Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port

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***Abstract*—Cold ironing, which is the procedure of supplying shoreside electrical power to a ship at berth when its engines are turned OFF, arises as the eco-friendly way to deliver power to ships while they are berthed in ports, thus avoiding the use of diesel engines onboard, which provokes the emission of large amounts of greenhouse gases into the atmosphere. The aim of this study is twofold. First, a survey of research developments on cold ironing is carried out in order to show the state-of-the-art on the problem of greenhouse gases emitted by ships while docked and how to tackle it. Current regulations and examples of current ports that make use of technologies for cold ironing purposes are also shown. Second, the study proposes the use of a cold ironing system in the port of Barcelona, where the power generation is entirely given by renewable energy systems (wind turbines and photovoltaic panels). The idea is to contribute to the wide spread of cold ironing within smart port microgrids to achieve the goal of zero emissions from berthed ships.**

***Index Terms*—Cold ironing, microgrid, renewable energies, smart port.**

List of Abbreviations

AMP	Alternative maritime power.
CMS	Cable management system.
CO_2	Carbon dioxide.
DER	Distributed energy resource.
DFIG	Doubly fed induction generator.
EEDI	Energy efficiency design index.
EPA	Environmental Protection Agency.
FACT	Flexible ac transmission system.
GHG	Greenhouse gas.
HVdc	High-voltage direct current.
HVSC	High-voltage shore connection.
ICCT	International Council on Clean Transportation.
IMO	International Maritime Organization.
LES	Local energy storage.
LNG	Liquefied natural gas.
LPG	Liquefied petroleum gas.
MARPOL	Marine Pollution.
MEPC	Marine Environment Protection Committee.
MMC	Modular multilevel converter.
MPPT	Maximum power point tracking.
NO_x	Nitrogen oxides.
PLL	Phase-locked loop.
PM 2.5	Particulate matter whose diameter is $< 2.5\ \mu$m.
PSS	Power system stabilizer.
PV	Photovoltaic.
RES	Renewable energy source.
RoRo	Roll-on and roll-off.
S2S	Shore-to-ship.
SECA	Sulphur emissions control area.
SO_2	Sulphur dioxide.
WT	Wind turbine.

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I. Introduction

Carbon combustion sends to the atmosphere the so-called GHGs, which contribute to climate change. Certainly, the increase in both global temperature and see level is one of the most critical issues that humanity needs to face up with. Among all the GHGs, the most common ones are NO_x, CO_2, SO_2, and PM 2.5 [1], [2]. It should be noted that GHGs emissions do not only cause global warming, but also a threat to human health. Indeed, the airborne particles that get into lungs are small enough to pass through tissues and enter the blood and thus provoking health problems, such as asthma or even premature death due to carcinogenic particles [3].

Between 2007 and 2012, one billion tons of GHGs were emitted by ships, which turned out to be around 3% of overall GHGs around the world [4]. The following GHGs are emitted (per year) to the atmosphere from international shipping [5]: 1.7 million tons of SO_2, 2.8 million tons of NO_x, and 195 000 tons of PM 2.5. In the case of ocean going vessels, they usually emit to the atmosphere between 1.2 and 1.6 metric tons of PM with diameter less than 10 μm, between 4.7 and 6.5 tons of SO_2, and between 5 and 6.9 tons of NO_x [6], [7]. Furthermore, studies reveal that PM 2.5 emitted by ships have been categorized to cause a major effect of cardiopulmonary and lung cancer mortalities in populations exposed in coastal areas [3], [8].

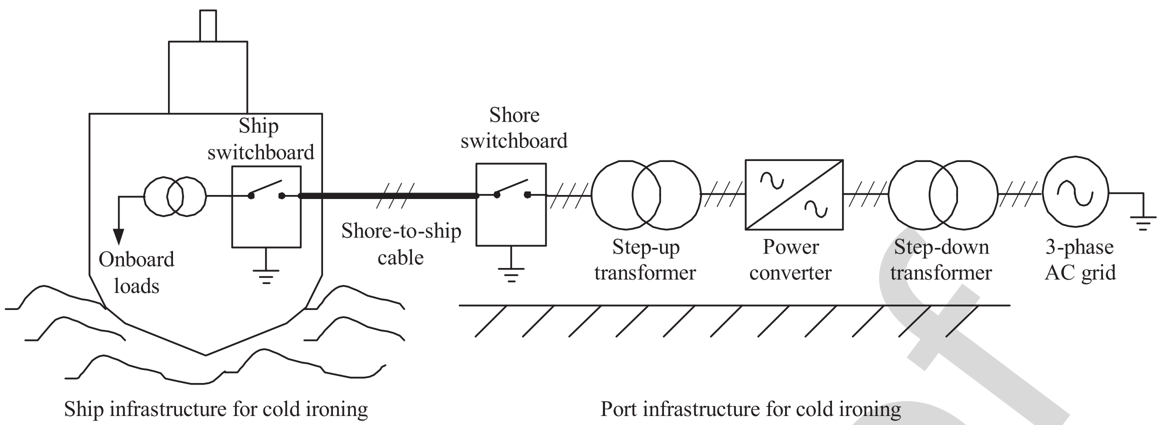


Fig. 1. Infrastructure requirements of a cold ironing system (adapted from [16]).

In order to solve the aforementioned problem, some restrictions in shipping are being proposed, such as the SECAs included in the International Convention for the Prevention of Pollution from Ships or MARPOL protocol proposed by the MEPC, which is a department of the IMO. The IMO is an authority which is responsible for organizing the global shipping industry, and according to the aforementioned regulation, it has proposed a limit of 3.5% of sulphur content of any fuel oil used on board ships, while this limit will be decreased to 0.5% by 2020, with the aim of reducing the SO2 emissions even more [9].

According to the ICCT, another way to reduce the GHGs emitted by ships is to build vessels in an energy-efficient way [10], [11]. This can be achieved by means of the EEDI, which is a guideline fostered by the IMO that envisions a reduction of 30% of shipping's overall CO_2 emissions by 2050 [12].

It should also be noted that around 70% of ship emissions take place in a range within 400 km from land [7], [13]. So, vessels are prone to polluting coastal areas. Moreover, although ships are berthed in ports, they keep on sending GHGs to the atmosphere, which is a real problem for inhabitants in coastal settlements. Cold ironing, which is the procedure of supplying shoreside electrical power to a ship at berth when its engines are turned OFF, can mitigate that problem, as detailed in this paper.

This paper is structured as follows. First, an introduction of the issue is given. In Section I , the background on cold ironing systems are described, where the attention is focused on ship requirements (both electrical demand and required infrastructure to supply it) while berthing, regulations on cold ironing and smart ports considered as microgrids, and some examples of current smart ports are given. In Section III, a topology on cold ironing system based on renewable energies (WTs and PV panels) is proposed for the port of Barcelona. Finally, in Section IV, the conclusions of this paper are drawn.

II. Cold Ironing Systems

A. Background

Reducing emissions in ports is a matter of special importance due to their proximity to human settlements. Ships require power even while they are docked in ports to provide electricity for their lighting, cooling, heating, and other ancillary services. The electricity is generated by electrical machines connected to diesel motors, which are placed onboard [14]. So, diesel engines are the primary source of energy for ships. An alternative is to use either LNG or LPG to run diesel engines [15], but it has the drawback of noise pollution. An eco-friendly way to generate this electricity for berthed ships is to do it on-shore, so that the ships' diesel engines are turned OFF. This process is named cold ironing (i.e., iron pipes in the smokestack become "cold" as they are not working) [16], [17], which is also known as AMP [18], HVSC [19] or S2S power [20]. To that purpose, RES, such as wind energy or wave energy, can be used to construct a smart port to achieve the aim of zero emissions while berthing [21]. Naturally, the use of cold ironing eliminates the emission of GHGs due to the use of carbon combustion in diesel engines and shifts the burden to power generation facilities in local grids. The different applications of cold ironing systems can be found in [22] and [23].

B. Ship Requirements While Berthing

By using cold ironing systems, emission-free solution would be fulfilled for berthed ships while plugging to the shore-side electrical grid. The essential equipment to provide electricity to berthed ships consists of a step-down transformer, a power converter, a step-up transformer, a shore-to-ship cable, a shore-side switchboard, and a ship-side switchboard, as depicted in Fig. 1 (adapted from [16]).

First, a step-down transformer is needed to decrease the high-voltage level given by a three-phase electrical grid into a mid-voltage level (from 10 to 35 kV [24]). Second, a power converter is used to obtain the required frequency for a ship. It should be noted that different countries might work at different frequencies. For example, the grid frequency in Europe is 50 Hz, whereas in North America, it is 60 Hz. It implies that if a ship is built in one continent, the cold ironing system in another continent must use a proper power converter which is able to feed voltage to either 50 or 60 Hz [24]. Third, a step-up transformer is needed to adjust the shore-side voltage to the ship voltage requirements (6.6 or 11 kV) [24]. Finally, a cable must connect both shore-side transformers with the ship electrical infrastructure. This cable is connected by means of two switchboards

TABLE I
VOLTAGE AND POWER REQUIREMENTS FOR BERTHED SHIPS (FROM [24])

Ship type	Voltage requirements (phase-to-phase value)	Power requirements
Cruise	6.6 kV or 11 kV	16-20 MVA
Container	6.6 kV	7.5 MVA
LNG carrier	6.6 kV or 11 kV	10.7 MVA
RoRo	11 kV	6.5 MVA
Tanker	6.6 kV	7.2 MVA

at the two ends of the shore-to-ship cable. It should be noted that this cable is very heavy, as it needs to provide mid-voltage level, so a CMS, such as a crane, is needed to handle it [25]. Additionally, the traditional ships need to be modified to allow connection to the shore power system, and some ships may also need a high-voltage certified electrician onboard [26].

A proper cold ironing system must be designed to satisfy the electrical demand (both voltage and power requirements) of different ships at berth. Ships and their electrical demands can be classified into the following:

1) cruise ships, which require either 6.6 kV or 11 kV and 16–20 MVA;
2) container ships, whose requirements are 6.6 kV and 7.5 MVA;
3) LNG carriers, requiring 6.6 kV or 11 kV and 10.7 MVA;
4) RoRo ships, whose needs are 11 kV and 6.5 MVA; and
5) tankers, which require 6.6 kV and 7.2 MVA.

Table I summarizes these requirements (adapted from [24]).

C. Regulations on Cold Ironing

Until recently, there has not existed a universal regulation on cold ironing. There have been different regulations in different countries regarding the reduction of ships' GHGs emissions, which are compared in [27]. In 2012, the first international standard on cold ironing was launched: the IEC/ISO/IEEE 80005-1 provided the utility connection requirements in ports for HVSC systems [28], and in 2016, the second part of this international standard established data communication for monitoring and control [29]. According to this international standard, the general issues to look at when implementing a cold ironing system can be categorized as power quality, socket/connector configuration, conversion equipment, galvanic isolation, neutral earthing resistor and equipment bonding, short-circuit protection, circuit breakers, safety interlocks, and interface equipment.

D. Microgrids and Smart Ports

Nowadays, there has been a noticeable increase in energy consumption worldwide, and people's awareness on environmental issues is gaining importance and energy market liberalization is progressing steadily. Furthermore, traditional power systems based on centralized power plants are being substituted by distributed generation based on RES. The aforementioned reasons make it possible for governments to foster policies in order to promote the use of RESs and distributed power systems. To that purpose, the concept of microgrid arises as the way to create an independent grid with distributed generation which has the ability to either operate connected to the main grid or in the islanding mode [30], [31].

In port areas that have enough amount of renewable energy resources, DERs can be used to implement a microgrid within them [32]. When managed correctly, the port becomes a "smart port" or "wise port" [33], in resemblance with the so-called "smart grids", where there exists not only a flow of energy but also a flow of data, which are managed properly to determine an efficient and intelligent distribution of energy through all the power system [34], [35].

DERs include both LES systems and renewable-based distributed generation, such as marine energy generators (e.g., wave or marine current), PV farms or wind farms. When implementing a microgrid within a port infrastructure, both costs and regulations, as well as sustainability issues, need to be considered. Moreover, it should be noted that the port operation requires high amounts of electricity [36], [37], which can be compared with the electrical loads of a small city. Consequently, microgrids provide an interesting opportunity to allow ports meet their energy requirements by making use of RES.

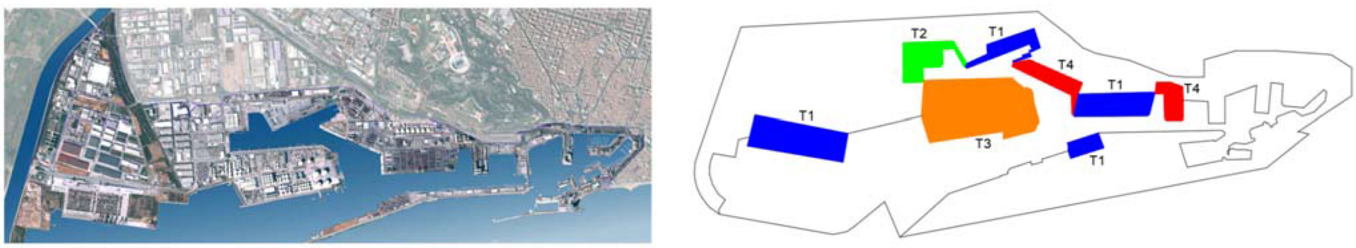
E. Current Ports With Cold Ironing Systems

Cold ironing systems are being used nowadays in some ports around the world. An example of a smart port using this technology is the USA Port of Long Beach in California [38]. The California Air Resources Board has estimated that GHGs emissions could be reduced by 70% (around 18 tons per day) if every ship berthed three or more times per year in California's ports made use of a cold ironing system [39]. Furthermore, since 2010 the EPA from the State of California has been promoting the use of standards on cold ironing in order to meet the emissions reductions limits [40]. Then, due to these and other environmental laws, more ports in both California and Alaska are nowadays using HVSC systems for cruise and large container ships. California's ports have planned 6.6 kV supply voltage with power delivery up to 7.5 MVA per berth. Coordinated development of analytical techniques, port infrastructure, and onboard electrical generation will ease the execution of cold ironing systems for ships [41].

More examples of ports using cold ironing systems can be located in Europe, such as

1) the port of Gothenburg (Sweden [42]);
2) the port of Oslo (Norway) [43];
3) the port of Rotterdam (The Netherlands) [44];
4) the port of Hamburg (Germany) [45]; or
5) the port of Vigo (Spain) [46].

In Asia and Oceania, the port of Tanjung Perak (Indonesia) [47] can be taken as an example. In all the aforementioned cases and the future smart ports, the integration of microgrid technology in ports and the government's policies to increase people's awareness on climate change is an essential requirement to achieve the goal of zero-emissions port.



(a) (b)

Fig. 2. Layout of the port of Barcelona. (a) Orthophotography (obtained from [48]). (b) Port terminals (authors' composition). T1 = terminal for containers and multipurpose ships; T2 = terminal for car carriers; T3 = terminal for LNG carriers and tankers; and T4 = terminal for bulk carriers.

III. Proposed Cold Ironing System for the Port of Barcelona

A. Port Layout and Terminals

The port of Barcelona has terminals for passengers, a leisure port called "Port Vell," and terminals for commercial activity. This paper focuses its attention on the latter. The commercial port is divided into four terminals according to the ship type, as depicted in Fig. 2 (adapted from [48]). The port terminals are subdivided as follows: T1 has two sections, one used by containers and another one used by multipurpose ships; T2 has one section, which is used by car carriers: T3 is used by liquid cargo vessels and is divided into two sections, one for LNG carriers and another one for tankers; finally, T4 has two sections that are used by bulk carriers.

B. Electrical Demand From Berthed Ships

Table II (adapted from [49], [50] and from confidential data given by the Authority of the Port of Barcelona) shows the hourly electrical demand from berthed ships at the port of Barcelona, considering all the per-hour arrivals and departures. The demanded power by berthed ships at a given time i, P_i, is calculated as follows:

$$P_i = P_{i-1} + P_{\mathrm{arr}} - P_{\mathrm{dep}} \quad (1)$$

where P_{i-1} is the power demanded by berthed ships at the previous time, P_{arr} is the power demanded by ships that arrive to the port, and P_{dep} is the power demanded by ships that depart from the port. The power requirements of each ship type are given in Table I. Table II shows that the per-hour average power demanded by berthed ships is 221.9 MW, which is the value to be used for sizing the proposed renewable energies-based cold ironing system.

C. Wind and Solar Resources

Table III (obtained from [51], [52]) shows the average daily wind speed (v_w) and the average daily irradiation per square meter (H) at the port of Barcelona, whose geographical coordinates are 41°20′42″N and 2°08′30″E. The wind speed has been obtained from the database [51], assuming a WT height of 100 m, whereas the solar irradiation has been obtained from the database [52], assuming an optimal inclination of the PV panels that corresponds to the latitude at port of Barcelona –5°.

With respect to the wind resource, in order to obtain the extracted power from the wind, the following expression can be used [53]:

$$P_w = \frac{1}{2}\rho c_p A v_w^3 \quad (2)$$

where $\rho = 1.225$ kg/m^3 is the air density at sea level (assuming the normal temperature $T = 298$ K), c_p is the power coefficient of the WT, $A = \pi R^2$ is the area swept by the rotor (R = blade's length), and v_w is the wind speed. Assuming that there exists an MPPT algorithm [54] that allows the WT to obtain the maximum power from a given wind speed, then the *Betz*'s limit [55] can be used as the maximum power coefficient of the WT, i.e., $c_p = 0.593$. Assuming the WT V150-4.2 MW from Vestas [56], whose rotor diameter is 150 m, it means that its radius (or blade's length) is 75 m. According to all the aforementioned values, the extracted power from the wind (2) for the average wind speed at the port of Barcelona (5.28 m/s) corresponds to 944.8 kW, which is also shown in Table III.

Regarding the solar resource, the peak sun-hours (PSH) of the PV panel can be obtained by dividing the average irradiation per square meter at the port of Barcelona (H = 5.64 kWh/m^2) by the theoretical irradiance that a PV panel would receive under normal meteorological conditions (i.e., with no clouds in the sky, with the sun directly overhead, etc.), which corresponds to of 1000 W/m^2 [57]. Therefore

$$\mathrm{PSH} = H/1000 \quad (3)$$

giving a result of PSH = 5.64 h, as shown in Table III.

D. Required Number of WTs and PV Panels

Considering that a WT delivers much more power than a PV panel, then WTs will satisfy the highest power demand from ships at berth. As a result, 3/4 (or 75%) of the demanded power (221.9 MW according to Table II) is assumed to be supplied by WTs, giving a value of 166.42 MW. As stated in Section III-C, a WT can extract 944.8 kW from the wind. Assuming no mechanical losses and no electrical losses in the WT, the (output) electrical power equals the (input) wind power, i.e., 944.8 kW. Then, the required number of WTs (N_{WT}) can be easily obtained as follows:

$$N_{\mathrm{WT}} = \text{Power demanded by ships/WT power} \quad (4)$$

giving a result of 177 WTs.

TABLE II
HOURLY ELECTRICAL DEMAND (POWER) FROM BERTHED SHIPS AT THE PORT OF BARCELONA FOR ONE WEEK (ADAPTED FROM [49] AND [50])*

Time	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Average power (MW)
	Arriv./ Depart.	Power** (MW)	Arriv./ Depart.	Power (MW)	Arriv./ Depart.	Power (MW)	Arriv./ Depart.	Power (MW)	Arriv./ Depart.	Power (MW)	Arriv./ Depart.	Power (MW)	Arriv./ Depart.	Power (MW)	
0 h	0 / 0	132.5***	0 / 0	219.0	0 / 0	199.1	1^3 / 0	213.4	1^1 / 1^1	232.6	0 / 0	211.4	0 / 1^3	261.9	**210.0**
1 h	0 / 0	132.5	0 / 0	219.0	0 / 1^1	191.6	1^3 / 0	219.9	1^1 / 0	240.1	0 / 0	211.4	0 / 1^1	254.4	**209.8**
2 h	1^1 / 0	140.0	0 / 0	219.0	0 / 0	191.6	0 / 0	219.9	0 / $1^{1,3}$	226.1	1^1 / 0	218.9	0 / 0	254.4	**210.0**
3 h	0 / 0	140.0	0 / 0	219.0	0 / 0	191.6	1^3 / 0	226.4	1^1 / 1^3	227.1	0 / 0	218.9	$1^{1,3}$ / 0	268.4	**213.1**
4 h	0 / 0	140.0	1^1 / 0	226.5	0 / 0	191.6	$1^{2,3}$ / 1^1	232.6	0 / 1^1	219.6	0 / 0	218.9	0 / 0	268.4	**213.9**
5 h	0 / 0	140.0	0 / 0	226.5	0 / 0	191.6	1^3 / 0	239.1	$1^{2,3}$ / 1^1	225.8	0 / 0	218.9	1^1 / 0	275.9	**216.8**
6 h	0 / 0	140.0	2^1 / 0	241.5	1^1 / 1^1	191.6	1^1 / 1^1	239.1	1^1 / 0	233.3	1^3/ 0	225.4	0 / 0	275.9	**221.0**
7 h	0 / 0	140.0	0 / 0	241.5	0 / 0	191.6	$1^{1,3}$ / 0	253.1	0 / 0	233.3	1^1 / 0	232.9	0 / 0	275.9	**224.0**
8 h	0 / 0	140.0	0 / 0	241.5	1^3 / 0	198.1	1^1 / 1^1	253.1	1^2 / 0	240.5	2^1 / 0	247.9	1^3 / 0	282.4	**229.1**
9 h	1^2 / 0	147.2	0 / 0	241.5	0 / 0	198.1	0 / 0	253.1	0 / 1^1	233.0	0 / 0	247.9	0 / 1^2	275.2	**228.0**
10 h	1^2 / 0	154.4	0 / 0	241.5	$1^{1,2}$ / 0	212.8	1^2 / 1^2	253.1	0 / 0	233.0	0 / 0	247.9	0 / 0	275.2	**231.1**
11 h	0 / 0	154.4	0 / 1^2	234.3	0 / 1^1	205.3	2^1, $1^{2,3}$ / 1^3	275.3	$1^{1,3}$ / 0	247.0	0 / 0	247.9	0 / 2^1	260.2	**232.1**
12 h	1^2 / 0	161.6	0 / 0	234.3	2^1, 1^3 / 1^2	219.6	0 / 1^1	267.8	$1^{1,3}$ / $1^{1,2}$	246.3	0 / 2^1	232.9	0 / 0	260.2	**231.8**
13 h	1^1 / 0	169.1	0 / 0	234.3	0 / 1^3	213.1	0 / 0	267.8	0 / 2^2, 1^3	225.4	0 / 0	232.9	1^2 / 1^3	260.9	**229.1**
14 h	0 / 0	169.1	0 / 1^1	226.8	0 / 1^2	205.9	0 / 2^3	254.8	1^3 / 0	231.9	1^1 / 1^1	232.9	0 / 0	260.9	**226.0**
15 h	0 / 0	169.1	0 / 1^2	219.6	0 / 0	205.9	1^1 / 1^3	255.8	0 / 0	231.9	0 / 0	232.9	0 / 2^3	247.9	**223.3**
16 h	1^1 / 0	176.6	2^1 / 1^1	227.1	0 / 0	205.9	0 / 0	255.8	1^2 / 1^1	231.6	0 / 0	232.9	0 / 0	247.9	**225.4**
17 h	0 / 0	176.6	0 / $1^{1,3}$	213.1	1^2 / 1^3	206.6	1^3 / 1^2	255.1	1^1 / 1^3	232.6	0 / 0	232.9	0 / 0	247.9	**223.5**
18 h	0 / 0	176.6	0 / 1^3	206.6	0 / 1^2	199.4	0 / 1^1	247.6	1^1 / 0	240.1	1^1 / 0	240.4	0 / 0	247.9	**222.7**
19 h	0 / 0	176.6	0 / 0	206.6	0 / 0	199.4	0 / $1^{1,2}$	232.9	0 / $1^{1,3}$	226.1	1^1 / 0	247.9	0 / 1^1	240.4	**218.6**
20 h	1^1, 2^2 / 0	198.5	0 / 1^1	199.1	0 / 0	199.4	0 / 0	232.9	0 / 1^1	218.6	1^3 / 0	254.4	0 / 1^3	233.9	**219.5**
21 h	$1^{1,3}$ / 0	212.5	0 / 0	199.1	0 / 0	199.4	1^2 / 1^1	232.6	0 / 0	218.6	0 / 0	254.4	1^1 / 1^1	233.9	**221.5**
22 h	1^3 / 0	219.0	0 / 0	199.1	0 / 0	199.4	0 / 0	232.6	0 / 0	218.6	0 / 1^1	246.9	0 / 1^1	226.4	**220.3**
23 h	0 / 0	219.0	0 / 0	199.1	1^1 / 0	206.9	0 / 0	232.6	0 / 1^2	211.4	2^1, 1^3 / 0	268.4	$1^{1,3}$ / 1^3	233.9	**224.5**
														Per-hour average power (MW)	**221.9**

Notes:

[1, 2, 3] Superscripts 1, 2 and 3 stand for the ship type: 1 = Container; 2 = Tanker (including LNG carrier); and 3 = RoRo. Their corresponding power requirements are given in Table I.

[*] All data corresponds to cargo merchant ships that arrive to / depart from the port of Barcelona for 1 week. Sources: [49]-[50] and confidential data from the Authority of the Port of Barcelona.

[**] The power demanded by berthed ships at the port of Barcelona has been calculated as: $P_i = P_{i-1} + P_{arr} - P_{dep}$ (where P_i is the power demanded by berthed ships at the current time; P_{i-1} is the power demanded by berthed ships at the previous time; P_{arr} is the power demanded by ships that arrive to the port; and P_{dep} is the power demanded by ships that depart from the port).

[***] Albeit no arrivals and departures, there were 18 berthed ships at the port of Barcelona on Day 0 at 23:59h. Among them, 12 ships were containers, 5 ships were tankers and 1 ship was a RoRo. It gives an overall value of 132.5 MW of demanded power (according to the ships' power requirements in Table I), which is the initial condition for this study.

With respect to PV panels, they will satisfy 1/4 (or 25 %) of the demanded power, which corresponds to 55.47 MW. As this corresponds to the hourly average power, the energy demanded by berthed ships to be supplied by PV panels will be 55.47 MWh. The required number of PV panels (N_{PV}) can be easily obtained as follows:

$$N_{\mathrm{PV}} = E_T \,/\, (V_{\mathrm{MPP}}\, I_{\mathrm{MPP}}\, \mathrm{PSH}\, \eta) \qquad (5)$$

where E_T is the energy demand (55.47 MWh), PSH $= 5.64$ h (see Table III), η is the PV panel efficiency (usually around 90%, i.e., $\eta = 0.9$) and V_{MPP} and I_{MPP} are the voltage and the current at the maximum power point, respectively. Assuming the monocrystalline 144-cell module STP375S-24/Vfh from Suntech [58], its maximum power point voltage and current are 39.9 V and 9.4 A, respectively. Then, taking into account the aforementioned values and according to (5), the following number of PV panels would be required: 29 137 PV panels.

E. Proposed Cold Ironing Topology

The proposed cold ironing topology for the smart port of Barcelona consists of three main parts, as depicted in Fig. 3.

First, the offshore wind farm (left side of Fig. 3) is based on a set of DFIG-based WTs ($\mathrm{WT}_1 \ldots \mathrm{WT}_n$) (including their corresponding gearbox and a back-to-back converter, where a battery bank is connected to the dc link through a chopper, and a filter is connected at the inverter's output to reduce harmonics),

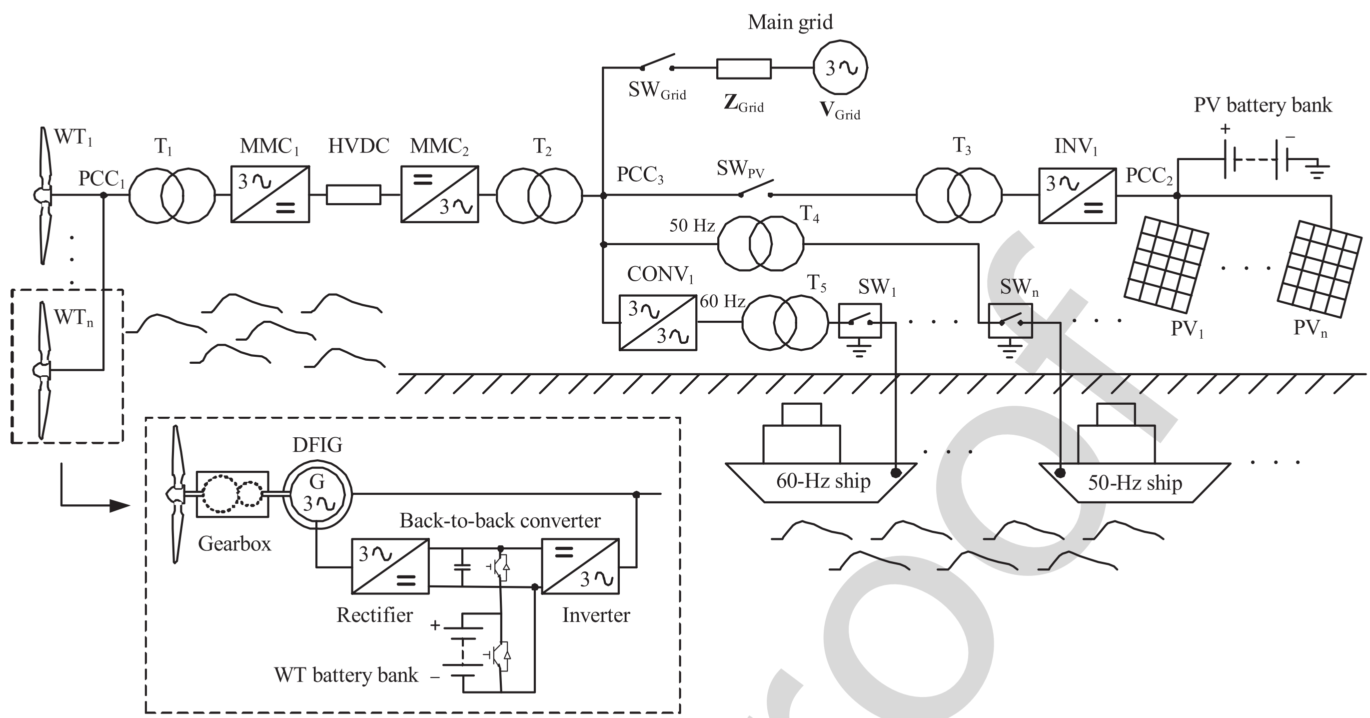


Fig. 3. Proposal of a renewable energies-based cold ironing system for a smart port microgrid (particularized for the port of Barcelona). Single-line diagram.

TABLE III
DAILY WIND AND SOLAR RESOURCES AT THE PORT OF BARCELONA (OBTAINED FROM [51] AND [52])

Wind resource		Solar resource	
v_w (m/s)*	P_w (kW)	H (kWh/m^2)**	PSH (h)
5.28	944.8	5.64	5.64

* Obtained from [51] assuming a WT height of 100 meters.
** Obtained from [52] assuming a PV inclination of 36 degrees.

which are connected to a point of common coupling (PCC$_1$); an off-shore-side step-up transformer (T_1) to increase the voltage level in order to transmit it to the shore-side installation; an HVdc transmission system, which consists of a rectifier unit (off-shore side) based on an MMC (MMC$_1$), a dc line and an inverter unit (shore side) with another MMC (MMC$_2$); finally, a shore-side step-down transformer (T_2) reduces the voltage level in order to adapt it to the voltage requirements. This topology corresponds to the usual approach when modeling HVdc systems for offshore wind farms [59].

Second, the PV farm (right side of Fig. 3) consists of: a set of PV panels (PV$_1 \ldots$ PV$_n$; including their load regulators), which are connected to a point of common coupling (PCC$_2$); a battery bank connected to PCC$_2$ in order to reduce power swings; a three-phase inverter (INV$_1$; with its filter) in order to transform the dc variables provided by the PV panels to the required three-phase ac variables with no harmonics; and a step-up transformer (T_3) with the aim of increasing the voltage level to adapt it to the port microgrid's voltage requirements. This topology corresponds to the usual approach when modeling PV power plants [60]. The PV farm is connected to the PCC$_3$ by means of the switch SW$_{\mathrm{PV}}$. Note that both WT and PV plants are linked by means of the point of common connection PCC$_3$, so they must be properly controlled and synchronized in order to provide the same RMS voltages with equal phase angle and the same frequency, which can be achieved by choosing a proper PLL, such as the well-known three-phase PLL described in [61].

Finally, the installation that adapts the phase-to-phase voltage and the frequency that comes from the renewable energies to the ones required by the ships is depicted in the center of Fig. 3. It consist of two different parts, depending on the frequency level: One part works at 50 Hz (which is the frequency that inject both WTs and PV panels), so no additional power converter is needed, whereas another part works at 60 Hz, so a three-phase ac/ac power converter (CONV$_1$) is needed to obtain that frequency from the generated one (50 Hz). Both parts need a transformer (T$_4$ and T$_5$, respectively) to adapt the phase-to-phase voltage to the ship's requirements, according to Table I. Finally, switchboards (SW$_1 \ldots$ SW$_n$), are needed in order to physically connect the electrical system of the ship to the shore-side installation, as explained in Section II (Fig. 1).

It should be noted that under certain circumstances, not all the power demanded by berthed ships could be satisfied. For example, at night, there is no Sun and the batteries associated with PV panels could not satisfy the 25% of the demand during all night hours. Under these (or other similar) circumstances, the power that cannot be satisfied from renewable energies must necessarily come from the main grid. As a result, the main grid (modelled as a voltage source and a series impedance) could be connected at PCC$_3$ through the switch SW$_{\mathrm{Grid}}$, as shown in Fig. 3.

F. Study Cases

The proposed renewable energies-based cold ironing system for the port of Barcelona has been simulated with

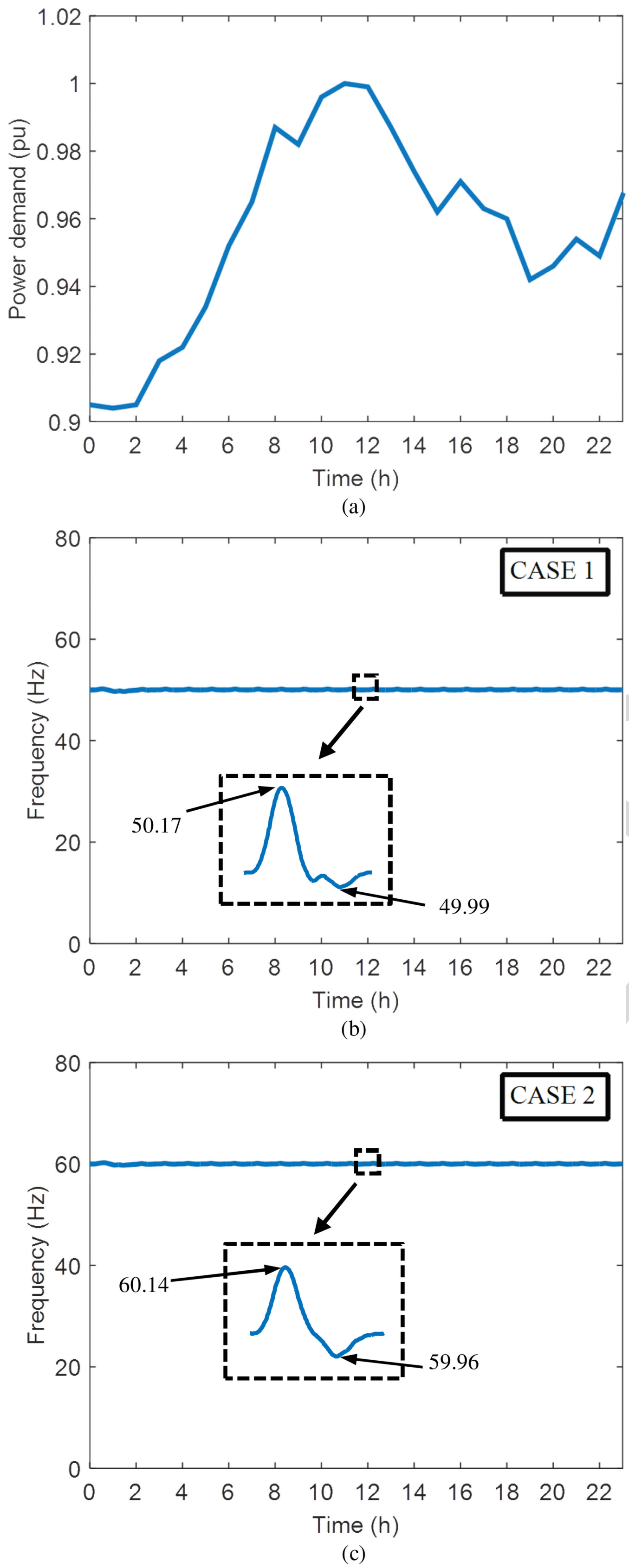


Fig. 4. Stability of the proposed renewable energies-based cold ironing system at the port of Barcelona. (a) Pattern of power demanded by berthed ships for a day. (b) Frequency response to the load change considering 50-Hz ships (case 1). (c) Frequency response to the load change considering 60-Hz ships (case 2). Frequency corresponds to voltage obtained by simulation at PCC_3 in Fig. 3.

TABLE IV
REQUIRED NUMBER OF WTS AND PV PANELS TO SATISFY THE PER-HOUR DEMANDED POWER BY BERTHED SHIPS AT THE PORT OF BARCELONA

Time	Power (pu)*	Number of WTs**	Number of PV panels***
0 h	0.905	167	27,577
1 h	0.904	167	27,551
2 h	0.905	167	27,577
3 h	0.918	170	27,984
4 h	0.922	170	28,089
5 h	0.934	173	28,470
6 h	0.952	176	29,021
7 h	0.965	178	29,415
8 h	0.987	182	30,085
9 h	0.982	181	29,940
10 h	0.996	184	30,348
11 h	1.000	185	30,479
12 h	0.999	185	30,439
13 h	0.987	182	30,085
14 h	0.974	180	29,678
15 h	0.962	178	29,323
16 h	0.971	179	29,599
17 h	0.963	178	29,350
18 h	0.960	177	29,245
19 h	0.942	174	28,706
20 h	0.946	175	28,824
21 h	0.954	176	29,087
22 h	0.949	175	28,929
23 h	0.967	179	29,481
	Average	**177**	**29,137**

Notes:

* Power is given in per unit (pu) assuming that the base power is the highest power value given in the rightmost column of Table II, i.e., 232.1 MW.

** According to (4), assuming that WTs satisfy 75% of power demand.

*** According to (5), assuming that PV panels satisfy 25% of power demand.

MATLAB–Simulink. It has been assumed that WTs provide 75% of the energy demanded by ships, whereas PV panels provide 25%, as stated in Section III-D. It has also been assumed that the ships' voltage requirement corresponds to the most unfavorable phase-to-phase value, i.e., 11 kV according to Table I.

A load change (i.e., the power demanded by ships at berth) has been programmed for a day according to the per-time demanded power given in the rightmost column of Table II, whose profile is shown in Fig. 4(a). The required number of WTs and PV panels to provide the per-hour demanded power is shown in Table IV, whose values have been calculated according to (4) and (5), respectively. The average values are 177 WTs and 29 137 PV panels, which correspond to the ones calculated in Section III-D.

The following cases have been studied.

1) *Case 1:* 50-Hz load change, i.e., power demanded by 50-Hz ships according to the pattern shown in Fig. 4(a).

2) *Case 2:* 60-Hz load change, i.e., power demanded by 60-Hz ships according to the pattern shown in Fig. 4(a).

Fig. 4(b) and (c) depicts the simulated frequency at the point of common connection between the wind farm and the PV farm (PCC_3 in Fig. 3) for the aforementioned two cases. The frequency has been obtained by means of a PLL [61]. The issue of voltage and frequency fluctuations due to load changes is a well-known problem [62]. Apparently, the simulated system has no problems of frequency oscillations, as the frequency remains constant during all the entire day. However, if a zoom is made in the time instants when the load suddenly increases or decreases (e.g., at 12 h), a frequency fluctuation is observed. However, this oscillation is not critical, as the depicted minimum and maximum values of frequency are close to the corresponding steady-state values for each case. Nevertheless, if the problem of frequency fluctuation were to be tackled, a PSS or an FACT could be used [63], which is out of the scope of this paper.

IV. Conclusion

First, this work has stated the importance of cold ironing systems in order to reduce the GHGs emissions from berthed ships, which are harmful for both atmosphere and human health. The electrical requirements of docked vessels, the current regulations on cold ironing, the concept of smart ports as a microgrid, and examples of current ports that make use of cold ironing systems have been given.

Second, the power demanded by ships that are berthed at the port of Barcelona and the available wind and solar resources on that place have been analyzed in order to propose a proper cold ironing system based on renewable energies, focusing the attention on the use of wind turbines and photovoltaic panels to satisfy the ships' power demand. The proposed cold ironing topology has envisioned that 75% of power demanded by berthed ships is supplied by offshore WTs, whereas 25% is supplied by PV panels. The proposed system has been simulated in MATLAB–Simulink assuming two cases in which the power demanded by berthed ships varies through a day. The simulations have revealed that the proposed renewable energies-based cold ironing system is stable, as there are no noticeable frequency fluctuations.

To sum up, cold ironing systems are absolutely necessary to reduce GHGs emissions from berthed ships, and the technology based on renewable energies appears to be a plausible solution, according to the results shown in this paper particularized for the port of Barcelona. This paper tried to shed some light into the problem, but more studies need to be performed to make it possible.

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