Cold Ironing Integration in City Port Distribution Grids

Sustainable electrification of port infrastructures between technical and economic constraints.

IN THE NEAR FUTURE, A STRONG DEVELOPment in port infrastructures is expected in response to the ecological transition. At the same time, tight environmental requirements in city ports make compulsory new actions for site decarbonization. These two aspects are forcing toward a port electrification, where renewable energy resources and storage systems can increase port sustainability in accordance with the green deal.

Introduction

Most of the human resources are moved by transportation on seas and rivers; therefore, the ports usually represent the departure-arrival hub for international business. On the other hand, each transportation is related to a considerable use of energy to manage goods such as tower cranes, port platforms, and so on. Therefore, the load demands of large ports is experiencing a worldwide increase while opening compelling challenges on how to manage such large amounts of energy. As container maritime transport is the most pervasive in international goods trading, similarly impressive is the volume of standard marine fuel conventionally adopted on these traditional ships. Consequently, the production of greenhouse gases is enormous as well as the potential benefit of a sustainable renewal in emission optimization and total cost savings. By focusing only on Europe, maritime trade is responsible for 15.3% of the continent overall transport emissions and for the 3–4% of the European Union carbon dioxide (CO_2) grand total. In 2018 alone, marine transportation has produced around 138 million tons of CO_2, while 155 million tons of CO_2 are supposed to be emitted in 2030. Not only the huge amount of greenhouse gases is to be critically decreased, when not nullified, by the decarbonization, also other harmful substances [e.g., sulfur oxide (SO_x) and nitrogen oxide (NO_x)] are to be largely reduced in marine transportation. These considerations acquire more importance when the port is in the proximity of a city center, when ships are expected to comply with both environmental pollution and no-emissions requirements. To pursue the goals of ecological transition in the environment of industrial harbors, a smart control and monitoring platform must be conceived to ensure the efficient and sustainable management of complex port infrastructures. Usually, port electrification is the solution that is followed to reach the new energy prospective in reducing the fuel usage. Evidently, the adoption of fossil fuel is completely avoided when the port electrical power supply is totally based on renewable energy sources (RESs) or green energy purchases from third (also foreign) parties. When moored, the ships are responsible for more than 70% of the port carbon emissions. Indeed, docked ships usually require electrical power to keep several services (e.g., container refrigeration, cabin lights and power, air cooling systems) running, while the primary source conventionally relies on marine internal combustion engines. As a way for solving this issue, the electrified piers with shore-to-ship infrastructure can prevent ships from relying on their diesel engines to feed their internal power systems. Although the ships are responsible for a great quota of pollution and carbon emissions, basically they are not the only source in the port area. In fact, there is also a large number of auxiliary activities that, when electrified, could further decrease the carbon footprint of the port structure. Some examples include the introduction of electric vehicles dedicated to the movement of goods and smarter cranes and trains. Again, there is a further benefit for the environment when the electrical energy production is totally green, while opening the critical issue of contemporaneity among load demand and RES availability. To meet the energy load profile of the ports, such RESs are often supported by a significant employment of storage systems like batteries. The real-time coordination of RESs, storage, outside purchases, and electric loads is therefore required to guarantee the daily operation for the entire integrated system, while optimizing the harbor expendability. By considering these features, future smart ports will need a high-performance energy management system to monitor and control all the electrical power flows in the power system as in a controlled microgrid. Beyond the sustainability goals, the port microgrid must smartly manage power peak demand with a defined provided capability. To proficiently supply not only the ships that are very energy-intensive loads for few hours, but the entire port system, the hardware transformation must be combined with a digital software improvement. This article wants to discuss the electrification of the Port of Trieste, one of the most important port infrastructures on the Adriatic Sea. This case study is relevant as its demand is expected to increase more than twice the present power amount to host ship-to-shore (STS) connections and electrical energy usage. Thanks to a techno-economic-environmental analysis, the study identifies how to enable the electrification by managing the peak power among distributed energy resources, storage buffer systems, and potential green energy import from foreign countries.

Overview on Electrical Port Loads

In port areas, a wide diversity is expected in the definition of electrical loads, each of which with specific power quality requirements and priorities. Some loads require a large power quota for a very short time, while others always request less power for the entire time, then finally constituting a constant load to be fed by the electrical grid. By focusing on this variable power demand, ports represent a very complex case study from the point of view of the power system designer as well as when considering quality of service and economic management. To provide an inexhaustive list about the most common loads, it is possible to observe the following:

1) STS quay cranes
2) shore connections (SCs) to feed the moored ships as cold ironing
3) SC platforms to store the energy on the on-board batteries of the newest cruise ships, thus enabling no-emission maneuvers in ports
4) rubberized land cranes, thus rubber-tired gantries (RTGs)
5) electrically powered trains
6) ground overhead traveling cranes on rails
7) refrigeration systems inside the port area
8) electrical infrastructure to charge the batteries on electric vehicles
9) power supply of any industrial settlement
10) buildings and facilities of port operators.

Given the large variety in load characteristics and the impressive value of a total power balance for a medium-industrial port (i.e., even hundreds of megawatts), a great attention is to be spent in managing the peak power. Most of these loads have a very particular load profile that can be approximated with a square wave. Other ones have particular needs, such as in the cold ironing infrastructures whose supply certainly represent one of the greatest challenges in the management of a port. In such a case, when a large ship at berth is supplied by the electrical port grid, the intermittent load request is about 10 MW. Particular attention is therefore required when exploring the modularity of the dockside equipment, as the supply of few ships can easily saturate the port power availability. The wise management of these energy-intensive loads is therefore essential to be ensured by means of a well-designed, or rather, optimized power grid and a careful planning of SC requests. One effective approach foresees the time-shifting management of the important loads, for example by coordinating the use of cranes. Second, also the energy storage systems are essential when powering the peak, they provide the buffer functionality while making possible the use of stored energy, at times green thus sustainable. In general, an optimization in loads management can flatten the power demand curve, whereas the adoption of controlled storage systems can provide the necessary power also with notable dynamics. In this way, the large requests from intermittent loads are also properly satisfied without the need of oversizing the local power production or purchasing from the external distribution grid. An effective load coordination, a smart employment of storage, and a leveling in the peak power required by the port can therefore lead to a strong energy saving. Important outcomes in greenhouse emissions reduction and cost reduction in port management are then consequent.

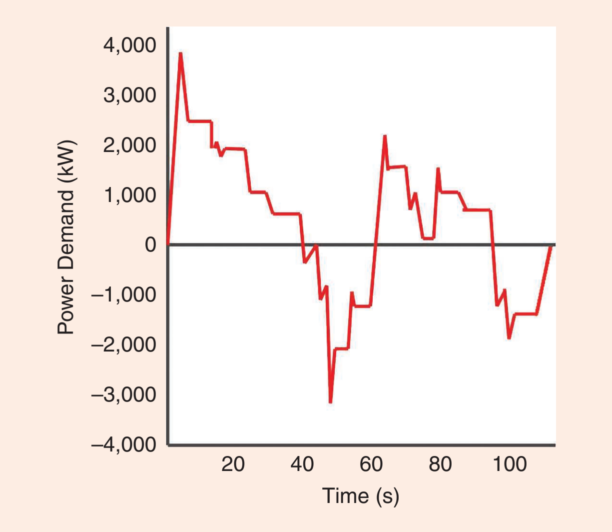

Figure 1. The load profile of an STS crane.

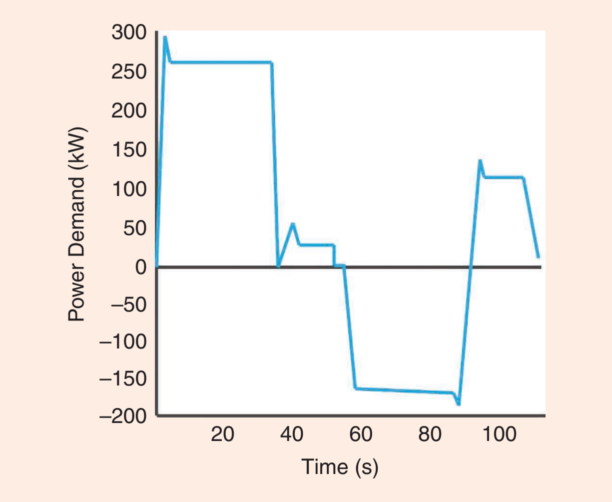

Figure 2. The load profile of RTG crane.

Analysis on the Profiles of Most Demanding Loads

For a medium/large-size port, the electrical grid is conveniently designed to provide a power that can reach several hundreds of megawatts as peak value. As already expressed, this total power quota reaches such relevant value as several are the different-mandatory loads to be supplied. Evidently, this large number of megawatts is delivered by means of medium-voltage or even better high-voltage power lines to minimize the current and related losses. In the following, a short recap on the most demanding loads is provided to explain how to get the final total amount of requested power.

Cranes

The typical load profiles of the most important cranes are in Figures 1 and 2. Particularly, these two figures represent the power demand transient for STS and RTG cranes. Along the entire transient (110 s) for the STS crane, a considerable peak power (up to 4 MW) to be provided in about 3–5 s makes the STS one of the most critical loads (Figure 1). Evidently, both energy recovery between cranes and storage systems within the port area becomes of vital importance when supplying such an impressive request. Most modern cranes are indeed equipped with a dc interface to battery storage systems. Focusing on RTG cranes (Figure 2), a more manageable peak value of 250 kW is reached by means of a 60-kW/s ramp.

Electric Vehicles for Goods Handling and Electric Trains

In port management, electric vehicles and electric trains are characterized by a slighter load profile to be satisfied. Although the power demand is relevant (i.e., 4–6 MW for a freight train, 1–2 MW to charge tens of electric vehicles), the power request is almost constant over time, thus facilitating both port and storage management. During daily operation, these electric systems can also behave as moving energy storage, then providing an important support for the port distribution grid. This additional function clearly represents a notable benefit in the working activity of a complex port infrastructure. Also in this case, proper planning and coordination of vehicles can foster a reduction in the required peak power.

Shore-to-Ship Connections

The cold ironing infrastructure can be installed to remove both CO_2 production in accordance with green transition and environmental externalities during the mooring at port docks. When thinking about a large cruise vessel, the requested power can be near 12 MW during the navigation breaks in order to maintain the supply of shipboard services (i.e., air conditioning, galleys, lighting, and so on). Until few years ago, the diesel engines coupled with onboard ac synchronous generators were employed in furnishing such a large amount of power for each stationed cruise line, then at the end constituting a temporary (i.e., the stop endures for 8–12 h), but significant, source of CO_2, NO_x, SO_x, and PM_x. As the cruise ports are usually situated in the city centers, these negative effects are not only troubling for the environment and climate but even more dangerous for human health. Evidently, these considerations on cruise liners are to be transferred to the other vessels (i.e., container ships, ferries, and so on) that similarly can lower their negative externalities by means of the SC technology. When implementing the cold ironing, each type of vessel is related to a specific maximum power at berthing. As a consequence, the ac supplying voltage also results defined (i.e., some kilovolts when the requested power is limited to 3–8 MW, more than 10 kV when the power exceeds 10 MW), while the frequency could be either 50 Hz or 60 Hz in accordance with the technical standards of each country. The most common vessels as well as the SC data are highlighted in Table 1, whereas Figure 3 shows a high-voltage SC (i.e., more than 100 kV at the primary line) to power large cruise liners which demand even 12 MW. This technical solution is evidently simplified when the requested power is less.

The Port of Trieste as Case Study

An interesting example in which finding all the challenges mentioned previously is the port of Trieste, in Italy. This Italian port constitutes a good case study, as its ongoing modernization can open a new scenario where implementing the measures conceived in the green deal plan. As port demand is expected to increase more than twice today's scenario, the Trieste case is noteworthy in the context of sustainable development. The port of Trieste is located in the northeast part of Italy, at the intersection of Balkan and Germanic countries. This particular position along with a deep seabed has determined the strongest points for the development of Trieste, both in the past and also at the present day. Today, the city of Trieste presents one of the most important port infrastructures on the Adriatic Sea, where covering the role of main hub for intercontinental maritime traffic from the Suez Canal toward the northernmost part of Europe. For almost ten years, the port of Trieste has been experiencing a strong development in maritime traffic, trading, and industrial business. Following this trend and considering the development scenarios, the total installed power for the electrified port operation will presumably grow double the current installations, reaching the value of 160 MW. As this additional power is even more than the actual demand in the city of Trieste (110 MW), it is clear how a smart design, control, and management in providing this peak request becomes necessary, rather mandatory, for the reliable operation of the electrical infrastructure. The Trieste port is made up of several areas, each one with a specific use. All these areas are located very close to the historic center of Trieste; therefore, the port activities that are envisaged for the near or far future are to be planned by posing on a convinced electrification, then forcing toward the system decarbonization. Particularly, the port infrastructure hosts/supplies the docks and all the harbor utilities, but at the same time it influences the entire city, being central to its position and its huge power demand.

TABLE 1. Technical data of shore-to-ship connections for each vessel typology.

Vessel Typology	Frequency	Typical Voltage	Maximum Power at Mooring
Large cruise ships	50/60 Hz	11 kV	8–12 MW
Small to medium cruise ships	50/60 Hz	6.6 kV	3–7 MW
Container ships	50/60 Hz	6.6 kV	5–10 MW
Ro-Ro ferries	50/60 Hz	3.3 kV	3–7 MW

Port Areas

In this article, the port of Trieste is organized in five different areas. Each zone has a peculiar use as well as the moored vessels differ in typology, utilization, tonnage, and so on.

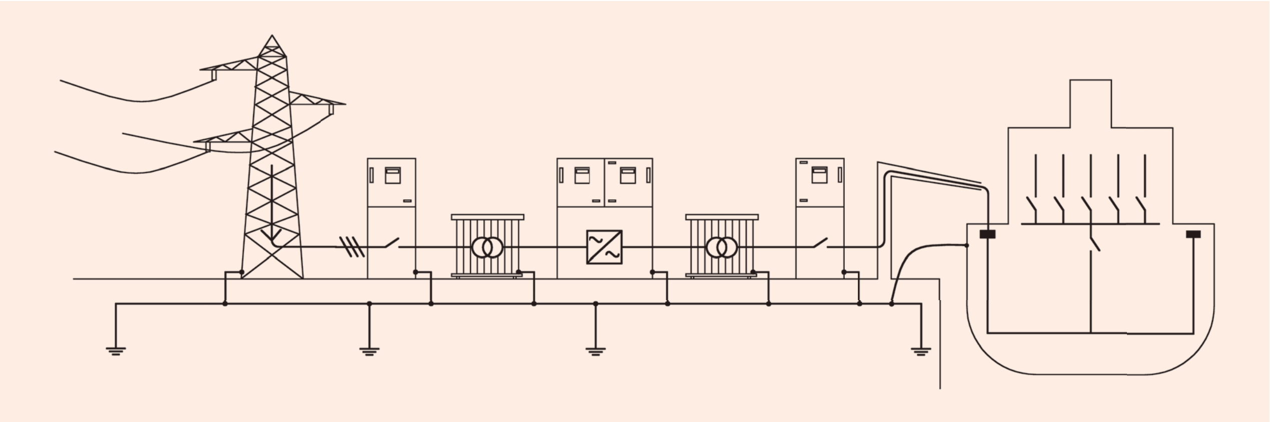

Figure 3. High-voltage SC.

1) *The area of Bersaglieri pier*: This zone is mainly dedicated to the sea transportation of people: therefore, the cruise ships are conventionally located here in front of the main square. In recent years, this area has experienced a sharp surge in the reservation demand for cruise ships at berth.
2) *The area of piers 5 and 6*: This zone, named Riva Traiana, is the hub for roll-on roll-off ferries. The piers have a contemporaneity factor near unity: when a ferry leaves the quay, a new one takes its place.
3) *The area of pier 7*: In this commercial pier, the moored cargo ships mainly feed air conditioning systems and refrigerated containers. From an energy point of view, the containers that are loaded on the ship during mooring can exploit the shore-to-ship interconnection for their powering thus switching off the diesel engines on cargo ships.
4) *The Adriaterminal area*: Also in this zone, located in the so-called Old Port of Trieste, other energy-consuming cruise ships will be hosted during mooring. Therefore, cold ironing installations can again avoid the production of CO_2 and toxic substances when powering the moored vessels.
5) *The logistics platform area*: In the medium term, this port area will experience the installation of new industrial-type settlements, which will have a significant power impact for the distribution system operator (DSO). Given the zone size, the direct interface toward the transmission system operator is also under evaluation.

As high growth is foreseen in a short time for the ship traffic in the Trieste terminal, and especially cruise liners at Adriaterminal and Bersaglieri docks, this port will experience a complex electrification plan for the entire site. The new advanced power system will be designed to power all the future port users (160 MW is the final goal), with a particular attention on the technologies to promote the ecological transition. This electrical infrastructure on one hand will lead to a strong boost in port operations, but on the other it will enable a drastically reduction in CO_2 emissions and pollution for the entire area close to the city center. Evidently, to predispose an effective strategy in electrifying such an important asset, preliminary studies must be carried out to precisely identify the peak power that can be requested in particular conditions. The following methodology is proposed to define all the necessary evaluations to obtain the final power estimation.

Methodology for Estimating the Peak Power of a Cold Ironing Pier

Following the plausible scenarios of development, the port of Trieste will largely modify its configuration on supplied loads. Therefore, an analytical methodology becomes mandatory to evaluate the peak power that the new port configuration will possibly absorb in the next five years. The estimation method has the aim of calculating the energy needs of port users and facilities, by taking into account both their power request but also the expected absorption profile. The different profiles can greatly vary depending on which load topology is taken into consideration. The main goal of the methodology is therefore to estimate the load profiles of the individual elements. By overlapping the single requests, the overall profile is finally defined for the entire port. To give some examples, the refrigerated containers have an almost constant load profile; thus, their request remain fairly stable over time. This fixed load then constitutes an almost constant contribution to be summed with the others time-varying requests. Differently, other loads like the shore-to-ship connections are not only energy-intensive but they also have a discontinuous load profile, then provoking a strong impact on the port electrical grid. Basing on the notable power demand (i.e., each cruise ship can request 3–12 MW during mooring) and on the square-wave profile of each cold ironing request (i.e., ON–OFF–ON…), a more precise evaluation on shore-to-ship facilities becomes mandatory in the port strategy. Considering the highlighted criticality of cold ironing arrangements, the article wants to put attention on a practical method to identify the peak power profile of a pier that was implementing these no-emissions operations. The considered pier is thus supposed to host the stationary cruise ships that receive the external power supply. The time frame is one year, while the adopted resolution is one hour. To perform an accurate estimation, two inputs are necessary: the chronology on ship reservations at each dock and the knowledge of the electrical power that each ship requires during mooring. The methodology consisting of the following steps is effective to establish the peak power of a single specific pier where the ships are supplied from the land during their stops. Evidently, the same process is to be replayed and integrated to cover all the piers that are implementing the cold ironing technology:

1) on-site assessment to comprehend how the docks are organized in a specific pier
2) information on historical and future calendar of moorings. (For each planned mooring, ship name, date of arrival/departure, time of arrival/departure are the minimum knowledge.)
3) collection on the requested power for each docked ship during stops. (These data are hardly defined; an estimation could be based on technical data sheets and similarity assumptions.)
4) cross-referenced on CSV inputs at points 2–3 by means of ad-hoc a software tool wrote in Python language. (The megawatt weight of each supply during ship mooring is combined with each booking.)
5) the results of the estimation procedure for each pier are then displayed in two ways:
    - *Calendar*: a matrix in which the days are on the *y*-axis, while the 24 hours of the day are on the *x*-axis. Each matrix cell then shows the cumulative power in that hour/day and the number of ships that are present in that particular pier. The number

of ships define the maximum number of shore-to-ship connections to be activated in each pier.

- *Bar chart*: a graphical representation where the 8760 annual time slots (i.e., 365 days multiplied by 24 hours) are on the x-axis, while each cumulative power is on the y-axis.

6) data analysis on the obtained results to establish type, size and number of feeding points that are required for each specific pier.

Hybrid Solution for the Pier Electrification

The following study wants to propose the hybrid electrification for the Bersaglieri pier. After evaluating a possible power demand, a photovoltaic power plant and a battery storage system are integrated in an ac–dc distribution to provide the partial carbon-free supply of the SC infrastructure. When the remaining energy quota is purchased from a certified renewable supplier in the grid, the moored ship is entirely powered by green sources, thus fostering the system sustainability. The performed analysis is concentrated on the Bersaglier pier, in an area very close to the historic center. In such a zone, the cruise ships are expected to periodically stay at mooring for the entire year. This aspect, combined with the plausible increase in mooring bookings (i.e., the port of Trieste is starting to welcome many cruise liners initially addressed to Venice), makes this hosting pier as the most significant study case on which envisage the green feeding of cold ironing infrastructure. By hypothesizing a typical annual profile for the requested power on Bersaglieri pier, a techno-economic-environmental analysis will prove how the hybrid solution results the most feasible approach.

Technical Evaluation

In this article, the Homer software is adopted to find a practicable combination of renewable sources and storage systems to electrify the Bersaglieri pier. Such a toolbox is nowadays considered as the best solution when optimizing the design of microgrids. A complete study performed on this software can provide a wide perspective on the doable solution under study. To start the study, first the load demand (i.e., megawatts) is to be defined for the entire year. The latter constitutes the output of the methodology previously discussed. By assuming a small power request as initial example, the baseline data are in Figure 4. This constitutes the estimation of average power request for the cold ironing. The values are variable during the year, from a minimum in winter to the 8 MW in the summer tourist months.

Among the renewable sources that are currently available, photovoltaic technology is the one to be exploited in the optimized electrification of Bersaglieri pier. To hypothesize the PV installation, a typical annual irradiation profile of the city of Trieste is taken into consideration. This profile is generated by interpolating the data from a NASA database. This reference profile is shown in Figure 5, where the clearness index is a dimensionless number (i.e., near one in sunny conditions, lower values under cloudy conditions) to define the surface radiation divided by the extraterrestrial radiation. The daily radiation in Figure 5 presents its maximum in the summer months, where incidentally the power request also shows its largest values (Figure 4). Evidently, this time-correspondence is well-received when pursuing the carbon neutrality in supplying the cold ironing infrastructure. Basing on the cold ironing power request during the year and on the

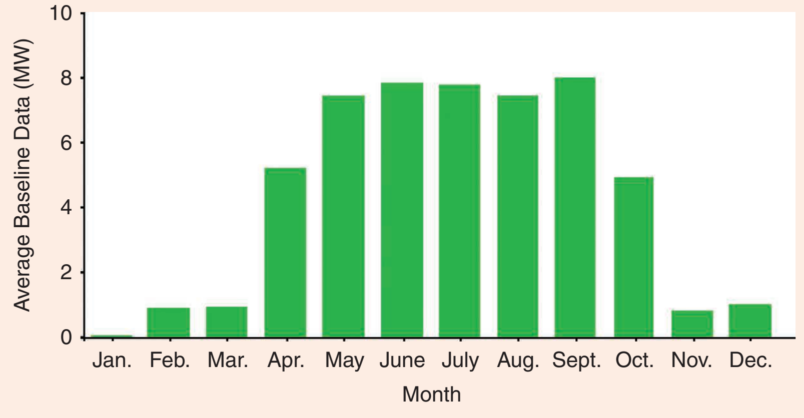

Figure 4. The power request estimation on Bersaglieri pier.

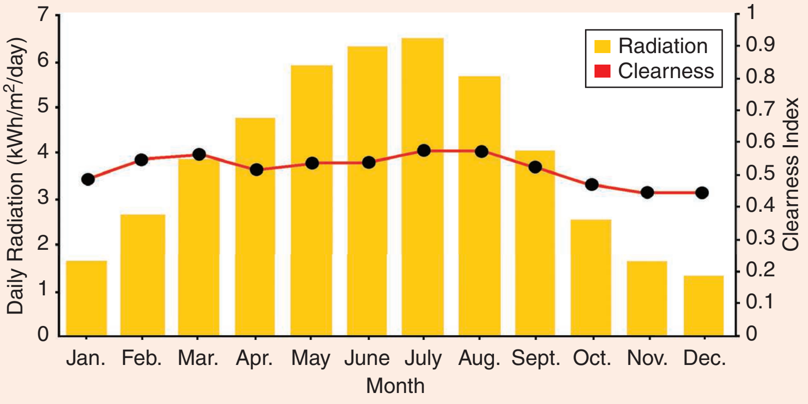

Figure 5. The daily radiation and clearness on Bersaglieri pier.

annual daily radiation, the optimization tool of Homer software has identified the microgrid in Figure 6 as the most economically convenient solution. In this power grid, the photovoltaic system and the storage system present, respectively, 8.8 MWp and 4.2 MWh as rated data. This optimal hybrid system presents two electrical distributions. The DSO grid and the electrical load are connected to the ac bus, while the PV system and a lithium-ion battery are conversely on the dc bus. The bidirectional ac–dc converter (2.25 MW as rated power) is the interface among the two distributions.

In the hybrid solution, both the PV peak power (MWp) and the battery size (MWh) are the result of the optimizer's action. It provides the best solution from an economic point, while exploring the different possibilities within the imposed boundaries. By hypothesizing a quite standard overall efficiency for the entire PV plant (i.e., 112.25 W/m^2 is the expected output from the incoming 1 kW/m^2), the desired 8.8 MWp are collected on a surface of about 78400 m^2, that means a square having 280 m both in width and in length. By observing these dimensional numbers, it is evident how the small output/input power ratio determines a significant total surface to host the PV arrays. On the other hand, the roofs of buildings and warehouse in Bersaglieri pier do not cover a sufficient area to entirely accommodate the PV power plant. This issue can be solved by combining the land installation on the pier facilities and two marine solutions. The first idea envisages that part of the PV panels is installed on the seawalls that protect the old port of Trieste. Differently, the second solution foresees the presence of floating islands to accommodate the remaining photovoltaic installation in the marine area between the old and new ports. Evidently, seawalls and islands can contribute to solving the space issue, only when proper submarine cables are laid on the seabed to transmit the off-board PV power to the collecting system on the pier. Second, the storage system is also to be dimensioned in accordance with the available space. When sizing a Li-ion battery system endowed with control, connections, and cooling systems, the energy density can be chosen equal to 40 kWh/m^3 in a first approximation. By following this tendency, the hypothesized storage system of 4.2 MWh occupies the space of 105 m^3, thus a parallelepiped measuring (3.5 m) × (3 m) × (10 m). This solid is to be located in the rooms of Bersaglieri pier buildings. By combining the starting data (i.e., annual power demand and annual radiation) with the optimized integration of PV and storage (i.e., ac/dc microgrid with 8.8 MWp as PV size and 4.2 MWh as battery capacity), Homer software can provide the final energy balance in Figure 7. The latter shows the monthly amount of energy supplied by the electricity grid in cyan and the monthly amount from local PV renewable source in orange. By summing the monthly quotas, it is possible to conclude that the 23.7% (equal to 5.6 GWh/year) of the total annual energy to power ships from land is green thanks to the optimized solution based on PV and storage.

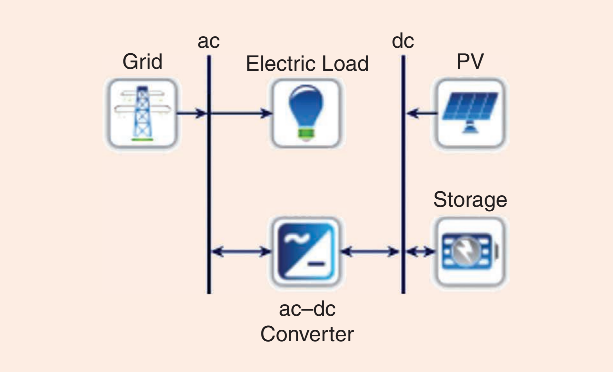

Figure 6. A hybrid solution for the electrification of Bersaglieri pier (Homer software).

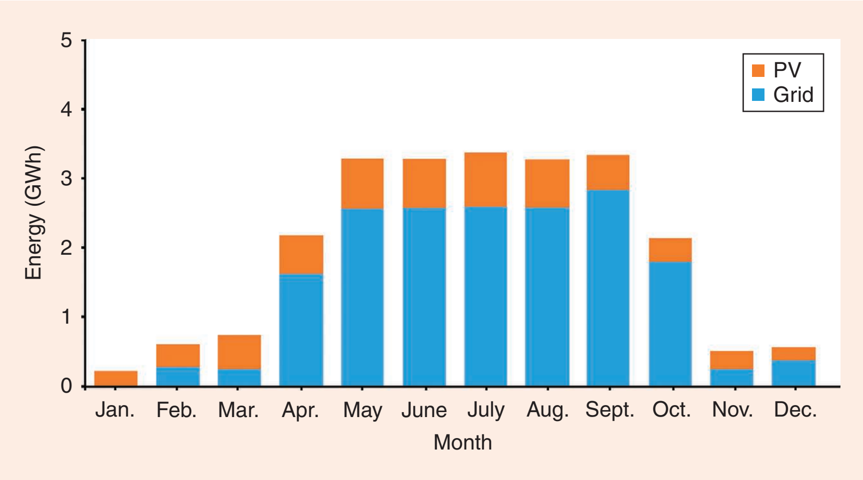

Figure 7. The electric energy balance in the hybrid solution (PV+Grid).

Economic Evaluation

Figure 8 shows an economic comparison between the standard case (i.e., cold ironing entirely supplied from the distribution grid) and the hybrid case implementing PV and storage to provide the green ship power. To evaluate the optimized electrification from an economic point of view, a lifetime of 25 years is assumed for the PV system, while 15 years for the ac–dc converter and for the storage system. This different lifetime determines a temporary change in the line-slope around the 15th year. Against an initial investment of US$10.5 million, the hybrid solution has an annual energy cost saving of about US$1.8 million, which implies a payback period of about six years. After 25 years, the total cost of hybrid case is about US$109 million.

The standard supply cost is near US$140 million, as the total energy is constantly purchased from the DSO.

Environmental Evaluation

Finally, the two scenarios are contrasted from the environmental point of view, then evaluating how the integration of PV and storage are effective in decreasing the emissions of greenhouse gases. The Homer tool is indeed able to automatically calculate the amount of CO_2, SO_x and NO_x as a function of the energy quota taken from the electrical grid. As the hybrid solution takes a smaller energy quota from the grid, consequently a reduction in greenhouse gas emissions is expectable. The Table 2 provides such a comparison between the two scenarios. The benefit of investing in the hybrid solution is evident, as the emissions reduction (i.e., –20%) can improve both health and quality of life for the people of Trieste.

The values calculated in Table 2 are part of the environmental analysis provided by Homer software. Conversely, the complete evaluation considers the six different pollutants in the following:

1) CO_2: nontoxic greenhouse gas
2) *Carbon monoxide*: poisonous gas from incomplete burning of carbon in fuels
3) *Unburned hydrocarbons*: incomplete combustion's products of hydrocarbon fuel, including formaldehyde and alkenes
4) *Particulate matter*: a mixture of smoke, soot, and liquid droplets
5) *Sulfur dioxide*: a corrosive gas by burning fuels containing sulfur (e.g., coal, oil, diesel fuel)
6) *Nitrogen oxides*: nitrogen dioxide (NO_2) and nitric oxide (NO) from high-temperature burning.

Although the Homer analyzer can take into account these six substances, only the ones numbered by 1, 5, and 6 are considered in the environmental balance of this article. To determine such a balance, the software estimates the emissions from three sources: 1) production of electrical energy from modeled generators, 2) production of thermal energy from boilers, 3) consumption of electrical energy from the grid. Evidently, the data in Table 2 are basically related to the energy withdrawal on the power grid. In this regard, Homer first calculates the purchase of energy from the grid (expressed in kilowatt/hours), net of any sales to the external power system. Then, such a number is multiplied by the grams/ kilowatt/hours factor of each pollutant to finally obtain the values in Table 2, once adopted the grams/tons rescaling.

Impact of Port Electrification on Economic Growth

In today's scenario of industrial development, large economic investments are necessary both when developing new energy sources and also when maintaining the power system infrastructure as able to distribute electricity to all the final users. On the other side, the power system functioning leads to high costs and constraints, above all the most impacting fact that power must be instantly balanced. At this moment, such a balance is attained by instantly modulating production or by adopting energy storage systems, whose cost is still rather high. As a consequence, the power grids without storage are conventionally sized to withstand the highest load. Although there are studies that consider energy as the only true driver of economic growth, the causality between energy consumption and gross domestic product is yet under verification. There is no doubt in accepting a correlation between energy and economic growth [i.e., gross domestic product (GDP)], but there is absolutely no consensus on causality or on the possible direction of this causality. To find a correlation, a lot of studies have analyzed the time series of GDP and energy consumption with statistical tools. Four hypotheses are proposed in literature as follows:

- *Growth hypothesis*: Energy-led growth. Energy consumption drives economic growth, and therefore a reduction in energy consumption leads to a decline in GDP.
- *Conservation hypothesis*: One-way causality between GDP and energy consumed. In this case, energy saving policies have little or no effect on GDP.
- *Feedback hypothesis*: The two quantities feed each other.

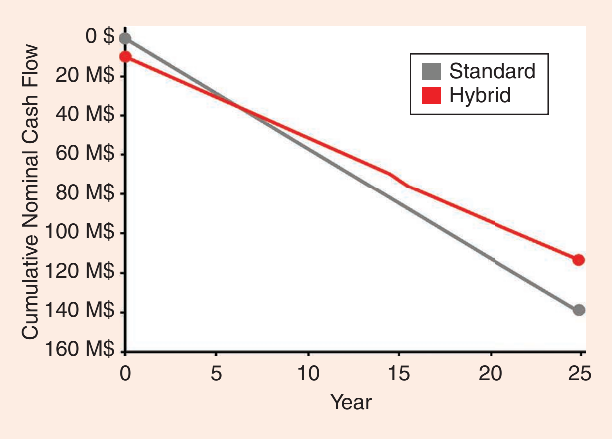

Figure 8. Economic comparison between standard and hybrid solutions.

TABLE 2. Greenhouse gas emission balance in the two solutions.

Scenario Under Evaluation	CO_2	SO_x	NO_x
Standard solution	13937 tons/year	60.43 tons/year	29.55 tons/year
Hybrid solution	11295 tons/year	48.97 tons/year	23.95 tons/year

- *Neutrality hypothesis*: GDP does not affect consumption and vice versa.

On the other hand, the following hypotheses are of paramount importance for decarbonization policies: By assuming that the growth hypothesis is true, a policy of containing consumption could have important repercussions on well-being. Actually, it can be stated that most of the studies consider the hypotheses of growth and neutrality to be unsupported by data. Therefore, it is possible to implement consumption reduction policies (for example through the efficiency and the use of less energy-intensive technologies) while maintaining a high rate of development. By considering the always positive correlation between energy consumption and country development (even if the causal relationship between the two remains unresolved), the main way to satisfy the constraints on CO_2 production while maintaining growth and well-being rates is the electrification of consumption with the sustainable production of RESs. In particular, a great interest is on the effects that investments in electrification of port infrastructures have on the local economy. In this regard, a study on four different North American ports shows a generalized growth in GDP and employment in proportion to the investments made in electrification. Part of the economic output is only shifted from a fossil energy carrier to an electric carrier. Half of the impact of these investments is believed to be related to spending on economic activities in the port region. In a period of 30 years, a hypothetical electrification of all port activities (comprising the cold ironing for berthing vessels) leads to a growth in net economic output by 2 to 5 times, depending on the preexistent economic multipliers for the specific country. In all the cases, the environmental benefits due to electricity transition are to be evaluated and weighted together with the expected economic growth.

Conclusion

The energy transition set up to tackle climate change finds an important enabler in electrification. The electrification of logistics and transport activities, if accompanied by the increase in the production of electricity from RESs, provides a decrease in the production of greenhouse gases. In this article, various electrification actions on port activities are analyzed, from the movement of goods to the permanence of ships on the quay. The electrification of these activities is initially based on a phase of analysis and forecasting of load profiles, in order to plan the infrastructural works. A methodology for analyzing the load profile required in the electrification of a cold ironing pier is proposed, while discussing the necessary works to be implemented to make the investments more efficient. By starting from the ship docking contracts, the load profile of an electrified pier is hypothesized for one year. From these data, an ac–dc hybrid microgrid with photovoltaic production, storage, and grid support is identified as the best solution to feed the cold ironing infrastructure in the Bersaglieri pier of the Trieste port. On one hand, the adoption of renewable sources cuts the emissions, on the other the electrical storage mitigates the peak demands while improving the use of infrastructure. When conveniently integrated in a smart electrical system, PV and storage lead to a substantial decrease in CO_2 and pollutants. The designed electrification not only ensures the environmental outcomes but also an economic return. The investment is indeed recovered in less than seven years, thanks to the avoided purchase from DSO. When the obtained results in terms of sustainability (23.7% of total energy is green and self-produced in the case study) are considered not sufficient, additional no-emissions power quota can be imported from foreign countries (i.e., the Balkan area for the port of Trieste). The electrification importance is finally demonstrated in the article end, where evaluating the impact of port electrification on economic growth. The structural investments can indeed determine a long-term increase in the wealth of the port region, in terms of economic benefits (i.e., GDP) and employment. Future studies will concern the operative integration of renewable resources from adjacent areas. From the economic point of view, an interesting topic will regard the definition of a convenient tax mechanism to convince the ship owners in adopting the on-board cold ironing platform.

For Further Reading

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