

Article

Electrical and Energy Systems Integration for Maritime Environment-Friendly Transportation

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Abstract: The policies against climate change require the reduction of greenhouse gas emissions of marine transportation. To reach the planned goals, the most promising approach is working both on ships improvement and ports redesign. The latter must enable the new green ships supply with sustainable electrical energy, by integrating shore connection systems, local renewables, and energy storage systems. In this paper, a methodology to obtain such an objective is proposed, capable of taking into account both ships' and ports' characteristics. The methodology workflow is explained through a case study, where two shore connection power sizes and two different operative approaches for recharging the ship onboard energy storage are considered. A discussion about the most suitable energy storage technologies is also provided. The case study shows how the methodology can be applied, as well as demonstrating that the port infrastructure has a direct effect on the ship environmental performance.

Keywords: transportation electrification; hybrid-propelled ship; electric ship; energy storage; shore connection; renewables; port power system; design methodology; zero-emission navigation



Citation: Vicenzutti, A.; Sulligoi, G. Electrical and Energy Systems Integration for Maritime Environment-Friendly Transportation. *Energies* **2021**, *14*, 7240. <https://doi.org/10.3390/en14217240>

Academic Editors: Nicu Bizon and Andrea Mariscotti

Received: 4 October 2021
Accepted: 26 October 2021
Published: 3 November 2021

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1. Introduction

At the present time, significant attention is being given to the environmental impact of the human activities. Regarding maritime transportation sector, both the Paris Agreement [1] and the International Maritime Organization (IMO) resolutions [2] push towards a significant reduction in pollutant emissions. In particular, the most challenging requirements are the ones related to greenhouse gas (GHG) emissions, which need to be reduced by at least 50% at entire fleet level by 2050 in respect to the 2008 levels, including a CO₂ specific emission reduction of 70% per transport work. In addition to these demanding goals, the European Union (EU) also adopted in 2021 the “Fit for 55” policy to address climate changes, to be applied on the EU area, as well as to all inbound and outbound transportation routes. Besides the introduction of an emissions trading system on maritime transport (such as the one already existing for land power producers), the FuelEU Maritime Initiative and the Energy Taxation Directive were also introduced. The FuelEU sets a maximum limit on the GHG intensity of the energy used onboard a ship, and obligations on shore-power supply or zero-emission technologies use during ship stay in port. The targets are evaluated using as a base the fleet average GHG intensity in 2020, and progressively reduced from 2025 onwards, down to 75% by 2050. The Energy Taxation Directive defines new taxation structure for fuel and electricity, based on the energy content and environmental performance, promoting sustainable and environmentally-friendly fuels usage.

In order to reach such demanding reduction goals, the most promising approach is not only the vessels improvement (by designing new greener ships and refitting existing ones with proper technological solutions), but also to intervene on rest of the value chain in which the ship operates. In fact, several of the technical solutions actually in use or in study for improving the environmental friendliness of maritime transport systems

require a proper land side infrastructure to enable the expected gains. As an example, the shore connection (SC) apparatuses are used more and more in ports to supply the berthed ships with electrical energy for the onboard loads, thus allowing to shut-off the onboard generators and significantly reducing the local pollutant emissions [3]. In such a case, significant environmental benefits can be achieved if the energy comes from renewable sources. Conversely, an energy supply from a non-renewable source is mostly a pollution delocalization action, whose impact on global emissions reduction is much lower (down to being negligible). Such a simple example demonstrates how an integrated approach that considers not only the ship, but also the port infrastructure (and possibly the energy supply) is required for improving the environmental performance of the maritime transport as a whole.

In the literature, several papers have addressed the issue of reducing the environmental impact of maritime transport by means of different approaches [4–7]. In [4], it is stated that several methods can be used to increase efficiency and environmental performance of all-electric ships (i.e., ships using electrical propulsion): energy storage integration with intelligent power management; DC power distribution usage; installation of new propeller types; adoption of low carbon content fuel (such as liquefied natural gas); installation on onboard renewable energy production systems; fuel cell integration. Reference [5] concludes that hybrid propulsion architectures integrating advanced control strategies can lower fuel consumption and emissions up to 10–35%, while providing less noise, improved maneuverability, maintainability, and comfort. The authors of [6] affirm that onboard DC power systems, coupled with a smart power management and control system, can increase efficiency by 20% in respect to conventional AC systems, while saving up to 30% of space and weight for the electrical equipment. Finally, in [7] the focus is on shipboard renewables integration with generators and energy storage systems, to enhance the overall ship efficiency. It is clear from these examples that there is no single solution to the issue, but different approaches can be successfully exploited to improve upon the actual environmental performance. The design of ship power and propulsion systems is also a hot topic [8–10], due to the similarities between shipboard and land based microgrids [11]. As an example, in [8] the authors apply the model-based approach to the design of a DC shipboard power system, by means of a multiphysics real-time simulator. Similarly, a battery based shipboard power system design is presented in [9], discussing different operation scenarios and using a MATLAB based model to validate the results. The optimal management of new onboard power sources and energy storage is another prolific research branch [12–15]. Examples can be made referring to [12], where the optimal energy management for a fuel-cell powered ship is presented, as well as to [13], where the authors discuss about the dynamic management of the onboard power system. Moreover, in [15] the effect of integrating energy storage systems in a ship is assessed, considering the ship mission profile. The SC integration in ports is also discussed in the literature [3,16,17]. As an example, in [3] the pros, cons, and the technical aspects of the shore connection systems for actual ships are presented, while the supply infrastructure required to recharge the onboard energy storage systems for modern battery-powered vessels is addressed on a technical point of view in [16].

Despite the prolific literature on these topics, the approach in most of them is to focus on a specific component, subsystem, or even main system (such as the ship or the port), and to try to achieve the most from it. However, as will become evident from the results of this paper case study, the same green ship can provide very different results in terms of environmental impact, depending on the supporting port infrastructure. Substituting a conventional propelled ship with a new green one may provide very limited environmental benefits, if the port is not ready for enabling its full use. Moreover, there may be some limitations related to the port infrastructure (such as maximum power level of existing power system, funds availability for new components installation, and so on) and to the land power system (e.g., available power lines for supporting the increased port power requirements, carbon intensity of the provided energy, etc.) that can greatly affect the final

results. Thus, the reduction in the environmental impact of maritime transport requires a wider approach, which encompasses the ship, the port, and the related elements (e.g., the environmental friendliness of electric energy supply). This coupled nature between the ship and the port design is an aspect that is not sufficiently addressed in the literature.

Therefore, in this paper a methodology to integrate shore connection apparatus (i.e., the charging station for the ship's onboard ESS), energy storage systems (both onboard and on-shore), and port electrical infrastructure is presented. The methodology is aimed at defining the shore infrastructure required for supporting a given new green ship, by determining the port main elements, considering its actual and future performance, and the expected impacts in terms of route environmental-friendliness. To allow comprehending the already mentioned mutual effect between the ship and the port infrastructure, a case study is also presented. Four different cases are analyzed, considering two power sizes for the shore connection apparatus and two different operative approaches for the energy use by the ship. For the sake of simplicity, the results are here presented in terms of ship's daily zero-emission navigation. However, they should be evaluated with more extensive indexes during the application of the proposed methodology to a port infrastructural redesign. A discussion about the most suitable energy storage technologies is also provided, including the hydrogen conversion option.

The paper is structured as follows. Section 2 presents the methodology that has been conceived to allow the integration of ship, port, and land power system with the aim of increasing the environmental-friendliness of the maritime transport. In Section 3 the case study used to explain the methodology application is described. Section 4, Section 5, and Section 6 refer each to one of the sub-processes in which the proposed methodology is subdivided, describing in detail how the methodology is applied to the case study. The results of the case study are discussed in Section 7, and finally, Conclusions are given in Section 8.

2. Proposed Integration Methodology

The methodology proposed by the authors for the correct integration of environment-friendly ships, port electrical infrastructure, and local renewables sources is depicted in Figure 1. It has several inputs (both in terms of data and design choices) and outputs. Moreover, it requires to provide starting guesses in some steps, due to the presence of iterative loops. To ease the methodology workflow explanation done through the case study, it has been subdivided in three macro areas (sub-processes). The latter are clearly visible in Figure 1, where the blue lines represent their boundaries, and the bold text refers to the specific paper section where they are discussed.

The methodology starts from the ship, and then provides a design for the port infrastructure suitable for supporting its green operation. This means that operative choices related to the ship operation (such as the number of onboard battery recharges, or the power size of the ship's shore connection) have a direct effect on the port infrastructure design.

The input (green labels in Figure 1) data collection concerns everything that exists or has already been defined in the system, and therefore cannot be changed. The inputs are:

- a. Ship's power system architecture and main components sizing;
- b. Ship's daily operative profile;
- c. Port power system architecture and main components sizing;
- d. Port loads (besides the ship);
- e. Planned near/mid-future improvements to port power system;
- f. Additional port energy storage functions besides the ship's supply (e.g., ancillary services for the land power grid);
- g. Basic data about land power system supplying the port.

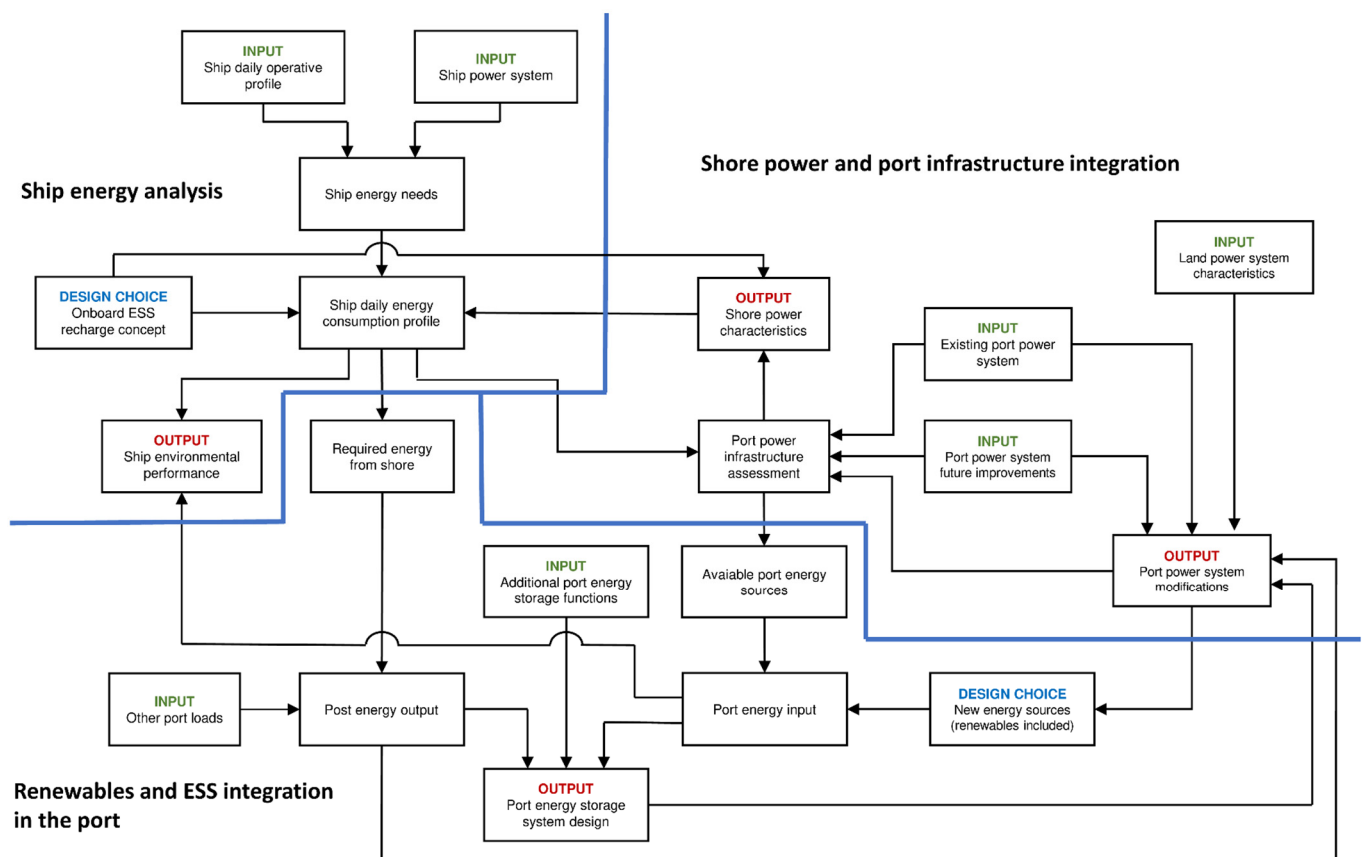


Figure 1. Proposed methodology for the integration of environment-friendly ships, shore connection apparatus, energy storage system, and port electrical infrastructure, including the subdivision in sub-processes (blue lines), whose denomination (bold black text) refers to the title of the paper sections in which their application to the case study is described.

Regarding the ship input data (bullets a and b), it is supposed that a green ship design (or even a built one) is already available for extracting it. This is coherent with the scope of the paper, which is the definition of the shore infrastructure required for supporting a given ship. A green ship design can be obtained by means of a data-driven design approach, such as the one presented in [18], which allows to optimize the ship towards specific requirements (environmental friendliness on a specific route in this case). The bullets c and d address the port existing infrastructure (electrical equipment of its power system and loads), while bullet e points towards already planned port power system improvements (such as substation revamping, installation of new loads, power lines substitution, etc.). Bullet f both concerns the port power system and the land power grid. In fact, the installation of an ESS in a power system enables several different functions besides the one here discussed (support for the ship recharge), such as peak-shaving, frequency support, voltage regulation, and so on. Knowing all these additional functions allows to correctly design the storage system. Finally, bullet g requires collecting data such as the land power system capability to supply power to the port, planned improvements in the area infrastructure, or other actions that may possibly affect the port operation (e.g., installation of a big PV plant nearby, from which the port can buy green energy).

The design choices (blue labels in the Figure 1) are particular inputs that have a significant effect on the environmental performance results. These choices must be taken in collaboration with the ship owner and the port management. In particular the following items must be discussed:

- Ship's onboard ESS recharge concept (e.g., how is it recharged? how many times a day? it is recharged at berth by shore connection or by DGs during sailing? etc.);
- New (possibly renewable) energy sources to be integrated in the port.

The first item is significant, as it affects the amount of energy that the ship receives from the port (a more detailed discussion in this regard is provided in Section 4). Such information is then used by the Figure 1 process, along with the other data, for defining the SC apparatus and the required port infrastructure. The second item combines with the first and the other inputs to determine how much energy needs to be stored in the port by means of a shore-side ESS, to enable the ship recharge and the other functions (bullet e of the input list). The new energy sources to be integrated in the port are depicted in Figure 1 process as part of an iterative loop. Their installation can be a given input coming from other decision processes or can be motivated by the need of supporting the ship energy supply. In both cases, the new energy sources can be set as fixed, or their sizing can vary depending on the process outcomes.

The expected outputs of the procedure (red labels in Figure 1) are:

1. The environmental performance of the ship;
2. The characteristics of the shore power interface;
3. The required changes to the existing port power system to achieve the expected integration;
4. The design of the ESS system to be integrated into the port.

For a ship that can obtain a part of its energy from the port, the environmental performance (bullet 1) depends not only on its energy consumption profile, but also on the port energy input carbon intensity. The ship's environmental-friendliness can be evaluated with different indexes, such as total fuel consumed, total emissions, and so on. The choice of the specific indexes and the evaluation method is upon the designer, as it directly depends on the specific route and port's location (different rules and regulations can apply in this regard). It is relevant to notice that in most applications it will be required to consider multiple indexes, but the definition of the best weighting factors for producing a ranking among different solution is still an open research point. The shore power interface characteristic (bullet 2) is both one of the outputs of the process and an input for defining the ship daily energy consumption profile. The latter is again required to achieve the output item through the Figure 1 process. In such a case, a first guess has to be made for the set of data required to close the loop, and then the process has to be run iteratively until a feasible solution is found. In this case, the shore power characteristics that is required for the definition of the following item is the SC power, which in turn depends on the onboard ESS recharge concept. Thus, a power level needs to be set during the first process iteration, and then it has to be corrected (if needed) following the loop feedback. Besides the power, other SC characteristics must be defined during the process to provide a complete shore power interface design, such as voltage, ambient conditions, plugs type and size, specific applicable rules and regulations, and so on. Among the methodology outputs, there are also the changes that have to be made to the existing port power system to enable the SC installation, the port ESS integration, and so on (i.e., all the infrastructure required to enable the green ship use). These are referred to in bullet 3 of the above list, and can include new substation installation, modification of existing power equipment, replacement of power cables, and so on. The last output of the process is a port ESS design suitable for supporting the ship recharge and all the other port needs (bullet 4). This output can be a simple estimation of power, energy, and technology requirements (to be given to a third part for design, construction and supply), or can be a more detailed design, depending on the specific application.

Overall, the proposed methodology is flexible, making it possible to take into account for different levels of accuracy and detail in its inputs and outputs. This can be done by using different design approaches and/or methods for each step depicted by the Figure 1 items. Thus, it can be applied at different design stages, also iteratively each time more detail is required. The presence of several feedback loops in the Figure 1 process is due to the strict interconnection between several items (e.g., SC power level and berthing time allows to determine the amount of energy that can be injected in the onboard ESS, but the first depends also on the port power system capabilities, which in turn depend on the electrical infrastructure). Following common design practice, it is suggested to start

with a preliminary design where all the items are defined by basic parameters and where the constraints can be very simple (such as a given range for the SC power level). This allows to approach the problem with linear programming methods (or more complex ones if desired, such as genetic algorithms, particle swarm optimization, and so on) to achieve one or more preliminary solutions. Then detailed design can be done for each specific equipment, and correction can be applied where needed.

3. Case Study

The Figure 1 methodology can be further explained by applying it to a case study. The application shown in this paper is a simplified one, although being based on real data. It does not address the detailed design of each component, but focuses on depicting the cause-effect relations between the items and the reasoning that must be applied to proceed with each step. In fact, each step can include several specific very detailed design processes, which can be attained by means of several approaches (which include not only standard industrial design procedures, but also novel proposals from the research literature). However, from the Figure 1 methodology point of view these are only tools to obtain, in each step, the expected outputs from the given inputs, and can be freely chosen by the designer. Therefore, the case study is presented using a low detail level for the analysis, to allow the readers focusing on the methodology and fully comprehend its operation.

3.1. Ship Power System

The ship is a bi-directional Ferry using the series-hybrid (SH) architecture discussed in [18]. In particular, the ship is endowed with a hybrid propulsion configuration, which include electrical propulsion motors, an integrated power system with Diesel generators, an energy storage system, and a shore connection. The ship's DC integrated power system is shown in Figure 2. Being the ship symmetrical, it has two propellers, one on each extremity. Both are used for navigation, with the back one (depending on which direction the ship is going) providing most of the propulsion power and the front acting only to keep the ship sailing direction (such as a rudder).

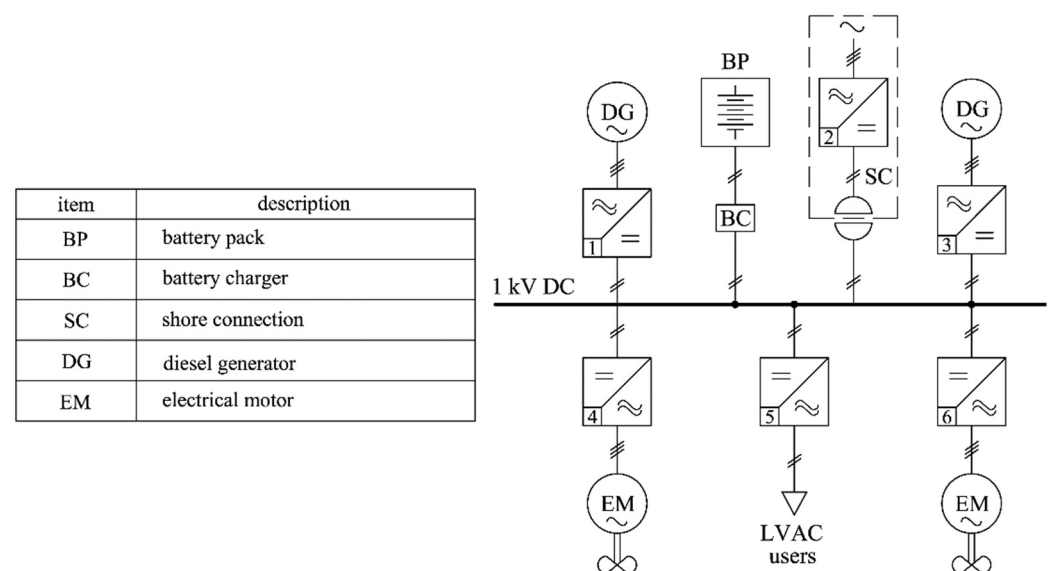


Figure 2. Bidirectional ferry onboard DC power system [19].

The two electrical propulsion motors (EM) take power from a common busbar. The latter is supplied by two synchronous diesel generators (DGs) and a battery pack (BP). Being the power system a DC one (1 kV bus voltage), power electronics converters are required to interface the subsystems. The DGs power the bus through dedicated AC-DC rectifiers (converters 1 and 3), while the AC loads require DC-AC inverters (converters

4, 5, and 6) to be supplied from the main bus. The shore-connection (SC) architecture depends on the shore side infrastructure. If a 1 kV DC connection is available in the port, a direct plug to the ship power system can be used. Conversely, if an AC supply is used, a dedicated converter is needed (rectifier number 2, Figure 1). The latter may be installed on the shore, or even integrated onboard. The use of a dashed box in the figure depicts this range of possibilities. The main power system data and the simplified load balance are shown in Tables 1 and 2, respectively.

Table 1. Main data of the bidirectional ferry power system.

Component	Power/Capacity
Diesel generators	800 kW each
Electrical motors	600 kW each
LVAC users' inverter	100 kW
Battery pack	750 kWh

Table 2. Simplified load balance.

Load	Sailing	Maneuvering	At berth
Propulsion	480 kW	200 kW	0
Hotel load and auxiliaries	80 kW	80 kW	80 kW

3.2. Ship Daily Operative Profile

The ship daily operative profile directly results from its route. In this case study, reference is given to the route presented in [18,19], connecting two small ports in Croatia (Brestova and Porozina) and providing both passengers and vehicles crossing services. A complete crossing from one port to the other is 35 min long. This time is composed by 15 min of sea navigation and 10 min of maneuvering in each port. The ship remains berthed for 15 min, to allow for passenger and cars embark/disembark. Therefore, each trip lasts 50 min, and is performed up to 16 times per day in summer (while in winter less trips are made).

The ship speed profile during the navigation phases (maneuvering and sea navigation) can be found in [18]. By using the ship power-speed curve and the speed profile it is possible to evaluate the propulsion power needed during the crossings. Then, by adding to it the hotel and auxiliaries' power (which is considered constant), the Figure 3 power profile can be attained. Single operation profiles differ a little bit between the two route directions, as well as if it is a day-time or night operation, but basically are very similar and can always be divided into the above-mentioned sections.

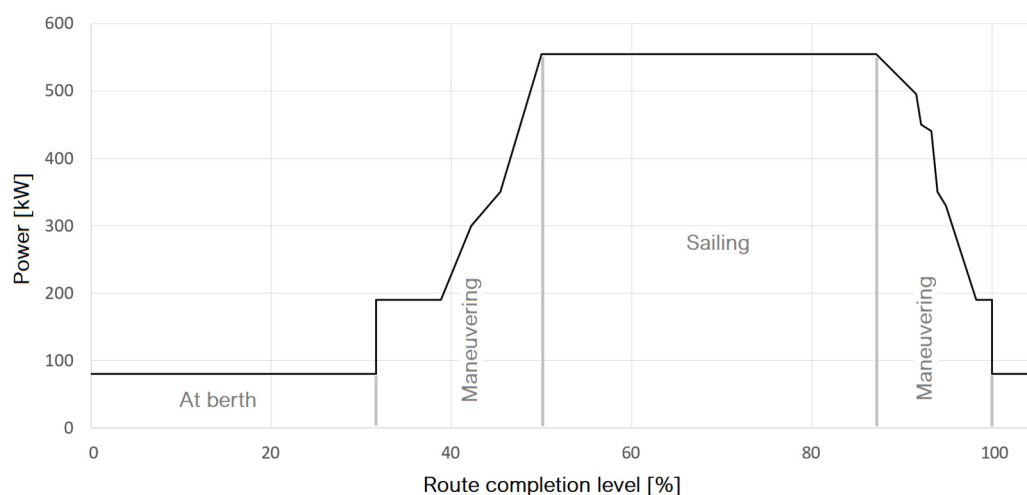


Figure 3. Ship power versus route completion level for the Brestova-Porozina route.

3.3. Existing Port Power System, Port Loads, Land Power System, and Future Improvements

In Brestova port a single step-down 50 kVA 20/0.4 kV AC transformer is installed. It supplies the port loads at 400 V, stepping down from the 20 kV delivery provided by the local Distribution System Operator (DSO). The transformer is oversized for the actual port loads, because the latter are limited to a lighthouse, a small restaurant, and a ticket shop. The existing housing can fit a transformer with a size up to 250 kVA with limited effort, if needed. The 20 kV DSO power line can deliver up to 2 MVA to the port, thus making it possible to support a higher port load if a bigger substation is built, for installing the transformer and its auxiliaries and protections.

In the Porozina port, the existing power system is sized for about 50 kVA. In this case the power is fed directly at 400 V by a single cable belonging to the DSO. The cable starts from the DSO transformer substation, whose maximum power is approximately 100 kVA (which is shared by the port and other users in the area). The DSO substation and LV power line are therefore the limiting factor regarding possible port power expansion plans. However, the DSO is planning for an overhaul to the electrical infrastructure in the area. In particular, two new transformer substations will be built. One will be connected to the 20 kV cable that is currently supplying the existing substation, and one will be supplied by a new 20 kV cable. The latter substation will be then used to provide up to 400 kVA to the port by means of a new 400 V cable. If such a power demonstrates to be insufficient for enabling the correct port integration with the environmentally-friendly ship, there is space available in the port for building a dedicated substation, connecting it directly to the existing 20 kV cable line. The latter can support up to 4 MVA, and is actually loaded for less than 1 MVA, thus presenting an abundant margin for the scope.

4. Ship Energy Analysis

This section of the methodology aims at determining the overall energy balance of the ship throughout the entire day. Being part of the ship energy coming from the port through the shore connection, the SC power level determines how much energy can be attained by the ship through this source, and how much energy should be generated onboard. Such energy is then used at the moment and/or stored into the onboard ESS for later use. Therefore, both the onboard ESS recharge concept and the SC power affect the ship daily energy consumption profile. Being these two items intertwined (the power of the SC determines how much energy can be provided to the ship, and how much times and for how long the ship is recharged affects the SC size), it has been decided to set the ESS recharge concept as a design choice (thus use it as an input), and then obtain the correct SC sizing as an output from the process. This is an arbitrary assumption that can be reversed if needed.

As previously stated, the ship is the starting point for the design. The ship energy needs can be determined by using its daily operative profile (coming from the route scheduling) and its power system data. To this aim, it is convenient to split the case study ship behavior on a single route in its operative modes.

The ship performs 15 min (=0.25 h) of sea navigation. Combining this data with the power used during sailing by the motors (480 kW) and the other loads (80 kW), the required energy is 140 kWh. The 10 min maneuvering phase happens twice in a single trip (one at each port, thus a total of 0.33 h), with an applied power of 200 kW by the EM and 80 kW by the other loads. Thus, the required energy results in 94 kWh. At berth, the only active loads are the hotel and auxiliaries ones, requiring 20 kWh (80 kW power applied for the 15 min stop). By summing the three terms, the total energy required to perform a single route is 254 kWh. Being the ship performing up to 16 trips/day (in summer), the energy consumed during a day of operation is nearly 4 MWh. A brief summary of these values is depicted in Table 3.

The energy that the ship can obtain from the port each day (i.e., the ship daily energy consumption profile) however depends also on other parameters. These, as depicted in Figure 1, are the “shore power characteristics” and the “onboard ESS recharge concept”.

Table 3. Ship energy consumption for a single trip and throughout the entire day in summer.

For a Single Trip (Port A to Port B)			For Summer Daily Operations (16 Trips/Day)
Sailing	Maneuvering	At Berth	Total
140 kWh	94 kWh	20 kWh	4064 kWh

Besides its use as a recharge point for the ship onboard battery, a shore connection is also a widely applied solution for lowering pollutant emissions in ports [3]. Thus, a starting guess for the shore power characteristics definition is the requirement of supplying the ship loads during the berthing time. In the case study, the minimum required power level for enabling this operation is the installation of an 80 kW shore connection (which is the total ship load at berth, Table 2) in both ports. Such SC does not exploit any of the advantages given by the green ship, but it has the added advantage of being usable also by conventional ships (if equipped with a SC). By using this minimum power level, it is possible to start evaluating the ship daily energy consumption profile. It is relevant to notice that neither of the ports is capable of supplying such power with their actual power system (refer to Section 3.3). Therefore, the integration of this basic SC system will require application of port power system modification, such as the ones described in Section 3.3.

The “onboard ESS recharge concept” item refers to the approach used to recharge the onboard ESS (BP in Figure 2). It has a significant impact on the SC design, because different type of recharge may require different sized shore connection apparatuses. Consequently, it has a direct effect on the overall integration results. In this regard, two possible options are here considered, with a subsequent impact on the other design items (Table 4). Both proposals leverage the shore connection for recharging the onboard ESS at night, but differ in terms of daytime ESS energy refill. The first option uses a Low Voltage Shore Connection (LV-SC) for recharging the ship during the night, while during day time the energy is entirely supplied by the onboard generators. The second option uses a Medium Voltage Shore Connection (MV-SC), to supply the ship during both day and night berthing periods. These two options require shore connection apparatuses with very different power levels, which are both greater than the 80 kW minimum level set before. Therefore, the onboard ESS recharge concept also affects the shore power level, as shown in Figure 1.

Table 4. Options considered for the recharge of the ship’s onboard ESS.

Onboard ESS Recharge Concepts	Daytime	Nighttime
Combined recharge using DGs and LV-SC	DG during sailing condition	Full recharge with LV-SC at berth
Fast recharge using MV-SC	Fast charge with MV-SC at berth	Full recharge with LV/MV-SC at berth

In this paper both options are considered, and the process is developed in parallel. This is done to provide an example about how a single input data change can affect the results of the entire process. This will allow not only to provide some preliminary comparative results regarding these two possible recharge concepts, but also to demonstrate the flexibility of the proposed methodology. As a final remark, the battery swapping method for recharging the ship’s ESS [20] has been ignored in this case study, due to its cost, infrastructure requirements on the shore side, and the need of a specifically designed vessel for its use.

4.1. Onboard ESS Recharge Concept: Combined Recharging from DGs and LV-SC

The first onboard ESS recharge concept uses a single DG during sailing for both producing power for onboard loads and recharge the BP. The stored energy is then used for performing zero-emission maneuvering and waiting at berth. The result is a reduction in

coastal and port emissions, with beneficial effects on the environment and population. At night, a LV SC recharges the 750 kWh onboard battery, to make it ready for the next day. By assuming 5 h of night berthing, which is a timeframe compatible with the ship scheduling, a 160 kW SC power is required (thus increasing its power above the starting 80 kW level).

The total power required by propulsion and other loads in sailing operation is 560 kW (refer to Table 2), while one DG can provide up to 800 kW. The power difference can be used to recharge the onboard battery, while at the same time making the DG operate at a higher efficiency. Two cases can be set, depending on the amount of power used for ESS recharge:

- (a) Load the DG up to 100% rated power (aiming for the DG's maximum achievable power);
- (b) Load the DG up to 85% rated power (aiming for the DG's maximum efficiency point).

In case (a), the power available for recharging the ESS is equal to 240 kW, which means that a total of 60 kWh can be stored during the 15 min long sailing. Conversely, in case (b) only 120 kW are available, thus leading to recharging the ESS for only 30 kWh in the same timeframe.

During both maneuvering and at berth conditions, the ship stops the onboard DG and uses the energy stored in the onboard ESS. The energy required for this zero-emission operation is 114 kWh (i.e., 94 kWh for maneuvering and 20 kWh at berth).

In case (a), by taking into account the 60 kWh provided by the DG during the navigation, the resulting energy balance is -54 kWh (discharge) for each route. This means that the zero-emission operation is not sustainable throughout the entire daily routine. Indeed, starting on the first route from the 750 kWh charged at night, the ESS becomes empty after 14 routes (i.e., $54 \text{ kWh} \times 14 \text{ routes} = 756 \text{ kWh}$). Therefore, in this case up to 14 trips can take advantage of zero emissions during maneuvering and at berth (Table 5), with the DG running only during navigation, while the two last trips require to continuously run one DG.

Table 5. Energy balance for case (a).

Starting ESS Energy	Single Trip			Trips for Using All Starting ESS Energy
	Recharge during Sailing	Discharge in Maneuvering and at Berth	Energy Balance per Single Trip	
750 kWh	+60 kWh	-114 kWh	-54 kWh	13.89

In case (b), the DG can recharge the BP for only 30 kWh during navigation, leading to a -84 kWh (discharge) energy balance at the end of each trip. The energy stored in the system at the start of the day (the 750 kWh recharged by night) can last only for the first 9 trips, leaving the last 7 to be performed with one DG always running (Table 6). In this case, less zero emission operations can be performed in respect to the previous one, but during sea navigation the DG is used in a more efficient operating point. If the environmental friendliness is sought only near the coast, this is surely a worse performing recharge concept in respect to the previous one. However, if the emissions of the ship throughout the entire route are evaluated, this solution may have some advantages.

Table 6. Energy balance for case (b).

Starting ESS Energy	Single Trip			Trips for Using All Starting ESS Energy
	Recharge during Sailing	Discharge in Maneuvering and at Berth	Energy Balance per Single Trip	
750 kWh	+30 kWh	-114 kWh	-84 kWh	8.93

4.2. Onboard ESS Recharge Concept: Fast Recharging from MV-SC

The second onboard ESS recharge concept implies installing a high-power shore connection in the port, to perform a fast-charge during the 15 min the ship stays at berth each trip. In this case, the SC power level has been defined following the ship requirements stated in [18]. Therefore, a 750 kW MV-SC is used, allowing the onboard ESS refill with up to 187 kWh during daily berthing time (provided that the onboard ESS is designed for accepting the charge pulse). Moreover, the ship operates in zero-emission mode also during sailing for as much trips as possible, to use all the energy supplied by the port during the night. After the battery is depleted, a DG is started to supply the ship in combination with the ESS (for the amount of energy that can be injected through the SC during the berthing period).

Two configurations for the recharge infrastructure have been considered:

- (c) Fast-charge in only one port;
- (d) Fast-charge in both ports.

In case (c), the fast-charge can be performed once every two trips. This means that a 187 kWh recharge by SC is followed by a 508 kWh discharge (i.e., 2 trips \times 254 kWh). Therefore, the 750 kWh stored in the BP at the start of the day are depleted in nearly 5 trips, due to the resulting net energy loss of 321 kWh for performing the two zero-emission trips between recharges (Table 7). The last 11 trips require one DG running to provide such energy.

Table 7. Energy balance for case (c).

Starting ESS Energy	Double Trip (between Two Recharges)			Trips for Using All Starting ESS Energy
	Recharge at Berth	Discharge in All Conditions	Energy Balance per Double Trip	
750 kWh	+187 kWh	−508 kWh	−321 kWh	4.67

A better accuracy in ship energy flows determination can be achieved by representing the sequence of charge and discharge operations on a graph, as shown in Figure 4. In the figure the trips are identified by an increasing number, and the recharge operation through the MV-SC by a capital R. As can be seen in the figure, the DG is required already during the fourth trip, to provide the missing 79 kWh. Then, from the fifth trip onwards the contribution of the ESS to the ship operation is reduced, as it can only provide 187 kWh in respect to the 508 kWh consumed by the ship between two recharges. Still, the ESS provides a nearly 37% contribution to the energy required for a complete round route (two trips).

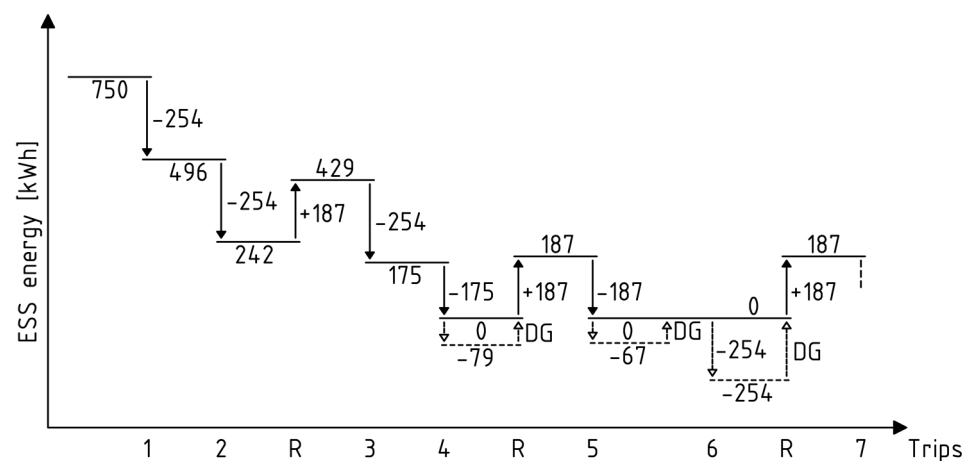


Figure 4. Energy stored in the ESS, consumption and recharge (R) during a working day, single MV-SC (case (c)).

In case (d), the double fast-charge infrastructure allows a 187 kWh recharge in each port, thus reducing the net energy loss down to 67 kWh for each trip (187 kWh recharge, 254 kWh consumption). In this case the energy stored in the onboard BP at the start of the day can last up to 11 trips in zero-emission mode (Table 8), while only the last five trips require the DG contribution.

Table 8. Energy balance for case (d).

Starting ESS Energy	Single Trip			Trips for Using All Starting ESS Energy
	Recharge at Berth	Discharge in All Conditions	Energy Balance per Single Trip	
750 kWh	+187 kWh	−254 kWh	−67 kWh	11.2

Again, it is possible to trace a graph regarding the ESS charge and discharge operations during the ship daily routine (Figure 5). From the figure it is clear that the DG needs to be started only during the ninth trip, to cover a 40 kWh deficit. Then, from the tenth trip onwards the DG must always be started during the navigation, to provide nearly 25% of the required energy. It is evident how the double fast-charge solution allows for a significant quota of the ship operations to be performed in zero-emission mode, thus improving its environmental-friendliness in respect to the previous solutions (both LV and MV -SC).

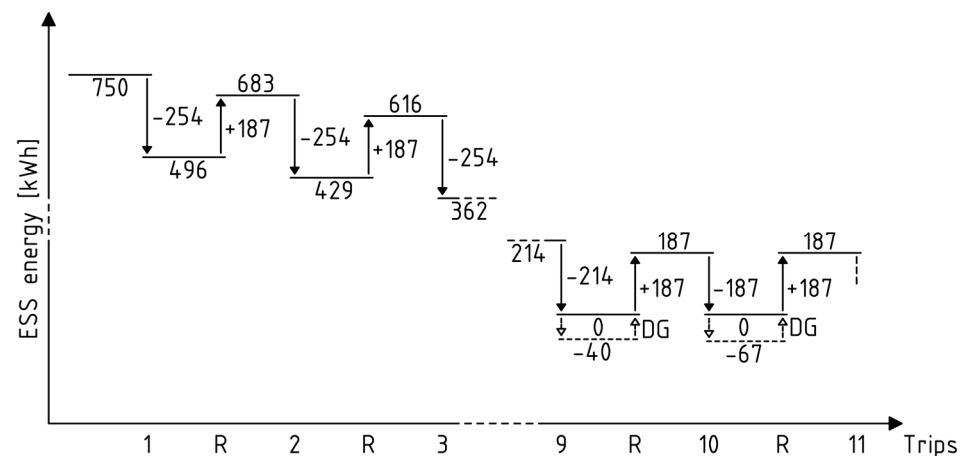


Figure 5. Energy stored in the ESS, consumption and recharge (R) during a working day, double MV-SC (case (d)).

At the end of the working day, in both cases the shore connection is used to completely recharge the ESS by night. Given the available power from the MV-SC, there are no issues for the total BP recharge. However, it may be useful to reduce the recharge power during the night, performing a slow charge and balancing the battery pack modules (which is beneficial for the ESS life).

It is relevant to notice that the results achieved through the graphical representation of the charge and discharge operations are more detailed in respect to the approximated evaluation made using the total energies only, but provide similar results. Thus, the less accurate approach can be considered sufficient for a preliminary study aimed at providing information to the designers in regard to the system architecture (for ship, port, and shore connection), to be selected and analyzed in depth in a later design stage with more complex approaches. Indeed, when more data about the system becomes available, more detailed ship energy analyses approaches can be used, such as the one shown in [9].

4.3. Ship Environmental Performance

As previously mentioned, the ESS and shore connection integration in the case study ship is capable of improving its environmental performance. This has been demonstrated

in [18], by means of a direct comparison between different propulsion architectures for the ship. Such comparison included annual consumables, annual energy consumption, annual carbon dioxide emissions, annual engine running hours, and annual operational expenditure. However, the results of [18] were calculated by supposing the capability of the port to fully support the ship, by means of a correctly sized shore connection and a given carbon intensity index for the port power. In the conclusions of that paper, it was remarked that the port infrastructure has a significant impact on the results, and a more integrated approach was needed for correctly supporting the ship. As in this paper a methodology to design the port infrastructure is proposed, it is significant to show the impact of the latter on these indexes. Among all the indexes used in [18], here it has been chosen to use the DGs' running hours, which in turn can be expressed in terms of daily zero-emission mode operation. This is because this index is relatively easy to evaluate in a simplified case study, and has a direct impact on pollution. Indeed, the quota of time during the daily operations in which the ship can keep their onboard generators shut off has a direct effect on gaseous pollutant emissions, as well as other less evident advantages. As an example, decreasing running hours reduces yearly maintenance, which has an environmental impact by itself and is a significant quota of the operative costs of the ship (along with fuel). Therefore, in the following the determination of the DG running hours is presented. The results are also recalled in Section 7 to provide a brief discussion about the effect of the input variables and design choices on the results of the proposed methodology. It is relevant to notice that a wider range of indexes can be calculated for the ship environmental performance evaluation, by means of the approach used in [18].

4.3.1. Combined Recharging from DGs and LV-SC

For the first onboard ESS recharge concept considered, one DG is used during the sea navigation for 14 trips in case (a), and for 9 trips in case (b). The remaining number of trips (which are two for case (a) and seven for case (b)) must then be performed with a single DG running in order to provide the required energy.

In case (a), the running time of the DG is 210 min during the ESS assisted trips (14 trips \times 15 min of operation each trip), and 100 min for the fully DG operated ones (2 trips \times 50 min operation). Consequently, the DG runs for a total of 310 min (=5 h 10 min) during the 14 daily working hours. Thus, the ship works for nearly 9 h in zero emission mode, which is 64% of total operating time.

For case (b), the ESS assisted trips are 9. The result is a 135 min DG operation time for the trips when the BP energy can be used, and up to 350 min of DG operation in the remaining ones. The DG run for 485 min (=8 h 5 min) during the 14 daily working hours. Thus, the ship works for nearly 6 h in zero emission mode, which is 43% of total operating time.

4.3.2. Fast Recharging from MV-SC

For what concerns the second ESS recharge concept considered, the two analyzed cases have a big difference in terms of emission-free navigation time.

The case (c), which is the fast-recharge in only one port, leads to a total of 550 min of DG operation. This means that the DG has to run for up to 9 h during the 14 daily working hours. In terms of zero emission operation, the result is only 36% of total operating time (nearly 5 h), which is the lowest result found in this case study.

On the other hand, in case (d) the DG runs for about 250 min each day (slightly more than 4 h). This results in nearly 10 h of zero emission operation, which is 71% of daily operating time. Such a result is the highest among all the examined cases.

5. Integration with the Port Electrical Infrastructure

All the options considered in the ship energy analysis sub-process provide a reduction in DG running hours, which means better environmental performance. To enable such result, the support from the port by means of a SC is required. The shore connection

installation in the port may require significant changes to the shore side power system for ensuring its correct operation. In this sub-process, the technical aspects related to the integration of the shore connection within the port electrical infrastructure are addressed. As mentioned above, the results of this design activities may lead to a change in the shore power characteristics (to meet some port side constraints), which is not only an output of the project but also an input for the Section 4 sub-process (i.e., ship energy analysis). If this happens, an iterative loop of the previous steps has to be made.

5.1. Shore Power and Port Infrastructure Integration

The two onboard ESS recharge concepts here considered have different impacts on the port, due to the different power required for the shore-connection system. Therefore, in this sub-process it is needed to continue addressing both options separately. In the solution using LV-SC, both the studied cases (case (a) and case (b)) require the same port side infrastructure, thus a single discussion is given. Instead, the MV-SC solution has different effects on the ports depending on the SC apparatuses installation in one or both of them. Therefore, a more detailed discussion is made. The specific shore power characteristic here addressed is the power level, as it is the one that allows to close the feedback loop in the Figure 1 process.

5.1.1. Low Voltage Shore Connection Integration in Ports

In both the cases considered for the combined recharging from DGs and LV-SC (i.e., case (a) and case (b)), the LV-SC is used only during the night for recharging the onboard ESS. A shore connection supplied by the 400 V three-phase AC feeder coming from the port substation can be used to this aim. A suitable power for the shore connection is 160 kW (AC side line current 230 A for the 400 V 3-phase supply, DC side current 160 A @ 1 KV), because it allows to fully recharge the onboard ESS in less than 5 h, which is a time coherent with the ship daily scheduling.

The LV-SC integration can be integrated in both ports without requiring the passage to a MV port power supply. The transformer installed at present in Brestova has an insufficient power level for the scope (i.e., 50 kVA), but the substation can accommodate a bigger transformer (up to 250 kVA) without civil works. Thus, it is possible to integrate the required LV-SC by changing the electrical machine and the switchboard in the substation, and by installing the shore connection apparatus. Regarding Porozina port, the DSO future plans for the area will increase the maximum power that can be delivered to the port up to 400 kVA. Such power is sufficient for supplying the LV-SC, and its installation can be added to the already planned port power system refitting (to support the higher power level). Although the night recharge is required only in one port, the LV-SC integration in both ports allows for an increased operational flexibility. However, to reduce as much as possible the investment it is also possible to install the LV-SC only in Porozina port, taking advantage of the already planned port power system overhaul.

5.1.2. Medium Voltage Shore Connection Integration in Ports

Given the data about the ports' electrical power systems, it is clear that the 750 kW MV-SC requires deeper modifications (and thus larger investments) in respect to the previous solution, in order to be integrated in the ports infrastructure.

Starting with Brestova port, a possible solution is building a new substation (including civil works, transformer, switchboards, and all the auxiliaries), to exploit the 2 MVA capability of the existing MV line. The investment will be substantial, being it necessary to install both the MV-SC apparatus and the new substation. Regarding the Porozina port, the MV-SC supply requirements goes well beyond the future power availability from the DSO substation (i.e., 400 kVA). Thus, also in this case a new electrical substation dedicated to the port power supply is required. In such a way, it becomes possible to have a direct connection to the existing DSO MV power line, which is suitable for transporting up to

4 MVA (3.5 MVA more than the present load). The investment will be significant also in this case.

The night charge function can be obtained by means of the MV-SC, in one or both ports depending on the analyzed case (cases (c) and (d)). In case (c) (only one port with MV-SC), there is also the possibility of installing a LV-SC in the other port, to allow the night recharge if the ship is berthed in the latter due to schedule needs.

An additional possibility is to use an ESS in the port for delivering the short-time high-power supply to the MV-SC, and recharge it by means of a low power port supply. This case is discussed in the following section, because it is a significant part of the “renewables and ESS integration” sub-process.

Finally, it is relevant to notice that at present automated plug-in shore connection systems are being tested, installed and used [20]. These allow, in the case of a properly fitted ship, to start the charging process as soon as 1 min after the ship docking. Therefore, the hypothesis of using all the berthing time for recharging the onboard ESS is suitable. Moreover, these systems are capable of delivering power in the range of MWs (up to 6.5 MW), which is nearly ten times the power hypothesized for the case study vessel [20].

6. Renewables and ESS Integration in the Port

As stated in Section 1, research focusing on the single components is already present in literature, and more is currently being done. This also concerns ESS storage systems design and management. Thus, it has been deemed more useful to focus this section on how the research and development results (both actual and future) can be used in the Figure 1 methodology framework, rather than providing an in-depth analysis of ESS storage systems.

The environmental impact of the first considered ESS recharge concept (combined recharging from DGs and LV-SC) is mostly related to DGs environmental performance. In both case (a) and (b), a significant quota of the energy used for zero-emission navigation is generated by the DGs, while only 750 kWh per day are provided by the grid by means of the night charge. Conversely, for the fast recharging with double MV-SC (case (d)) the amount of energy coming from the land power grid is significant. Indeed, the ship uses up to 3555 kWh, by means of seven fast recharges plus one slow one from the port where the ship is berthed at night, and eight fast recharges from the other. The single MV-SC solution (case (c)) falls in the middle between the two LV-SC options and case (d). Therefore, the performance in terms of pollutant emissions reduction of the double fast-recharge option is significantly affected by the energy mix used for the shore connection power supply, while the single MV-SC one has a lower but still sensible relation. This pushes towards a contract with green electrical energy producers, to further improve the solution environmental friendliness. Such an effect can be evaluated by applying the approach used in [18], using different values for the carbon intensity index for the shore connection power and comparing the results for the same ship architecture.

In addition to the latter, a smart idea is the exploitation of locally installed renewable energy sources for powering the SC. Given the case study ports characteristics, both photovoltaic (PV) systems and wind turbines can be suitably applied for exploiting local carbon-free energy production. The power of these new energy sources must be set as a guess for the first loop of Figure 1 procedure, and then modified with subsequent design loops. In the case study it has been supposed to have at least 50 kW of mean daily power coming from renewables installed in the port premises. Such power level is easily achievable with PV and/or wind generators within the available spaces. In particular, a 50 kW peak power PV system requires nearly 325 m², while a single wind generator can reach the same peak power with a 16 m diameter rotor. It is worth noticing that a mixed solution is the best option, to exploit the different productivity characteristics of both PV and wind generators and assure the required mean daily power production. Given the renewables power and their production variability, it is clear that the direct supply of the SC by means of these sources is not possible. Thus, the installation of an ESS in the port

premises is required, to store the renewable energy during their productive times and deliver it to the ship through the SC when needed. Such a solution is in fact coherent with several installations of ESS in Germany, which are aimed at improving the renewables consumption in commercial/residential applications [21]. In this regard, the Figure 1 proposed methodology allows the design of the port ESS, taking into account the ship needs, the port needs, the renewables production, and the land power system.

In the case study, the ports power requirements are very low in respect to the ship needs, making it possible to use only the latter as the base for the analysis (i.e., the “other port loads” input shown in Figure 1 has been set to zero). Therefore, the ship’s daily energy consumption profile (number, duration, and power of the recharges) has been coupled with the available port energy input to define the required land ESS size. The ESS installation calls for a port power system modification, which is an output for the design methodology and allows to close several of its design loops.

6.1. LV-SC with ESS

Having chosen to ignore port loads, in the case of LV-SC the shore-side ESS is used to store the daily renewables energy production for the ship night recharge needs only. To analyze the worst-case, it is hypothesized to not having renewables energy supply during the recharge. Thus, the port ESS size is required to be at least equal to the ship one (i.e., 750 kWh), to allow providing a full recharge. The ship is not connected to the LV-SC for at least 15 h per day (14 h of working time per day, plus 1 h that includes the time for SC connection and disconnection, night berthing preparation, etc.), which means that in such timeframe the port ESS can be recharged. The mean power required for the port ESS recharge is thus 50 kW (i.e., 750 kWh/15 h). The latter is a power level that can be also delivered from the actual ports power grids without requiring modification. This possibility allows to compensate for the days with insufficient renewable energy production by means of the grid supply. A notional scheme of this solution is shown in Figure 6.

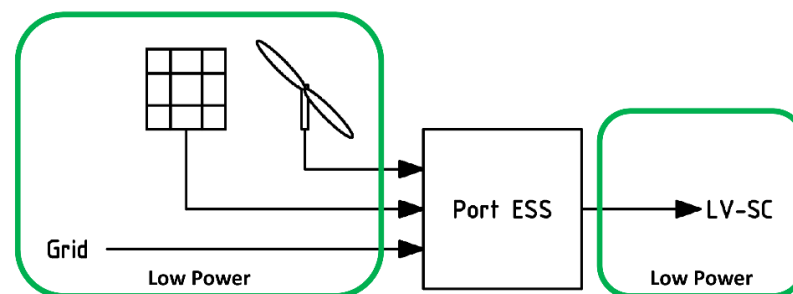


Figure 6. Integration among ESS, renewable sources, grid and LV-SC.

6.2. MV-SC with ESS

Regarding the MV-SC application, the ESS integration in the port can be performed using different approaches, depending on the functions it has to provide.

The first integration approach take advantage of the ESS in a similar way to the LV-SC case above-described. The port ESS is used to only store energy from the renewable sources during the day, enabling a green night recharge (Figure 7). Thus, the high-power port electrical infrastructure is still needed for supplying the MV-SC fast charges during the day. Part of the electrical energy used by the ship is surely green (at least the 750 kWh stored for the night recharge), while the power for the daily fast recharges is environmentally sustainable only if it is sourced from a green energy producer on the electricity market.

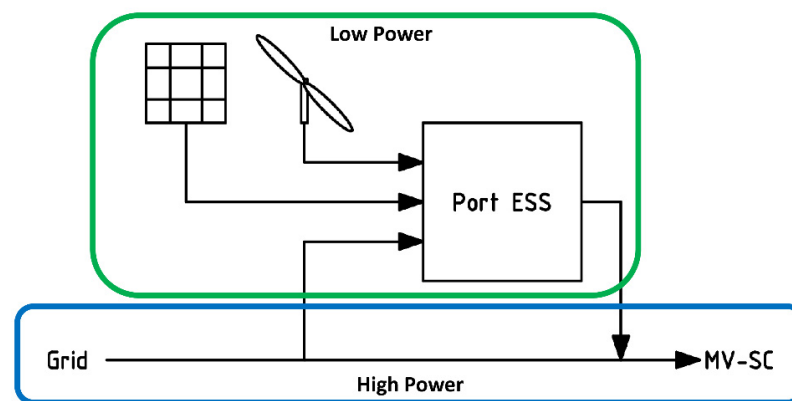


Figure 7. Integration among ESS, renewable sources, grid and MV-SC; first approach.

The second integration approach uses the shore-side ESS to store energy coming from the grid when the ship is not berthed, and then inject such energy in the onboard BP during the 15 min berthing period (Figure 8). Doing that, the 185 kWh (15 min @ 750 kW) delivered to the ship during the fast charge can be charged during the ship's absence by means of a lower power supply. Using 70 min as an approximated value for the latter time (sum of maneuvering phases, sailing to and from the other port, and berthing at the other port), the power required for the port ESS recharge results in less than 160 kW. Such a power is suitable for the Porozina port future electrical infrastructure, thus allowing the local integration of an MV-SC without building a new substation. Regarding Brestova port, such power is achievable by means of the low impact port power system modifications already described for the LV-SC integration (i.e., new transformer and switchboard change in the existing substation). With this approach a high-power interconnection to the land power grid is no more necessary, enabling the installation of the MV-SC in both ports with a lower investment in respect to a case in which the ESS is not present. With this approach, all the power supplied to the ship comes from the grid, which means that the only way to reduce the environmental impact is to source the energy from a green energy producer.

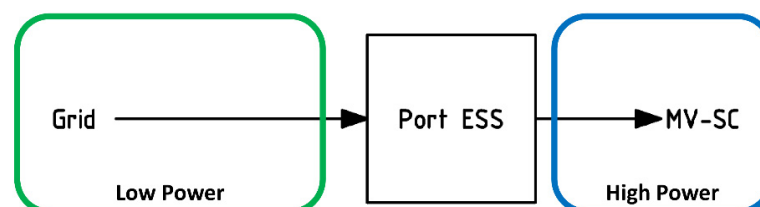


Figure 8. Integration among ESS, renewable sources, grid and MV-SC; second approach.

The third approach combines both of the previous ones, by using the ESS to provide the fast charge to the ship with a low power port infrastructure, and at the same time exploiting local renewables to reduce the energy quota taken from the land power grid. The resulting system provides the advantage of both the previous systems, presenting a similar integration effort. Therefore, this approach is considered as the best one for the MV-SC integration (for both cases (c) and (d)). The notional scheme of such integrated solution is shown in Figure 9.

6.3. Port Energy Storage System Design

The shore-side ESS that originates from the above integration procedure have different scopes, thus requiring different ESS designs. Indeed, the ESS in the LV-SC solution needs to store energy during the day and deliver it to the ship by night. The involved power is limited, and a single charge–discharge cycle is performed per day. This calls for an ESS technology endowed with a low self-discharge and high efficiency, while a low C-rate capability can be acceptable. Conversely, the ESS in the MV-SC solution performs fast

high-power discharges multiple times a day, while being continuously recharged while the ship is away. In such a case self-discharge becomes a minimum issue, but a high C-rate is required. Moreover, being the ESS performing several charge–discharge cycles per day, a high cycle life is required.

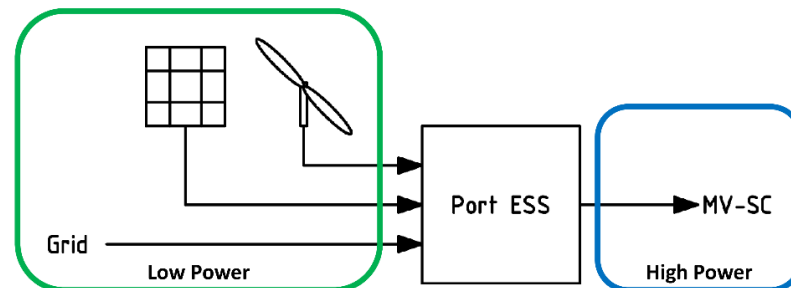


Figure 9. Integration among ESS, renewable sources, grid and MV-SC; third approach.

It is relevant to notice that it is always possible to design an oversized battery pack in respect to the base size required for the ship recharge. The available additional capacity can be then used for providing additional functions to the port power system, such as selling ancillary services to the grid (with additional revenues for the port), optimizing the port loads renewables energy consumption, enable islanded operation, and so on. Such needs are taken into account by the Figure 1 methodology, by means of the “additional port energy storage functions” input.

In the following a discussion about the most suitable technologies for building the two port ESS is made, based on the data of [21–47] for electrochemical system, of [37,48–51] for flywheels, and [52,53] for hydrogen. A synthetic representation of the discussion results is also depicted in Table 9, where the suitability of the each ESS technology to the two considered SC applications is shown along with some basic information. The ESS design (modules configuration, converter sizing, etc.) is not discussed in this paper, being it outside its scope.

Table 9. Port energy storage system technologies, basic information, and applicability (from very high ++, to very low --) to case study integration of SC in the ports.

Technology	Energy Density [Wh/kg]	Life [Cycles]	Efficiency	Daily Self-Discharge	Applicable to LV-SC	Applicable to MV-SC
Lead-acid	20–30	2500	80–90%	<0.3%	++	--
Sodium-sulfur	150–240	4500–5000	75–90%	0.05–1%	+	--
Redox flow	15–30	>10,000	75–90%	≈0	–	–
Lithium-ion	90–200	10,000	90%	<8%	+	++
Flywheel	5 (steel FWs)	Nearly infinite	85–90%	20% (per hour)	--	++

6.3.1. Port ESS for Supporting the Ship’s Slow-Charge (LV-SC)

The low power and low cycles per days required by the LV-SC makes the well-proven lead-acid batteries one of the first ESS technology choice. Lead-acid batteries present very good cycle efficiencies, have very low self-discharge rate, require low maintenance, and have a low capital cost [24–26,28–30]. Their low cycling life [27,28] is not an issue, being a single charge/discharge cycle per day applied at maximum. Considering a mean life of 2500 cycles, at least 7 years of continuous daily operations can be performed before some of the modules start failing. Additionally, the low power charge and discharge put them in the best conditions for reaching a long life. The low energy density is not an issue, as in a land-based application the required space can be easily found. Indeed, 750 kWh of lead acid batteries require nearly 15 m³ for the battery modules alone (given their volumetric energy density of 50–60 Wh/l), making them installable in a couple of 20-foot shipping

containers (internal volume of just above 30 m³ each) considering the required ventilation, safety systems, converters, and maintenance spaces.

Sodium-sulfur batteries, while being a good candidate and being used at present for similar applications, present significant drawbacks in terms of costs and management issues in respect to lead-acid batteries. In particular, the advantages over the latter (longer life, lower self-discharge, and higher energy density) are not so significant to overcome the disadvantages (high operating temperatures and corrosive nature of their molten cathodes, which requires a particular care in their construction and thermal management system) in this application [31–34]. The lower temperature version of this type of batteries, commercially known as ZEBRA batteries, present both lower issues and lower performance in respect to sodium-sulfur ones. Still, the higher cost in respect to lead-acid batteries is not justified for the LV-SC case.

Redox flow batteries may seem a good solution due to their very high life expectation [35–37]. However, the increase in costs in respect to lead-acid batteries and the dangers related to their operating concept is not justified by any other benefit in this specific application. Indeed, the possibility of swapping the exhaust electrolytes with charged ones for instantly recharge the ESS is not required in the case study, and the shore-side ESS capacity is still sufficiently low to make the advantage in terms of total volume of this battery technology non-critical [38–40]. A particular use case can be the installation of a larger capacity, to store the energy for several days. In such a way it becomes possible to overcome long periods of renewables unavailability and still supply the ship with green energy. However, being the port connected to the grid makes such solution unnecessary.

Regarding lithium-ion batteries, in the LV-SC use case the only relevant advantages in respect to lead-acid ones are the significantly longer life (more than 10,000 lifecycles) and the slightly higher efficiency. However, they present higher self-discharge and cost compared to lead-acid ones [28,37,41–47]. Thus, the choice of using lithium-ion batteries must be done on a cost base, considering a long-term use scenario where their life expectancy of more than four times the lead-acid batteries can lead to possible savings.

6.3.2. Port ESS for Supporting the Ship's Fast Charge (MV-SC)

The high daily charge/discharge cycles number required for the MV-SC application makes lead-acid batteries unsuitable. Moreover, the fast high-power discharge will further reduce their life, being such technology more suited to slow charges and discharges.

Similar considerations can be made for the sodium-sulfur batteries, whose higher number of achievable cycles is still not enough for their convenient exploitation (5000 cycles will only last up to 2 years, given the eight charge/discharge cycle per day in the case study). The high efficiency and the almost zero self-discharge advantages are still not enough to recommend their use.

The life expectancy of redox flow batteries (above 10,000 cycles) makes them a possible candidate for this application. However, their low efficiency (75%) for high load conditions, their complexity, and the hazards related to the fluid electrolytes makes them less interesting than other technologies here considered.

Lithium-ion batteries are the most suitable electrochemical energy storage technology for the MV-SC application. Their long lifetime (above 10,000 cycles for the LiFePO₄ ones) makes them suitable for the high number of daily cycles (seven fast recharges plus one slow one for the port where the ship is berthed at night, and eight fast recharges for the other), allowing to reach up to 3.5 years of continuous full charge/discharge operation. In fact, such a figure is higher, because the ship does not perform 16 trips a day for 365 days per year (in winter there are less trips per day), and because a suitable safety factor is always set during the ESS design. Moreover, being the cost of lithium-ion batteries reducing more and more as the time goes by, it is feasible to oversize the battery pack to further increase the expected lifetime. The high efficiency allows for reduced losses during the several charge–discharge operations, while the fast response rate is required for maximizing the energy amount delivered to the ship during the berthing time. Finally, their high energy

density allows to store all the fast charge energy (185 kWh) in just more than half a cubic meter. By adding the auxiliary systems and the power converters, it can be estimated that such an amount of energy can be stored in just above 1 m³ (similar figures can be found for commercial off the shelf ESS systems). Considering the much higher night charge needs, a 750 kWh lithium-ion energy storage system occupies less than 5 m³, which is six times less volume than a similarly sized lead-acid based ESS.

Flywheel energy storage is a technology that is suitable for the MV-SC application. Their characteristics make them very good at storing and delivering high amounts of power in short times, with a good efficiency and nearly infinite number of charge/discharge cycles [37,48]. Their low energy density is not an issue for a land-based application, while their high self-discharge rate (up to 20% per hour) makes them suitable only for the daily fast charge operation [49–51]. Thus, the night slow recharge must be performed through the grid supply if only flywheels are used.

As a final comment on the MV-SC case, a hybrid ESS may be the best for this application. In particular, by combining two technologies it becomes possible to exploit the advantages of both, as well as overcome their disadvantages. In this specific case, a promising solution is the use of flywheels for delivering the daily fast charge capability, while managing the night recharge with renewable energy stored during the day by means of lead-acid batteries. This makes the high self-discharge of flywheels a lesser problem, because they are used only for short periods of time in high power bursts, while their long life makes it possible to reduce maintenance costs. On the other hand, the high efficiency and low self-discharge of the lead-acid batteries make them ideal for storing the large amount of renewable energy produced throughout the entire day for the slow night recharge. A possible alternative for lead-acid batteries in such a hybrid ESS are lithium-ion batteries, if the flywheels presence leads to a lack in available spaces for their installation.

6.4. Hydrogen Storage Option

Besides batteries and flywheels, another possible solution for storing energy in the port (for renewables and shore connection integration) is its conversion into hydrogen. This can be either performed locally by the port or performed in another place by a third part and then supplied to the port. The hydrogen can be then converted back in electrical energy through fuel cells in the port (to be used for base load and/or ship shore connection) or supplied to the ship for being used in onboard fuel cells (if present, which is not the case of the ship considered in this paper) [52]. The former option implies adding more energy conversion stages (from electrical to chemical and back to electrical energy), while the latter requires hydrogen bunkering facilities in the port and suitably arranged ships, with related costs. Being the fuel-cells non-suitable for high-power loads with highly variable profiles, they can be used directly only for the night recharge of the ship's onboard ESS in both LV-SC and MV-SC cases. Conversely, for the daily fast-charge in the MV-SC an additional ESS has to be installed, making it also possible to optimize the fuel-cell size and reduce the total cost for the system [52,53]. The ESS can use flywheels technology, or even supercapacitor one, to provide the fast power pulse to the ship, while being slowly recharged by the fuel cell system. Although seeming less attractive in respect to a pure ESS solution, the hydrogen storage allows for an external supply, which leads to an increased port flexibility and continuity of service (hydrogen supply can be guaranteed also in periods of reduced or absent local renewables energy production).

7. Case Study Results Discussion

The proposed methodology provides a tool for integrating environmentally-friendly vessels with a green port infrastructure, with the aim of enabling the achievement of environmental benefits. By means of Figure 1 process, it is possible to consider not only the ship, but also the route, the port, and the land power grid in the decision-making process. Such a task is hard to achieve without considering the several interrelations among the subsystems (demonstrated by the several feedback loops in Figure 1), which

make impossible the complete separation of each design task from the others. An example of such a complexity is given by the case study results depicted in Table 10 (coming from the “ship environmental performance” output item), where the percentage of the daily operation time in zero emission operation are shown for all the examined cases.

Table 10. Results in terms of zero emission navigation capabilities for the considered solutions.

SC Configuration	Onboard ESS Recharge Concept	Daily Zero-Emission Navigation Quota
LV-SC	(a) DG at max power	64%
	(b) DG at max efficiency	43%
MV-SC	(c) SC in one port	36%
	(d) SC in both ports	71%

The high variability in Table 10 results in terms of daily zero-emission navigation quota demonstrates how the same shore connection technology can provide significantly different results depending on how the ship is operated, and vice versa.

Some final remarks can be made on the basis of the case study results:

- The LV-SC solution performs well if the energy recovered from the DG during the navigation can be maximized, leading to a 64% of zero-emission time. However, operating the DG at max power leads to increased emissions in respect to operating it at maximum efficiency point, requiring more fuel and maintenance for the same number of working hours. On the other hand, by making the DG work at its maximum efficiency operating point allows for a higher fuel efficiency and lower maintenance, but makes the zero-emission navigation quota drop by a significant amount (down to 43%).
- The MV-SC solution leads to the best results in terms of zero emission navigation, but only if both ports are endowed with the shore connection apparatuses. Though, it becomes the worst one when the shore connection is installed in only one port.
- In general, an LV-SC costs less than a MV-SC. In the case study the cheaper solution leads to results that are in the middle ground among the best and the worst one, while the MV-SC leads to the best results if a significant infrastructural investment is done in both ports. Therefore, in the case study it is better to make a significant investment for installing the MV-SC in both ports, or to invest significantly less to install the LV-SC and recharge using the DGs, rather than investing in a single MV-SC.
- The LV-SC with DG recharge at max-efficiency seems a solution capable of balancing low investment cost for the recharge infrastructure, low maintenance cost for the ship, and an appreciable amount of zero emission navigation in the case study. Thus, it may be a solution that is worth analyzing more in depth in the future for this case study.

8. Conclusions

The methodology presented in this paper has been conceived for integrating shore connection apparatus (i.e., the charging station for the ship’s onboard ESS), energy storage systems (both onboard and on-shore), and port electrical infrastructure. The methodology is aimed at defining the shore infrastructure required for supporting a given new green ship, by determining the port main elements and the expected impacts in terms of route environmental-friendliness. Such methodology has been deemed necessary, as the same green ship can provide very different results in terms of environmental impact, depending on the supporting port infrastructure. Indeed, if the port is not ready for enabling the full use of a new green ship, its environmental benefits over a conventionally propelled ship may be impaired. Moreover, there may be some limitations related to the port infrastructure (such as maximum power level of existing power system, funds availability for new components installation, and so on) and to the land power system (e.g., available power lines for supporting the increased port power requirements, carbon intensity of the provided energy, etc.) that can greatly affect the final results. Thus, the reduction in the environmental impact of maritime transport requires a wider approach, which encompasses

the ship, the port, and the related elements (e.g., the environmental friendliness of electric energy supply). This coupled nature between the ship and the port design is an aspect that is not sufficiently addressed in the literature, but it can be approached by means of the proposed methodology.

The case study shows how the proposed methodology allows to design a port power system that is able to supply an environmentally-friendly ship, as well as take advantage of the presence of local renewables and on-shore ESS. The results of the case study are depicted in terms of daily zero-emission navigation quota, which is only one of the several possible indexes that can be used to evaluate the ship's environmental impact. The comparison among the different proposed onboard ESS recharge concept results demonstrates that there are several items capable of affecting the environmental-friendliness of the ship, and that the proposed methodology is capable of consider them. In this regard, it is interesting to notice how the solution that is most impacting for the port (the medium voltage shore connection), is also the one showing both the worst and the best results, depending on the level of investment that the port owner is willing to make. Concerning the low voltage shore connection, it can be seen that a lower investment solution is capable of providing zero-emission navigation quota results that are close to the most impacting solution. Clearly, the zero-emission navigation quota is not the only parameter for evaluating the environmental-friendliness of the ship, as its overall environmental impact is greatly affected by the energy mix of the power grid, the presence and characteristics of the renewables production in the port, and the specific pollutant emissions of the ship's onboard DGs. However, such a simple example is still capable of highlighting that the shore side infrastructure can have a significant impact on the ship environmental performance, and thus its design must be done balancing the ship needs with the port infrastructure capabilities.

The general conclusion that can be drawn from the application of the proposed methodology to the case study is the need of considering both the ship and the shore infrastructure design as a whole, to allow reducing the pollutant emissions of maritime transport. This demonstrates why the impact of actions aimed at decreasing the environmental footprint of a transportation mean cannot be correctly determined if the overall system where such transportation mean has to be used and integrated is not taken into account.

Author Contributions: Conceptualization, A.V. and G.S.; methodology, A.V.; software, A.V.; validation, A.V. and G.S.; formal analysis, A.V.; investigation, A.V.; resources, G.S.; data curation, A.V.; writing—original draft preparation, A.V.; writing—review and editing, A.V. and G.S.; visualization, A.V.; supervision, G.S.; project administration, A.V.; funding acquisition, G.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by European Regional Development Fund (ERDF), through the 2014–2020 Interreg V-A, Italy—Croatia CBC Programme, by means of the 2017 Standard call research project “METRO—Maritime Environment-friendly TRanspOrt systems” (Project ID: 10044221), Priority Axis: Maritime transport.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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