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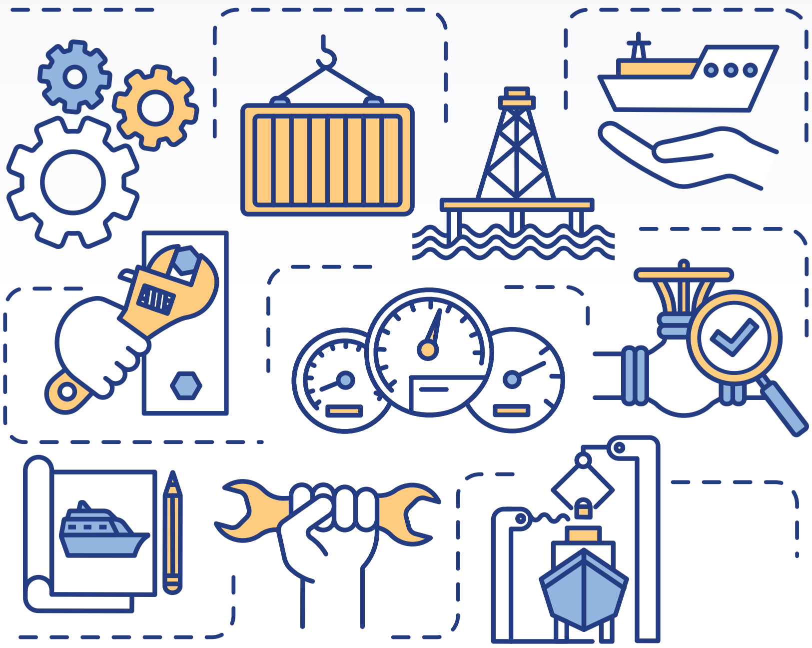
Holistic Energy Transformation of Ports



The Proteus plan.

THE ARTICLE PRESENTS THE PROTEUS plan, a holistic approach towards the transformation of ports into a sustainable energy hub encompassing cutting-edge smart grid technologies. More specifically, the Proteus plan, which has been developed by an interdisciplinary scientific team (the Proteus team) comprising maritime transport engineers, naval architects, and marine engineers, as well as electrical and computer engineers, aims at a smart port implementation of the integration of a series of actions, such as:

- ship-to-shore interconnection (cold ironing)
- charging of battery-supplied vessels with electric propulsion
- smart port lighting serving both illumination but also communication
- efficient cargo-handling cranes with regenerative braking
- smart multipurpose energy storage, such as charging of electric vehicles within the port
- deployment of renewable energy sources (RESs)
- a sophisticated energy management system (EMS) taking full advantage of digitalized modern distribution networks, etc.

Within this context, the main challenges raised by the smart decarbonized electrification of maritime transportation are discussed.

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Introduction

The maritime industry, following the International Maritime Organization (IMO) and European Union (EU)

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directives toward minimizing atmospheric emissions of ships, has been focused on designing and building greener ships or greening existing ones via alternate retrofitting techniques. Furthering this concept, modern ports playing a key role in the transportation chain are also facing similar challenges in terms of providing innovative services of superior quality without adverse environmental and societal impact. These challenges have increased at least in the EU by the advent of the so-called *fit-for-55%* package of directives, currently under consultation aiming at accelerating the pavement toward complete atmospheric neutralization.

To this end, all ports would resynthesize their master plan according to which they are subjected to a transformation into smart energy hubs where electrification plays a key role.

To this end, all ports would reform their strategic priorities, being transformed into smart energy hubs where sustainable and smart electric energy systems tend to predominate. In particular, the port facilities and services related to this target include the installation, operation, and management of systems like ship-to-shore interconnection, charging of battery-based ships, safer power supply, RESs, port lighting, cargo-handling cranes, and energy storage systems (ESSs).

This article concerns a discussion of the sustainable growth reformation of ports in alignment to green shipping demands, on the one hand, and the smart grid concept on the other. This combination consists a holistic approach of the port energy transformation, the so-called *Proteus plan*, which has been developed by an interdisciplinary scientific team (the Proteus team) comprising maritime transport engineers, naval architects, and marine engineers, as well as electrical and computer engineers. Within this context, we show that it is of major importance to design and develop a centralized supervisory EMS of a supervisory control and data acquisition (SCADA)-type in the port area that can integrate, monitor, and control all available energy sources (RESs, grid supply, batteries), as well as all loads served, which comprise ships in cold-ironing mode, battery ships in charging mode, cargo-handling equipment, refrigerating reefers, etc. In this way, all energy transactions can be performed in an optimum manner from the techno-economical point of view. For instance, energy can be stored from RESs or from the grid when the latter provides it in low price, or even from cranes operating in regenerative mode, and provided to loads and consumers upon demand.

The Ports as Major Electric Energy Hubs

Within the framework of greener shipping established by IMO resolutions, modern ports, being transportation hubs, are confronted with significant challenges in terms of providing innovative services of superior quality and high financial, environmental, and societal impact. To this end, all ports would resynthesize their master plan, according to which they are subjected to a transformation into smart energy hubs where electrification plays a key role. In particular, the port clients subject to penetration and sophisticated management of electric energy are:

- ship-to-shore interconnection (cold ironing)
- regulated reefer power supply
- smart port lighting
- efficient cargo-handling cranes
- smart ESSs,

the characteristics of which are discussed next, highlighting the important role of a central power management system (PMS) supervising all energy transactions in the port jurisdiction.

Ship-to-Shore Interconnection (Cold Ironing)

Ship-to-shore power interconnection (Figure 1) or alternate maritime power is one of the most appealing ways of eliminating the atmospheric pollution (and noise) produced by ships being at berth as their engines are shutdown, while they are supplied with electric energy from the National Grid via the appropriate port infrastructure

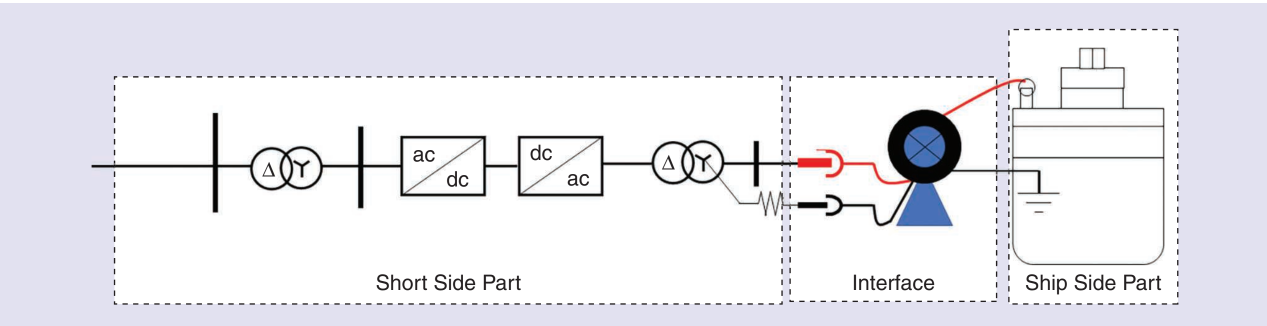


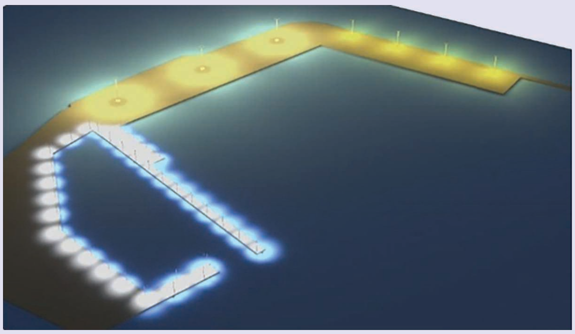
Figure 1. Ship-to-shore interconnection scheme (the red lines refer to three-phase flexible power cable connections, while the black line refers to the flexible earthing connections).

(Figure 2). The interconnection is recommended to comply with International Electrotechnical Commission/International Organization for Standardization/IEEE 80005 series of standards, namely -1, -2, and -3, while it comprises three distinct subsystems (Figure 2):

1) First is the shore side part, comprising one voltage transformer (matching the voltage difference between shore and ship grids), a frequency converter (often used to match the shore grid frequency with that of the ship to be served), and an isolation transformer used to match the different grounding schemes (the shore and the ship ones).
2) Second is the ship side part, consisting mainly of the switchboard used to connect the interconnection plugs and synchronize the ship with the shore grid.
3) Third is the interface between ship and shore part, comprising a sophisticated cable management system used to interconnect them. The interconnection cables comprise one or more three-phase flexible power cables along with a flexible cable connecting the earthing resistor of the isolation transformer with the common earthing point on the ship's hull (Figure 1).

An extension of this interconnection type consists in charging battery-driven ships via shore power facilities. Vessels with electric energy storage units (batteries, supercapacitors, etc.) and consecutively with electric propulsion systems, have become quite popular in the last decade as they have been proven both cost-effective and environmentally friendly. These ships have been successfully used for short-sea shipping applications in Northern Europe—e.g., in Norway, Denmark, and Sweden—while some feasibility studies have been performed for Greece where, due to the Aegean Archipelagos, there is a plethora of short-sea itineraries served by shuttle ferries. According to these studies, the investment in an electric transformation of a significant number of such vessels is worthwhile both cost-wise and environmentally.

Furthermore, the same infrastructure utilized for shore-to-ship can be exploited for the reverse power flow: i.e., from the ship to the shore grid. This "reverse cold ironing" can be used in the case of emergencies, such as environmental disasters, but since it can be treated as an energy transaction between the ship and the port it can be exploited in many ways. Thus, in certain cases it might be more beneficial from an environmental and economical point of view for this approach, with a typical example being the noninterconnected islands, the power of which in most cases is strongly dependent on oil, with all its subsequent side-effects (in terms of cost and pollution). In such a case, it has been proven appealing from many points of view to procure electric energy from ships, the electric power of which is based on greener fuels, like liquified natural gas.



	Energy Consumption of LED Lamps (kW)	Energy Consumption of Conventional Lamps (kW)	Energy Saving (%)
Main Port	16.5	24	31.25
North Port	5.056	8	36.8
Fishing Docks	3.264	8	40.8

Figure 2. Luminance of the Kyllini port (LED lights have been placed only in the fishing docks).

Regulated Reefer Power Supply

One of the most advantageous characteristics of reefers is that they are able to keep their thermal condition almost constant for fairly long intervals, on the order of 6–12 h, even if there is no power supply, which provides significant freedom in controlling the energy supply to them. Thus, they can be supplied on an intermittent basis according to an optimized operation scenario of the entire energy system of the port, as this is processed by the corresponding EMS. As already hinted, long intervals without power supply have no adverse impact upon the internal temperature conditions of the reefer and, consequently, to its content as well.

Smart Port Lighting

Modern energy-saving lighting devices, especially those based mainly on LED technology, provide significant reductions in energy demands (in terms of kilowatts) while offering equivalent levels of luminance (Figure 2). Of course, it is well known that LED light devices introduce harmonic distortion problems, which must be taken into consideration.

Efficient Cargo-Handling Cranes

Cranes are extensively used for cargo handling in container ships and car carriers. The energy profile of one port crane during operation is shown in Figure 3(a). As can be seen, a most critical issue is the negative power during lifting down of a load that corresponds to the regenerative braking of the driving motor. This regenerated amount of power can either be stored to battery systems of the port or supplied to ships in cold-ironing mode, or even supplied back to the main grid via the port distribution network. Moreover, what is also important to note is that due to this regenerative power, the mean power demand during the duty cycle of the crane is significantly lower than its peak demand. This is further reinforced when a set of cranes is examined. For instance, in Figure 3(b) the power demands during the combined operation of seven cranes is shown; the mean power demand is less than 30% of the maximum peak demand noted, which is something that should be taken into consideration by the EMS of the port grid.

RESs

RESs, like photovoltaic units (PVs) or wind generators (WGs), produce green energy. Hence, taking into account meteorological data, clusters of PVs and small-scale WGs can be deployed in locations available within the port jurisdiction. Moreover, based on economical criteria, the green energy produced can be stored in energy storage units or distributed to the port consumers or even sold to the main grid.

Efficient Parking Stations

The modern services offered in the port jurisdiction could include parking stations for electric or hybrid-electric vehicles:

- belonging to passengers
- belonging to the port authority and used for internal transportation needs (e.g., moving passengers between terminals, etc.)
- in combination with PVs (e.g., solar panels on top of the parking stations on the port side).

Smart ESSs

The battery units installed in the port jurisdiction can serve the following two-fold goal:

1) Provide energy buffering, i.e. storing electric energy, which is:
   - purchased from electricity providers when electricity price is low
   - generated by RES's deployed in the port area produced by regenerative braking of cranes battery swapping (ships and ports).
2) Facilitate energy bunkering, i.e., electric energy is provided to battery-driven ships, such as short-sea shuttle ferries. This bunkering can be performed either via:
   - direct charging through dc-to-dc ship-to-shore interconnection, or
   - battery swapping, i.e., battery modules that be easily transferred from shore-to-ship and vice versa, while they can be charged in port.

Furthering the aforementioned concept, all energy storage units installed onshore or onboard ships at berth could service providing storage on demand, provided that this mutually beneficial for all parties involved.

The Next Step

The energy transactions of all electrical subsystems described previously are figuratively depicted in Figure 4. Considering that some of these transactions (e.g., those between the shore grid and the ESSs or the cranes or even the interconnection with the ships) follow the trends of smart microgrids and are bidirectional (Figure 5) ports via their electrified facilities, and can be transformed into energy hubs buying and selling electric energy in bulk. The next step is that all energy sources in the port area, including vessels (with batteries) at berth, battery stacks, and RESs can store or provide energy upon demand. Within this framework, energy is not well located in certain providers but is rather distributed throughout an energy cloud with which transactions can be bidirectional too.

The Key Role of PMS

The PMS of the port is to have an overall supervisory monitoring and control of the energy transactions in

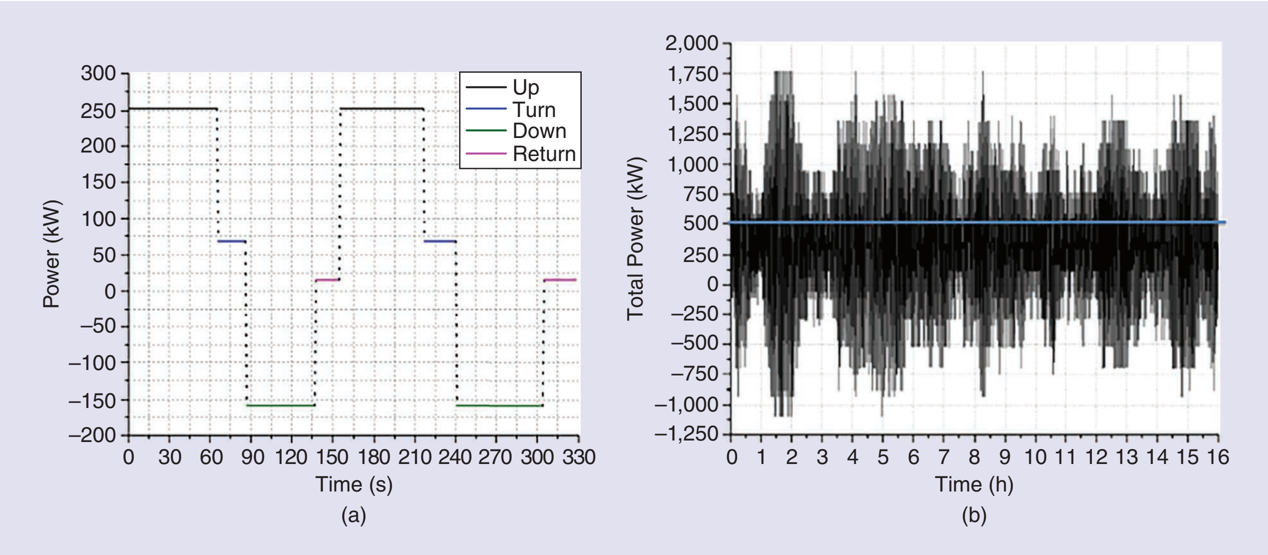


Figure 3. (a) Operating profile (two full cycles of operation) of one single port crane. (b) Total power demand of seven cranes operating concurrently; the mean power demand is in blue.

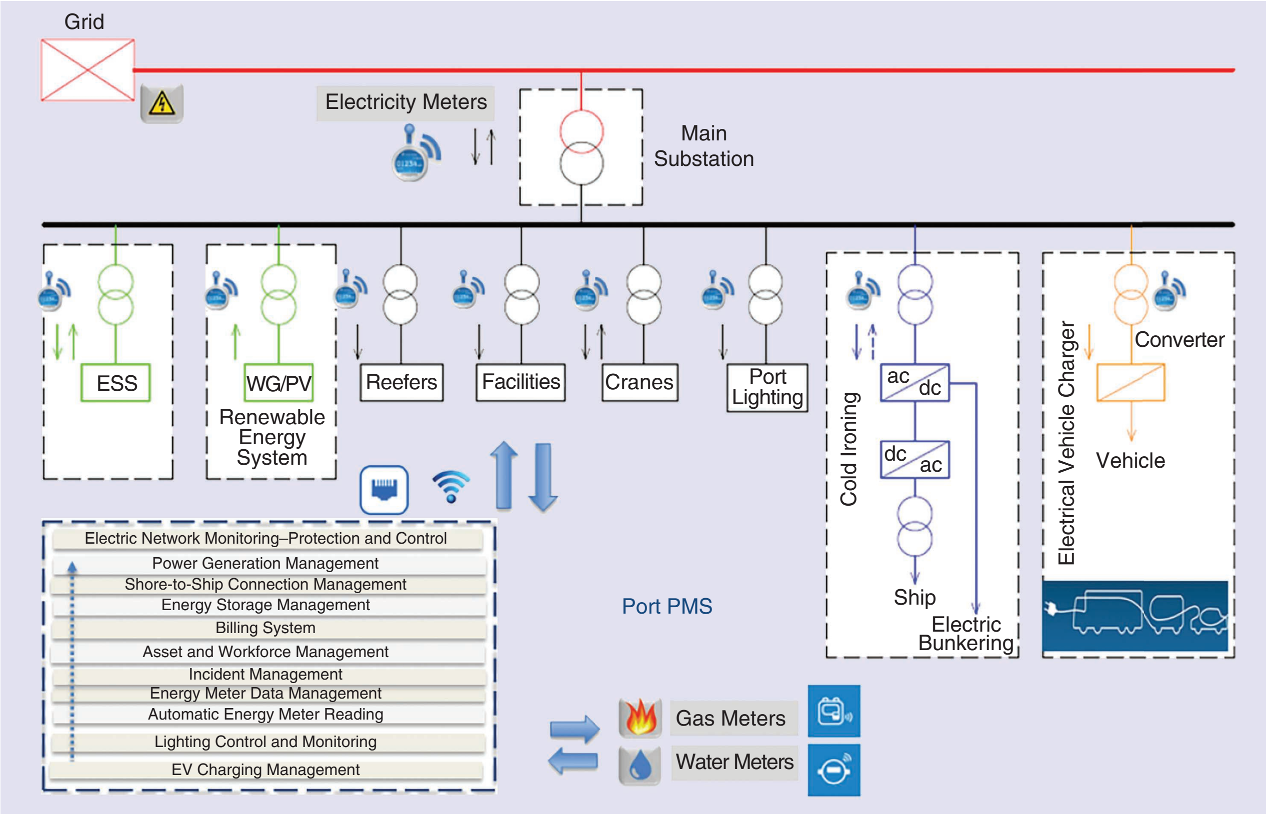


Figure 4. Overview of electric energy transactions within a port.

the port network (as depicted in Figure 5), remote-control of energy flow, protection, and visualized inspection of critical operating parameters, along with automatic meter reading, meter data management, and asset management for operation, maintenance, and billing purposes. Moreover, the SCADA-type PMS must have capabilities of providing energy to all loads by all available sources in an optimized manner, so that the ultimate target, i.e., the minimized atmospheric pollution by any thermal energy source in the port area, is achieved. To this end, the PMS should be comprised of the following components:

- optimal scheduling of the intermittent operation of reefers: since the temperature in their content is kept unchanged for long intervals, their supply is to be scheduled during off-peak time slots
- optimal exploitation of energy produced within the port jurisdiction (by energy generation sources like the RESs, the cranes operating in regenerative braking mode, ships in reverse cold-ironing mode, buffering/storing)
- optimal operation scheduling of shore power supplies, including reverse cold ironing
- optimal charging of battery-driven ships.

To this end, efficient algorithms for global optimized operation have already been developed. For instance, the port authority acts as the manager and all energy sources and loads are considered to be agents. According to this "win–win" cooperation scheme, the operation scheduling of each agent, as well as the electricity price for the energy transaction between each agent and the port, are finalized after a series of iterative negotiations between them.

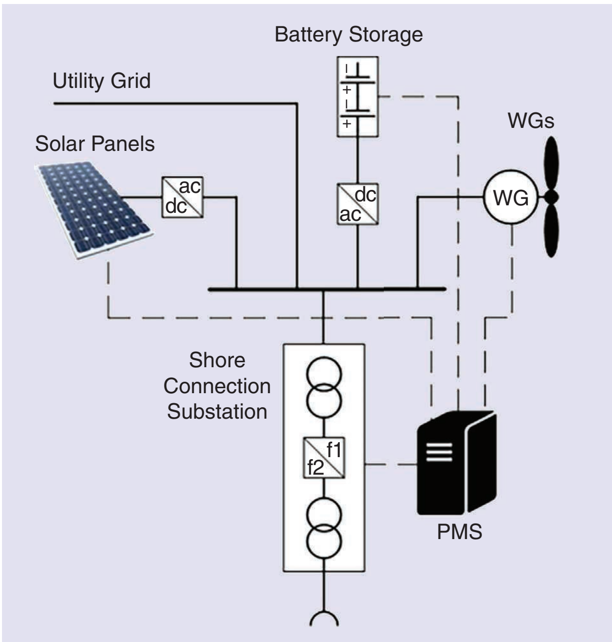


Figure 5. Integrating electric energy transactions within the port with its PMS.

Programming a Sustainable Reformation of a Port

Actions Required by the Port Authorities

Taking into account the aforementioned development perspectives of the ports, the following courses of action can be taken by the port authorities:

- A thorough auditing would be performed, focused on the perspectives for sustainable energy development. Thus, the capacity and the weaknesses of the port electric energy system would be traced, the perspectives of deploying RESs would be investigated (based on meteorological data and possible installation locations), the possibility of installing large battery units would be sought, etc.
- The master plan of the port (as an enterprise) is revised and reformed, taking into consideration critical parameters, such as environmental friendliness, green shipping, blue growth, and energy smart grid management transactions.
- Data are collected from all major agents engaged, i.e., port energy clients and producers (as outlined in the previous sections).
- Feasibility studies and cost–benefit analyses are performed for the investments regarding the related infrastructure expansion (e.g., installation of cold-ironing facilities, deployment of RESs, batteries, smart EMSs).
- The investment actions in sustainable development are prioritized so that the most economically appealing ones are selected.
- Funding schemes and instruments are investigated and critical decisions for the most feasible investments are made. Applications for funding are made.

Actions by the Network Operators

Within the context of port energy transformation, the electric network operators need to take some initiatives, in parallel. Thus, the Hellenic Distribution Network Operator has identified the challenge of the energy transformation of ports within the context of green shipping and, via the assistance of the Proteus team, has established a roadmap toward this end (Figure 6).

The main pillars of this roadmap are as follows:

- Based on the resolutions of the IMO and the EU, each member state makes its policy on the maritime transport affairs via the corresponding ministries.
- The future energy demands of ports are calculated based on appropriate load-forecasting procedures. Based on the importance and the transportation load of the ports, there is a prioritization, with first priority assigned to core ports, second to the ports of the comprehensive network, and last the other ports. Load forecasting (in terms of both power and energy) consists of:
  - ship-to-shore electrical interconnections (cold ironing of ships with their power demands varying from 500 kW up to 15 MW)
  - charging of ships with electric energy storage units (e.g. batteries)
  - charging of other batteries used, e.g., in electric vehicles (serving the port or belonging to travelers)
  - taking into account any injection from RESs (either directly or as virtual net-metering) in possible combination with energy storage devices
  - covering dock-lighting energy demands
  - meeting the energy demands of cooling reefers

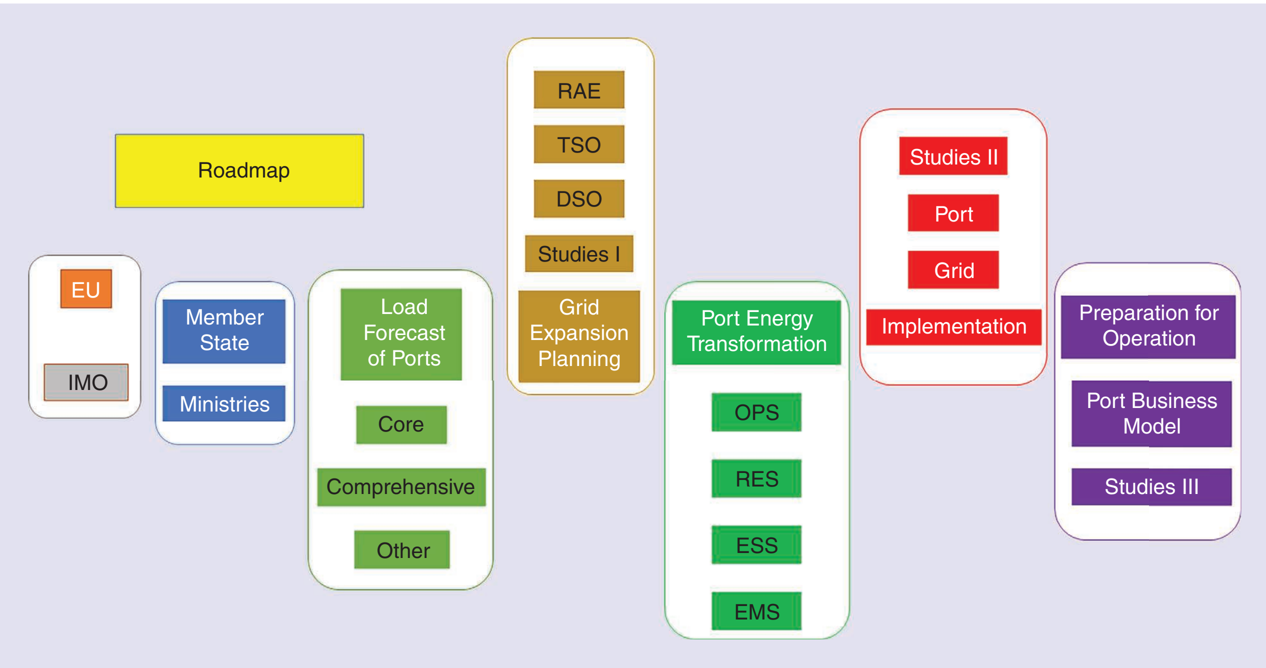


Figure 6. The roadmap of network operators to support port energy transformation. ONS: onshore power system; RAE: Regulating Authority of Energy.

- meeting the demands of cargo-handling cranes
- taking into account any other consumers.

- The distribution system operator (DSO) initiates the expansion planning procedure of the network in the vicinity of the port. Then, the transmission system operator (TSO) is informed if any expansion/reinforcement of the transmission network is required as well. At this stage, the case of upgrading certain ports into a high-voltage client is investigated too. The entire network development planning is subject to the approval of the RAE.
- The necessary port infrastructure upgrade design plans are developed, taking into consideration all major energy contributions (consumption, generation, storage) as described above in more detail.
- The necessary studies of interconnection of the upgraded port grid with the upgraded distribution and/or transmission network are performed.
- All pieces of infrastructure (referring to the port grid and the electric energy system around it) are procured and the new grids are commissioned.
- All preparatory actions regarding the operation of the port and its clients in the open electric market are made. In parallel, all final tests of operation are made while electrical training of the personnel is completed.

The Ports and the Ships in the Open Electric Energy Market

In this section, an effort is made to outline the role of the ports and, consequently, the ships within the electricity market according to the Proteus energy transformation plan as mapped versus the options offered by the directive 2019/944/EU. The latter establishes common rules for the generation, transmission, distribution, energy storage, and supply of electricity, together with consumer protection provisions, with a view to creating truly integrated competitive, consumer- centered, flexible, fair, and transparent electricity markets in the EU. First, the necessary terms are explained so that the operating schemes discussed are more comprehensible.

Terminology of the Electricity Energy Market

An *aggregator* is a natural or legal person who combines multiple customer loads or generated electricity for sale, purchase, or auction in any electricity market. The aggregators act as intermediaries in the electricity market. *Independent aggregator* means a market participant engaged in aggregation who is not affiliated to the customer's supplier.

A *closed distribution network operator* (CDNO) is where a closed distribution system is used to ensure the optimal efficiency of an integrated supply that requires specific operational standards, or where a closed distribution system is maintained primarily for the use of the owner of the system. It should be possible to exempt the DSO from obligations that would constitute an unnecessary administrative burden because of the particular nature of the relationship between the DSO and the system users. Industrial sites, commercial sites, or shared services sites—such as train station buildings, airports, hospitals, large camping sites with integrated facilities, and chemical industry sites—can include closed distribution systems because of the specialized nature of their operations.

An *active customer* is a final customer, or a group of jointly acting final customers, who consumes or stores electricity generated within its premises located within confined boundaries or, where permitted by a member state, within other premises, or who sells self-generated electricity or participates in flexibility or energy-efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity.

An *energy community* is a legal entity comprising natural persons, local authorities, including municipalities or small enterprises, that has for its primary purpose to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates, rather than to generate financial profits. Moreover, it may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or charging services for electric vehicles or provide other energy services to its members or shareholders.

Operating Models of Ports and Ships

Based on the fundamental definitions of the 2019/944/EU directive, the following alternative schemes have been identified as possible operating models of ports and ships in the electricity market in view of their extensive reformation via electrification.

First Operating Model

According to this operating model (Figure 7), the port operates as a CDNO; hence, the port is fully responsible for the reliable and resilient distribution of electric energy into the zone of its jurisdiction. Thus, all energy providers or suppliers inject their energy to the point of common coupling (PCC) of the port, which in turn dispatches it to the ships as well as to other customers served at the port energy terminals. In this operating scheme, the port cannot be an energy provider or producer (hence it cannot own or manage any power sources).

On the other hand, the ships are treated as active customers who participate in the electricity market either directly or as a member of one or more aggregators; the latter scheme, i.e., being members of an aggregator entity, could be proven even more beneficial for them in terms of pricing, as the aggregator can negotiate for large amounts of energy.

Second Operating Model

In the second operating scheme (Figure 8), the port once again operates as a CDNO, and hence, it cannot be an energy provider or producer (i.e., it cannot manage any power sources including RES's and/or energy storage units), at least directly. However, it is possible that another body related to the port (e.g., a subsidiary company) can be one of the energy providers. This can be done provided that the members of the board of this electric company are not the same executives as those with the port authority.

The ships are treated, once again, as active customers who participate in the electricity market either directly or as members of an aggregator, and they can negotiate with all energy providers, including the one related to the port authority.

Like the first model, this one is most favorable for big-sized ports, where the port authority is strongly interested

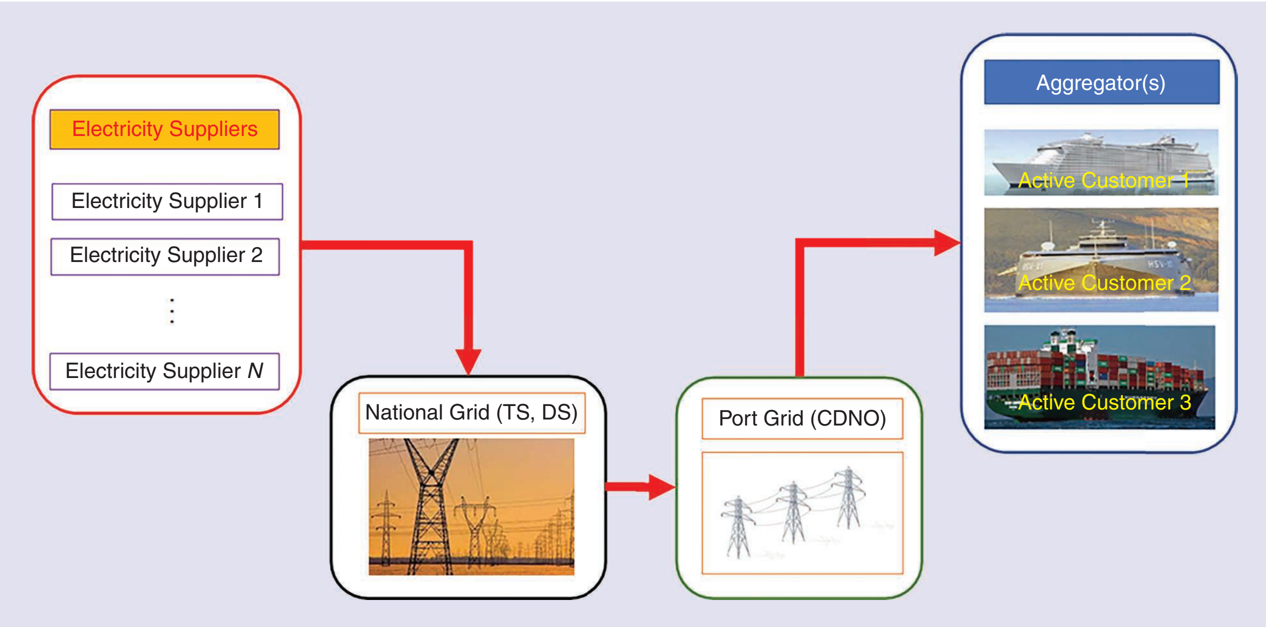


Figure 7. The first alternative operating scheme of ports and ships in the electric energy market.

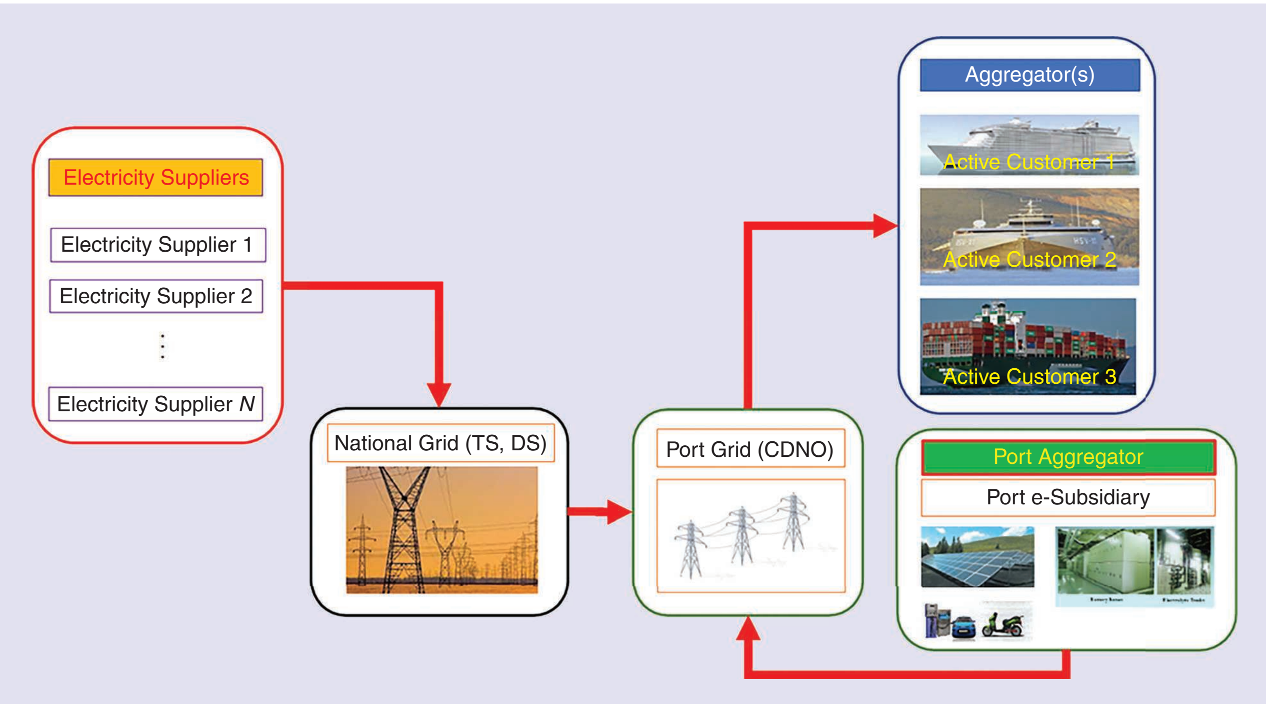


Figure 8. The second alternative operating scheme of ports and ships in the electric energy market.

in being a key player in the energy market. From the ship-side point of view, the electric company of the port could be treated as a last-resort power provider preferred, for instance, by ships visiting the port rather infrequently, and hence not interested in attaining the best available price of the market.

Third Operating Model

This third alternative model is fairly different from the previous two. In this case (Figure 9), the port along with the ships can comprise an energy community; both the port and the ships can be active customers too. The energy community entity can be engaged in all electric market activities, as it can own RESs and/or energy storage units, as well as serve other members of this very same community, namely the ships at berth, etc.

This operating model can be applicable in small-sized ports with a limited number of visiting ships. In this case, the ship-owning companies and the port authorities can both be small enterprises having convergent if not common benefits by being partners in the same energy community.

Implementing the Proteus Plan

The Proteus plan, as outlined above, has already been implemented in a number of ports within the framework of the following European projects:

- Electrifying Eastern Mediterranean corridor: The funding source for this was the Innovation and Networks Executive Agency of the EU [currently the Climate Innovation and Networks Executive Agency of the EU (CINEA)] and its objective was twofold. The first objective was to study the implementation of ship-to-shore interconnection to the ports of Piraeus, Killini, Kopper, and Vassiliko and to implement one ship-to-shore interconnection position to the port of Killini (southwest part of Greece). The second objective of this project has been to study short-sea shipping vessels powered by batteries (either solely or in a hybrid scheme), with a passenger ferry being the case study.
- European flagship action for cold ironing in ports. The funding source for this is CINEA, while its objective is to study the implementation of ship-to-shore interconnection in 16 European ports (mostly located in the Mediterranean Sea), including the ports of Piraeus and Rafina (focusing on the passenger-ferry terminals).
- Alternative fuel implementation in the port of Igoumenitsa. The funding source for this is CINEA, while its scope is to study the complete decarbonization of the port of Igoumenitsa by deploying ship-to-shore interconnection (all ship types but mainly passenger ones), energy storage units for electric storage and buffering, as well as for battery swapping of battery-driven ships, along with a central management system.
- Cold ironing in the Piraeus port (the final step). The funding source for this is CINEA, while it concentrates on studying the implementation of ship-to-shore interconnection in the cruise terminal of the port of Piraeus.
- Connectivity infrastructure upgrade and environmental viability for the port of Volos. The funding source for this is CINEA, while its scope is focused on studying the implementation of ship-to-shore interconnection in the passenger terminal of the port of Volos.

Technical Challenges to Face

According to the roadmap, at the initial stage of implementation there are a number of technical issues that need to be considered, studied thoroughly, and treated properly. Two of them are discussed below.

First is imbalance between power supply and demand. It is probable that the power demands of the ships at

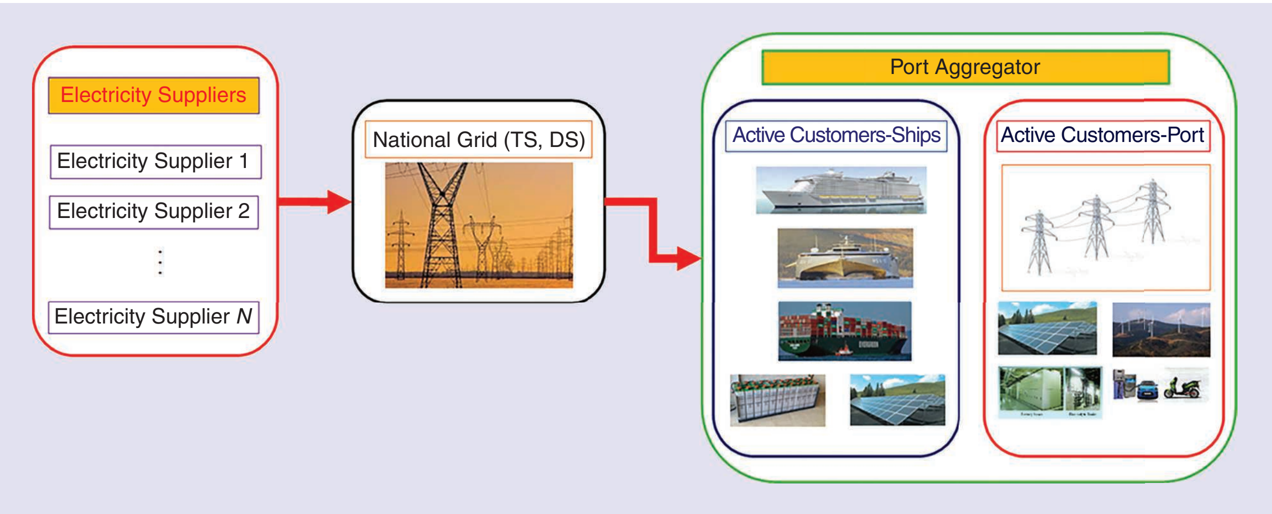


Figure 9. The third alternative operating scheme of ports and ships in the electric energy market.

berth might not be met by the grid and the port network. Considering that these power demands can correspond to huge energy amounts, this situation can provoke several adverse phenomena, like voltage and/or frequency stability problems to the entire grid. The solution could consist of exploiting flexibility in adjusting power demands by the ships in combination with efficient energy dispatching by the PMS of the port grid.

Second are power quality problems. Considering the equipment related to the port reformation mentioned above, there are a number of power quality phenomena engaged, such as:

- Harmonic distortion problems due to the operation of high-power frequency converters, the battery chargers (rectifiers), and the LED lights. Provided these problems are proven to be significant, the solution could comprise filters eliminating the harmonics components.
- Transient phenomena, e.g., due to inrush currents (including sympathetic inrush ones), provoked by transformer energization or due to abrupt load changes. The remedial measures in this case could consist of a combination of controlled switching techniques along with the introduction of mitigation devices like resistors, etc.

Energy reformation of ports toward decarbonization via electrification necessitates the coordinated activities of a number of stakeholders and beneficiaries, like port authorities, electric grid authorities, and ship owners.

Conclusions

This article presents the Proteus plan, a holistic approach toward the transformation of ports into sustainable and smart energy hubs encompassing cutting-edge smart grid technologies. Thus, we show that energy reformation of ports toward decarbonization via electrification necessitates the coordinated activities of a number of stakeholders and beneficiaries, like port authorities, electric grid authorities, and ship owners. The numerous emerging challenges comprise technical and regulatory aspects but they can eventually be treated.

Acknowledgment

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For Further Reading

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