristics of transformers with core made of silicon and amorphous steel for the capacities widespread at enterprises shows a significant reduction of no load losses (Table 9). However, because of the higher cost and increased fragility of the magnetic core, the decision to install transformers with amorphous steel should be technically and economically justified.

Table 9. Technical and electrical parameters of 10/0.4 kV transformers.

| Nominal power, kVA | Core material | 100   | 250   | 400   | 630   |
|-------------------|---------------|-------|-------|-------|-------|
|                   | No load losses, W |       |       |       |       |
|                   | Load losses, W   |       |       |       |       |
|                   | Impedance voltage, % |       |       |       |       |
|                   | No load current, % |       |       |       |       |

The power supply system of the fishing port includes 51 terminals for shore power supply of vessels and portal cranes installed at intervals of 50 meters at the berths of the harbors. Since the power
consumed by the vessel during loading operations can reach 150 kW, the need to minimize the length of the 0.4 kV cable lines to the terminals should be taken into account when choosing the locations of new transformer substations. To minimize the length of cable lines, it is advisable to apply a ring main electrical distribution system with two-way power supply from two independent sources (Figure 16), which, combined with two-transformer substations, provides a high level of reliability and technical flexibility.

6. Results
The zero-emission strategy is likely to be future framework for operation of marine ports, converting them according to the key provisions of green port concept. The legal and financial pressure will increase putting old-style ports aside.

After a short introduction into zero-emission framework and green-port concept, a case study of Kaliningrad fishery port was discussed in the paper. The analysis of the wind and solar potential of the harbor area and territory of the Kaliningrad fishery port shows, that with modern wind turbines and solar panels, technical solutions available on the market, significant part of port power consumption could be covered. Analysis of port electrical power supply system with developed mathematical model, shows big potential to increase its efficiency with the use of distributed generation and modern equipment such as new transformers. To make it more clear, more complicated mathematical model with optimization algorithms should be developed.

As a result, on a first approximation, Kaliningrad fishery port shows great potential to be one of the first green port in the zero-emission strategy framework in Russia.

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