OPTIMIZATION MODEL FOR A HYBRID PHOTOVOLTAIC/COLD IRONING SYSTEM: LIFE CYCLE COST AND ENERGETIC/ENVIRONMENTAL ANALYSIS

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Abstract – Traditional cold ironing provides for powering berthed ships in port with electricity from the national grid. This way ships can shut down their auxiliary engines and exploit the onshore power supply. Alternatively, a local energy production improves the energetic self-sufficiency of the port areas and avoid stressing the national grid with continuous peaks of energy demand. The port area becomes a microgrid, characterized by both energy producers and consumers. This paper presents an optimization model for a combined photovoltaic (PV)/cold ironing system. The energy demand of a list of ferries has been analyzed, taking the port of Ancona (Italy) as case study. Then the match with the energy production has been investigated. The proposed model returns the percentage of the energy demand covered, the interactions with the national grid, the optimal size of the PV plant based on a Life Cycle Cost (LCC) approach and the environmental savings obtained. Results show that the optimal PV plant size is 2100 kW and 3700 kW for two scenarios with different initial and operational costs. The reduction of CO_2 emissions is 54.1 % for a traditional grid-based scenario, while 64.9 % and 73.1 % for the 2100 kW and 3700 kW scenario, respectively.

Introduction

Over the years the continuous increase in maritime traffic of goods and people, both by ferries and cruises (which have the highest growth rate), highlights the problem of environmental pollution in port areas, especially when the port is in the proximity of urban areas. According to IMO (International Maritime Organization), maritime traffic contributes to CO_2 global emissions for approximately 2.2 % (2014) [1]. In addition, ships contribute to NO_x, SO_x and PM emissions in varying degrees depending on the type of engines and fuel used by the ships. As reported from the 4th GHG study[1], the greenhouse gas (GHG) emissions of total shipping have increased of 9.6 % from 2012 (977 million tons) to 1076 million tons in 2018, passing from 2.76 % to 2.89 % of the global anthropogenic emissions. The progressive increase of the maritime traffics has caused an always greater impact on the ports, often located in densely populated areas. The decarbonization of maritime traffics turns out to be a mandatory step to reduce the environmental impact of the sector [2].

Among the studied solutions, cold ironing systems plan to power berthed ships with an onshore power supply [3]. In fact, ships keep the auxiliary engines running during the stay time at the quay, to produce the necessary electricity to hoteling activities (such as indoor air conditioning, lighting, pumps and fans). Cold ironing ensures a high level of local pollutants

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abatement [4], as allows to replace the energy from on-board diesel generators with energy from the national grid [5]. Globally, with a lower environmental impact of the grid energy mix, a higher abatement efficiency is achieved [6].

In addition, the trend of local and smart grid must be considered [7]. Traditional grid is designed to transmit electricity from centralized producers to consumers, while in future multidirectional network consumers are the producers themselves [8]. The local electricity production provides technical benefits [9], such as the reduction of losses and congestion in the grid [10]. In this sense the integration of renewable sources is fundamental to produce clean energy, given its proximity to urban areas, and to match the energy demand of ports [11].

This paper investigates the energetic, economic and environmental feasibility of a photovoltaic (PV) plant located in port area. An optimization model has been developed and implemented on MATLAB, to provide the best sizing of the production plant. The model is based on an hourly time step over a one-year period. The chosen parameter for the optimization is the Life Cycle Cost (LCC), as it allows to consider the entire life of the components [12]. The proposed model first provides the match between the energy production and the energy demand, returning the percentage of the energy demand covered and the interactions with the national grid. Then the optimal model with the size of the PV plant based on the minimum Life Cycle Cost (LCC) has been simulated. On this scenario the environmental savings obtained has been calculated.

Materials and methods

The optimization model proposed aims to provide the best sizing of a photovoltaic plant coupled to a cold ironing system. The port of Ancona is taken as case study. In this work the analysis is limited to ferry ships, but the methodology is valid for all kind of ships. Ferries are characterized by regular frequency of calls in port, and an average energy demand compared to cruises (higher power required) and container ships (lower power required). The calculation is hourly based over a period of one year. In the case study proposed, the period considered is from August 1st, 2018 to July 31st, 2019.

Once the pattern of ships has been chosen, the input data for the analysis are the nominal and the used power at berth, the duration of the stay and the number of calls. A typical week for each month has been determined, in order to model the annual profile of the electrical load.

The power required by the ships present in port at a given time i (hour), P_i, is calculated as follows (Eq. 1):

$$P_i = P_{i-1} + P_a - P_d \qquad \text{(kW)} \qquad 1$$

where P_{i-1} is the power required by ships at berth at the previous time step, P_a is the power of the ships that arrive in the port at time i, and P_d is the power demand of the ships that depart from the port.

Table 1 summarizes the ferry ships involved in this work. “EP” indicates the rated power of the generator, while “avg. power” the real power required during the berthing time (in summer and in winter). “t” refers to the number of hours in port related to the energy demand.

Table 1 – Energy demand of ships and dwell time at the quay.

			Summer			Winter		
	N° generators	EP nominal power [kW]	N° gen used	Avg. Power [kW]	t [h]	N° gen used	Avg. Power [kW]	t [h]
Ship 1	3	2100	1	1600	513.8	1	1600	893.2
Ship 2	3	1400	2	1400 150	314.2	1	1000	845.7
Ship 3	3	1400	2	1400 150	310.8	1	1000	859.5
Ship 4	3	1900	2	1900 300	254.7	2	1900 300	441.2
Ship 5	3	3800	1	2200	310.2	1	2200	433.8
Ship 6	4	850	2	850 350	573.0	2	850 350	253.2
Ship 7	3	1360	1	800	857.3	1	800	1007.8
Ship 8	2	960	1	500	272.2	1	350	131.4
Ship 9	4	783	1	600	871.0	1	600	946.1
Ship 10	3	945	1	800	694.5	1	800	0.0

Eq. 1 is calculated for the year under study and the trend is shown in figure 1. The energy demand is very variable during the different weeks and seasons and ranges between 0 W, in absence of ships in port, to 6400 kW, during the maximum contemporaneity of ships.

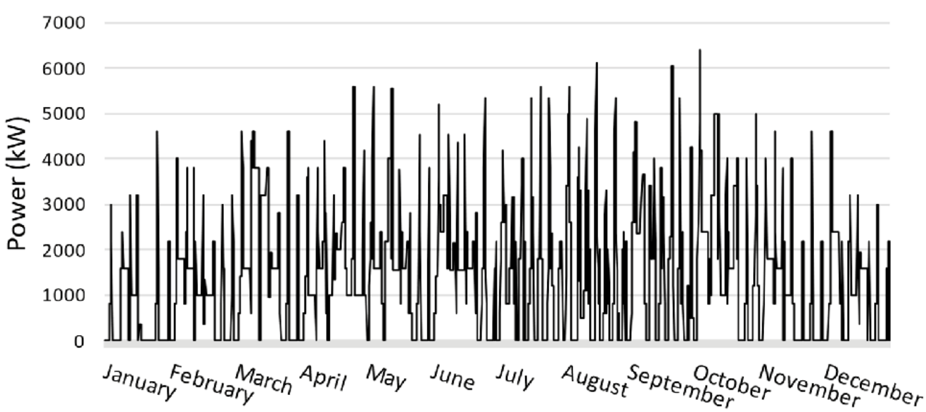

Figure 1 – Annual profile of the energy demand by berthed ships.

As regard the energy production, the proposed system consists of a PV plant, located in port area, that provides energy to cover the energy demand of berthed ships. In absence of solar radiation or in case of deficit of energy production, the electricity is taken from the national grid. In case of energy surplus, which means that the energy production is higher than the energy demand of ships, the energy surplus is given to the national grid. The data required for the calculation of the output power of a PV system are the ambient temperature and the irradiance over the analyzed period. The data were collected considering the climatic condition of Ancona (Italy), from 01/08/2018 to 31/07/2019, on an hourly basis. The output power (P_{PV}) is calculated with the following equation (Eq. 2):

$$P_{PV} = P_r \cdot f_{PV} \cdot \left(\frac{G_T}{G_{T,STC}}\right) \cdot \left[1 + \alpha_p \cdot \left(T_C - T_{C,STC}\right)\right] \quad \text{(kW)} \qquad 2$$

where P_r is the rated capacity of the PV array, meaning its power output under standard test conditions [kW]. f_{PV} is the PV derating factor [%], G_T the solar radiation incident on the PV array in the current time step [W/m^2], $G_{T,STC}$ the incident radiation at standard test conditions. αP is the temperature coefficient of power [%/°C], T_C the PV cell temperature in the current time step [°C] and $T_{C,STC}$ the PV cell temperature under standard test conditions. STC (Standard Test Conditions) refers to 1000 W/m^2 and 25 °C. The cell temperature during the working time of a PV panel can be expressed as a function of the ambient temperature and the incident solar radiation on the panel (Eq. 3):

$$T_C = T_a \cdot G_t \cdot \left(\frac{NOCT - 20}{800}\right) \quad (°C) \qquad 3$$

where T_a is the ambient temperature at the current time step [°C] and NOCT is the operative temperature of the PV panel. In this study, considering monocrystalline PV panels, the NOCT is assumed to be 45 °C and the coefficient of power α_P equal to − 0.5 %/°C. The PV derating factor f_{PV} is equal to 93 %.

The economic analysis has been performed through a Life Cycle Cost approach (LCC). This method allows to consider the initial investment costs and the operation and maintenance costs for all the duration of the system, and eventually the recovered value at the end of the life cycle. The method combines the energetic and economic aspect. The LCC index can be calculated with the following equation (Eq. 4):

$$LCC = C_I + \sum_{t=1}^{n} \frac{C_{M,i} + C_{O,i}}{q^i} \quad (€) \qquad 4$$

where C_I represents the initial investment costs, $C_{M,i}$ and $C_{O,i}$ are the maintenance and operation costs over the period i, respectively. q^i is defined as $(a + 1)^i$, where a is the discount rate during the n- years of the project. The method allows to compare different scenarios. The best one is the one with the lowest LCC index.

The environmental analysis aims, once the best scenario has been determined, to provide the emission saving. The method compares the pollutant emissions of the auxiliary engines of ships, usually diesel generators, with the emission factor of the energy mix of the grid. The analysis is provided for a list of pollutants, namely CO_2, NO_x, SO_x and BC. The environmental emissions of a pollutant can be calculated with the following equations (Eq. 5):

$$\varepsilon_i = EF_i \cdot E_i \quad (kg) \tag{5}$$

where ε_i (kg) is the emission of the pollutant "i", EF_i (kg/kWh) is the emission factor and E_i (kWh) is the energy withdrawn from the electrical grid. The values of the emission factors are taken from SINAnet ISPRA [13], which refers to electricity from the Italian energy mix. The emission factors are summarized in table 2.

Table 2 – Emission factors (kg/kWh) for grid and (kg/ kg of fuel) for ships.

	CO_2	SO_2	NO_x	BC
Ships	3.082	0.022	0.057	3.37E-03
Grid	0.258	4.81E-05	2.11E-04	3.99E-08

Two different numerical models have been developed and implemented on MATLAB. The first one allows to determine the share of energy demand of ships at berth covered by the photovoltaic plant. This is the share that directly match the energy production and the energy demand. The remaining share of the energy demand is provided by the national grid. The model is based on an hourly time step. The input data are the solar radiation (Gt), the ambient temperature (Ta) and the power required by ships (Pi). The model calculates and returns the PV production in according to Eq. 2 and Eq. 3, and then matches, for each time step over one year, the energy production and the energy demand. At each time step, in presence of ships in port, assigns the correct share of energy to the PV plant or to the national grid. The diagram flow of the model is shown in figure 2. In figure, Epv is the energy provided by the PV plant to ships, SU is the energy surplus and DE is the energy deficit.

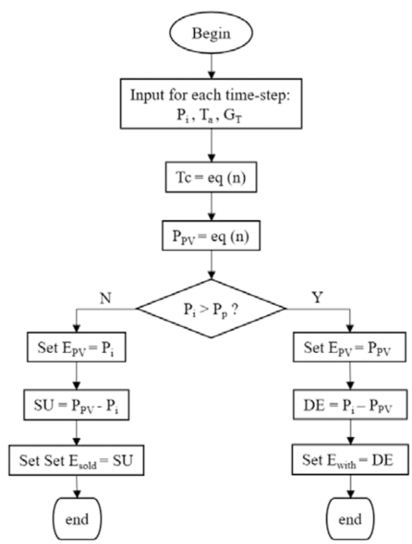

Figure 2 – Diagram flow of a photovoltaic scenario.

The second model is the optimization tool based on the minimization of the LCC index, as presented in Eq. 4. The input data are the results of the previous model (figure 2), and in addition the economic and environmental parameters, namely initial, operation and maintenance costs and emission factor. The model returns the LCC index, considering a life cycle of 20 years. Then the loop increases the PV plant size of a power step and repeats the loop. For each scenario the LCC index is calculated and at the end the optimal size of the plant is highlighted (the one with the lowest LCC). Figure 2 shows the diagram flow.

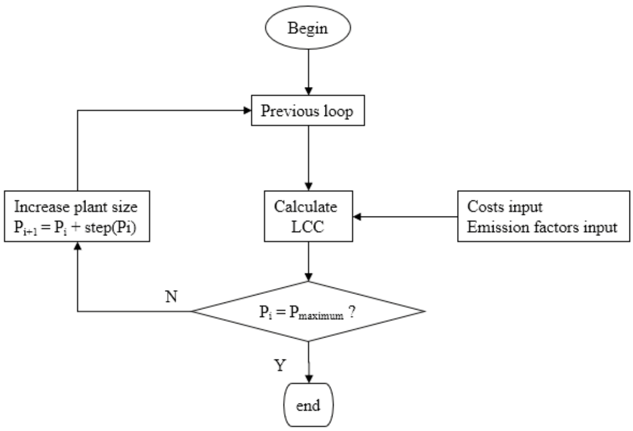

Figure 3 – Diagram flow of LCC loop.

Results and discussions

Two different scenarios have been simulated, comparing different costs:

- Traditional cold ironing, namely the energy demand is directly provided by the national grid.
- “Scenario 1”, with 1400 €/kW for the initial cost of the PV plant and 0.2 €/kWh for the energy purchased from the national grid.
- “Scenario 2”, with 1800 €/kW for the initial cost of the PV plant is, while 0.4 €/kWh for the energy purchased from the national grid. This scenario hypothesizes a spike of energy and material prices.

The first result analyzed is the match between the energy production (PV plant) and the energy demand (berthed ships). Both trends are characterized by a high grade of variability. In fact, the PV production strongly depends on the presence of the solar radiation, while the energy demand on the presence of ships in port. The PV plant size has been varied between 1000 kW and 10000 kW. Results are shown in figure 4.

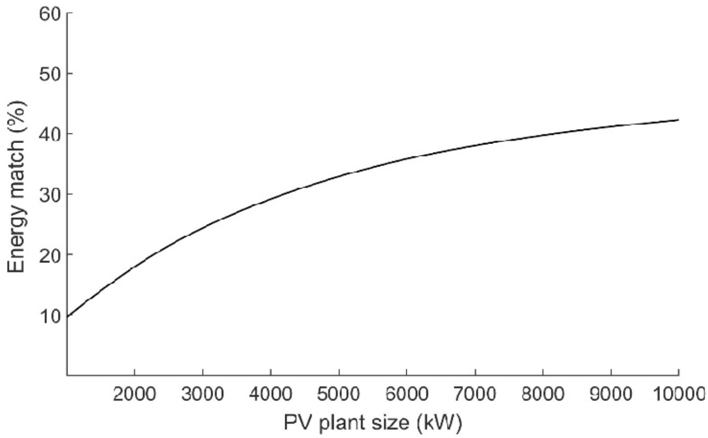

Figure 4 – Energy match (%) between energy production and demand.

The energy that directly met energy production and demand ranges from 9.5% (for a PV plant of 1000 kW) to 42 % (for the 10000 kW case). The trend is not linear, in fact increasing the PV plant size the slope tends to become horizontal. This means that a share of the energy demand occurs in period of absence of energy production (such as at night) and accordingly is independent from the size of the plant. In addition if while increasing the power of the PV plant the match with the energy demand does not increase, there is an increase of the energy surplus that is given to the national grid. This phenomenon has been investigated for the same range of power, from 1000 kW to 10000 kW. Result is shown in figure 5.

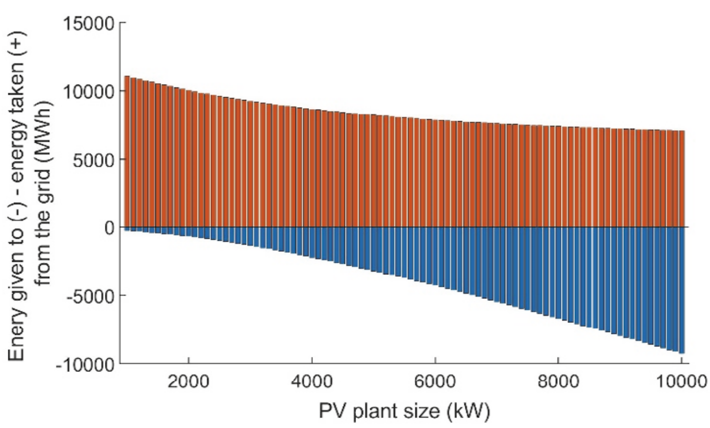

Figure 5 – Energy interaction with the national grid.

It is clearly visible that increase the PV plant size produces an increase of the energy surplus given to the grid, while the energy taken from the grid remains almost constant (after a first decrease). To investigate the optimal size, the LCC approach has been simulated.

The optimization model returns the best PV plant size based on a LCC approach. The model presented has been simulated for both scenarios. The best PV plant size turns out to be 2100 kW (with a LCC of 23.1M€) for the scenario with average prices, while 3700 kW (with a LCC of 42.7M€) for the one considering a spike of prices. In figure 6 the values of LCC have been normalized to better compare the two scenarios, setting a reference value of 100 to the minimum LCC.

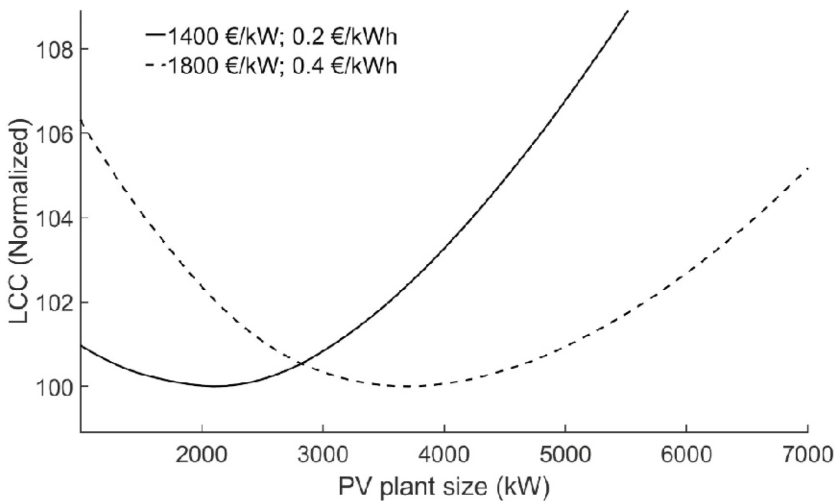

Figure 6 – LCC optimization for the two scenarios considered.

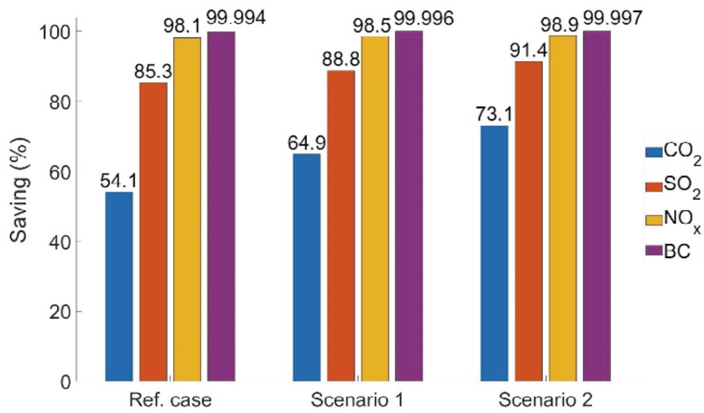

Figure 7 – Saving of polluting emissions.

The environmental analysis has been performed only for the two best plant sizes. Both scenarios are compared with a reference case, namely the traditional cold ironing entirely powered by the national grid. The CO_2 emission saving is 54.1 %, 64.9 % and 73.1 % for the reference case, the 2100 kW power plant and the 3700 kW power plant, respectively. Results for the all the pollutants considered are summarized in figure 7 and table 2. It is worth noting that the percentages of saving obtained depends on the energy mix considered.

Conclusions

This paper presents an optimization model for a hybrid photovoltaic/cold ironing system. The proposed system can limit the environmental pollution produced by berthed ships, replacing the on-board diesel generators with a PV plant located in port area and supported by the national grid. The ferries traffic of the port of Ancona (Italy) has been taken as case study. A numerical model has been written and implemented on MATLAB. The model investigates the match between the energy production (photovoltaic plant in port area) and the energy demand (auxiliary engines of berthed ships). Results show that the trend of the percentage energy match tends to become asymptotic, and ranges between 9.5 % (for a PV plant of 1000 kW) to 42 % (for the 10000 kW case). In fact, the analysis of the energy interactions with the national grid returns that the energy given to the grid increase with the PV plant size, while the energy taken from the grid remains almost constant. Then a second model provides the optimization of the PV plant size based on the Life Cycle Cost (LCC) approach. This approach allows to involve in the analysis the entire life of the plant, considering both the initial costs, the operation and maintenance costs and the residual value at the end of the life. The model returns that the optimal PV plant size is 2100 kW for the scenario with average prices, while 3700 kW considering a spike of prices. The results of the environmental analysis show that a traditional cold ironing (energy demand fully provided by the national grid) allows a reduction of the CO_2 emissions of 54.1 %. The two scenarios resulting from the optimization model ensure a CO_2 emission saving equal to 64.9 % and 73.1 %, respectively. A future extension of the work will include the possibility of an energy storage system, to increase and maximize the self sufficiency of the system.

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