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ECOLOGIC NAVAL POWER PLANT INSTALLED ON BOARD MARITIME TRANSPORT VESSELS

MIRCEA PREDA[1], GHEORGHE SAMOILESCU[2]

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The use of renewable energy sources on board ships is one solution to reduce pollution from maritime transport. Considering it one of the many solutions for the transition to "zero" emission ships, we studied the possibility of installing a new type of power plant on ships already in operation that uses solar/photovoltaic and wind energy conversion systems. The current electricity production system is transformed into a hybrid system, and by improving the available electrical power management algorithms, clean energy consumption will be prioritized. Monitoring daily electricity consumption and recording values for renewable energy source parameters during ship periods and voyages enabled calculations to determine the potential for electricity production from renewable sources and demonstrated the viability of the chosen solution. The results obtained highlight that installing the ecological marine power plant (ENPP) can achieve significant reductions in fuel consumption for producing electricity on board the ship.

1. INTRODUCTION

The use of renewable energy sources in the field of naval transport leads to the reduction of air pollution (by reducing greenhouse gas emissions), the reduction of marine pollution (by reducing the amount of residual water used in exhaust gas washing systems when using heavy fuel with a sulfur content above the permitted international standards) and, last but not least, the reduction of costs per unit of cargo transported.

The ecological marine power plant is intended to be a new concept introduced by this article. The ecological marine power plant represents a key element in the process of implementing and integrating renewable energy sources on board the current generation of transport ships. Unlike the numerous research projects on the use of renewable energy sources on board maritime vessels that deal with the issue of developing the next generation of ships, this type of power plant is intended for installation on cargo ships of the current generation of ships already in operation, or for ships that are built using the structure and construction principles of the current generation of ships in order to use renewable energies in the electricity production system.

Current research on the use of renewable energies on board ships is focused on the development of next-generation ship designs, GREEN ships with zero emissions. Research focused on the use of renewable energy mainly in the ship's propulsion system. Research is at various stages of advancement through the separate or combined use of wind energy and solar energy, or the use of hydrogen fuel cells or interchangeable accumulator batteries. From the multitude of research projects, we can exemplify:

- Planet Solar, a ship that circumnavigated the globe in 2012 using only solar energy [1],
- NYK Super Eco Ship 2050 project [2] - a project that envisages the combined use of solar photovoltaic energy and wind energy through the use of retractable soft sails,
- Oceanbird [3] – a research program - rigid sails,
- Germanischer Lloyd's and DNV project [4] - a concept for a 1000 TEU container ship whose energy source is hydrogen fuel cells. The ship would be used in the North Sea and the Baltic Sea, and the hydrogen supply would be made from offshore hydrogen production stations.
- ReVolt is a DNV research project for an autonomous battery-powered transport ship [5].

Another research direction was that of wind-assisted propulsion. That research has a point in common with the present study, namely, the fact that it addresses the current generation of ships in operation. Research on wind-assisted propulsion using the "Magnuson" effect is at a somewhat more advanced stage as far as ships are concerned, with Flettner rotors being installed on several ships in operation. The installation of Flettner rotors has generated a reduction in fuel consumption, depending on the type of ship and the number of rotors, in percentages from 1.8%, on the Viking Grace ferry equipped with one rotor, up to peaks of 40%, on the E-Ship 1 ship specially built for such propulsion [6].

Different from the research direction presented above, what we want to highlight in this article is a "niche research", applicable mainly in the electrical energy production system on board ships already in operation for the use of renewable energy sources.

To understand the place, role, and structure of the ecological naval power plant, we first presented the structure of the current electro-energy systems and the power plants of maritime transport ships already in operation.

In the next chapter, we present our concept regarding the ecological naval power plant, designed as an auxiliary element for the upgrade of ships already in operation.

Without going into details, we made a general description of the operating principle of the ecological marine power plant (ENPP) in the fourth chapter, and in the fifth chapter, we presented the results of the calculations regarding the electricity consumption and production potential of the ENPP for the date of June 20, 2021. Based on the results, we identified the transition of the ENPP from one operating mode to another for the efficient management of the electricity produced and the prioritization of the consumption of green energy. In part six, we listed, without details, some advantages of implementing the ENPP installation solution on board the maritime transport vessels in operation.2. Naval Power Plant

The naval power plant is the basic component of the naval electrical power system (NEPS) regardless of how it is structured [7]. NEPS includes all electrical energy sources, electrical energy converters, switchboards, electrical networks, and electrical energy consumers brought together in the process of production, transport, distribution, and consumption of electrical energy on board the ship [8].

One of the NEPS classification criteria concerns the origin of the primary energy sources used to generate electrical energy. According to this criterion, we have NEPS:

[1] Military Technical Academy „Ferdinand I", Bucharest, Romania. Email: mircea.preda@mta.ro
[2] Naval Academy „Mircea cel Batran", Constanta, Romania. Email: gheorghe.samoilescu@anmb.ro

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a. Autonomous,
b. With energy recovery from propulsion installations,
c. Combined with propulsion installations.

Autonomous NEPS [9] are those electrical energy production systems whose primary mechanical energy is not related to the ship's propulsion system. This category includes systems that include electrical generators driven by internal combustion thermal engines, forming a group called Diesel-generator.

NEPS with energy recovery or transfer from propulsion installations are those systems that include electrical energy production units whose mechanical energy comes from the energy produced by the propulsion system. In [9], NEPS is presented combined with propulsion installations. Where the ship's propulsion is done using electric motors regardless of the constructive form, with axial line, Podded Drive, or Azimuthing Podded Drive, or any other constructive form, it is recommended that the NEPS be combined with the propulsion system. The ship's power plant also provides electrical energy for propulsion and other consumers.

The naval power plant (NPP) represents the set of electrical energy sources together with the main switchboard (MSB).

The energy sources (SE) in the composition of the main power plant NPP are usually three diesel-generator (DG) groups. Are the main generating groups of the ship equipped with four-stroke thermal engines operating on heavy liquid fuel (fuel oil) or on light fuel (diesel/similar). The power of the generators is established when designing the ship through various calculation methods, the most common being the ship's energy balance method, calculated for different operating modes.

3. ECOLOGICAL NAVAL POWER PLANT

To integrate renewable energy sources into the ship's electrical power system, it is necessary to add a new type of power plant, different from the NPP main and EmcyPP (emergency power plant), which can be defined as an ecological naval power plant.

Conceptually, the ecological naval power plant is different from classic naval power plants both in its structure and in its operation and sources of electrical energy. Currently, this type of power plant does not exist on board transport ships in the current fleet. The ecological naval power plant has as its main function the production of electrical energy from renewable energy sources, its storage, and distribution to consumers. As a secondary function, it also stores part of the energy produced by the ship's main generators when they are ordered to operate at maximum efficiency [10].

The ENPP will have the following structure:

- Energy sources
  - Solar energy conversion system - photovoltaic system
  - Wind energy conversion system - wind system
- Electrical energy storage system with two battery groups
- Interconnection, command, and control board.

3.1 ENERGY SOURCE OF THE ECOLOGICAL NAVAL POWER PLANT

3.1.1 PHOTOVOLTAIC SYSTEM

Photovoltaic panels installed on board commercial cargo ships must meet a series of requirements specific to the environment in which they operate [11]:

- Increased resistance to corrosion due to increased humidity and salinity [12]
- High protection (IP) degree corresponding to the type of ship and the characteristics of the cargo transported. In the case of tankers, both the panels and the connection system will have an anti-explosion protection degree.
- Increased mechanical resistance to mitigate the effects of wind.

The requirements set out in points 1 and 2 are of a constructive nature and are the direct responsibility of the manufacturer of the panels, inverters, controllers, and connection elements.

The mechanical resistance requirement depends on the installation method of the panel system on board ships. To meet the requirement of protection against mechanical stresses in the case of installation on board tankers, we propose as a solution the adoption of a retractable system configuration that allows the withdrawal of the rows of panels towards the central axis of the ship and storage in protective compartments during adverse weather.

The research on the possibilities of implementing renewable energy sources on board current transport ships was carried out on a 50,000-dwt tanker. Available spaces were identified for the installation of photovoltaic panels with a total area of 3,450 square meters. To meet the installation conditions set out earlier, the installation of a photovoltaic field with an area (S_{fv}) of 3,000 square meters was considered.

In recent years, we have witnessed significant progress in increasing the efficiency of photovoltaic cells while reducing production costs. According to data published by the National Renewable Energy Laboratory of the United States of America in 2020, polycrystalline silicon cells without a concentrator reached an efficiency of 26.1%, and those with a concentrator reached an efficiency of 27.3% [13]. Manufacturers of photovoltaic panels declare an efficiency of between 22% and 24% for the products they sell. In the following calculations, we will use a cell efficiency value of 20%. The average annual value of solar energy reaching a flat collector is considered to be 1000 Wh/m^2/year. Using the above data, we can find out the capacity and indicative potential (Pot_{fv}), for producing electricity of the photovoltaic system that can be installed on board the ship.

$$C_s = S_s \cdot AL_s \cdot \eta_c, \tag{1}$$

$$C_s = 3000\ \mathrm{m}^2 \cdot 1000\ \mathrm{Wh/m}^2 \cdot \frac{20}{100}, \tag{2}$$

$$C_s = 600000\ \mathrm{Wh}, \tag{3}$$

$$P_s = 600\ \mathrm{kW}. \tag{4}$$

From weather data or navigation applications, we easily find out the time of presence of solar radiation by reading the time the sun rises and the time it sets.

Date: 20.06.2021. Sunrise time 06:39. Sunset time 19:54

$$19\mathrm{h}54' - 6\mathrm{h}39' = 13\mathrm{h}, \tag{5}$$

Solar radiation presence time result 13 hours 15 minutes

$$\text{time interval } \Delta t_{rad}\ 13\mathrm{h}15' \rightarrow \tag{6}$$

$$\text{numerical value } 13, \frac{15 \cdot 100}{60} = 13{,}25, \tag{7}$$

$$Pot_{fv} = C_s \cdot \Delta t_{rad}, \tag{8}$$

$$Pot_{sfv} = 600\ \mathrm{kW} \cdot 13{,}25\ \mathrm{h} = 8100\ \mathrm{kWh}, \tag{9}$$

$$Pot_{sfv} = 8{,}1 \text{ MWh}. \quad (10)$$

The result obtained has an indicative value since it is based on a value with a very broad character.

For a more precise determination of the production potential of the photovoltaic system during the ship's movement, we will use the values recorded in the databases for the level of isolation recorded [13] at the points where the ship was on 26.06.2021. Within the Rouen – Paranagua voyage, we will analyze the portion of the march executed on 26.06.2021 between the coordinate points φ = 24.03.3N λ019.52.1 W and φ = 18.36.2N λ021.16.4 W.

Table 1

Level of solar radiation recorded.

No.	Wh/m^2	No	Wh/m^2	No	Wh/m^2	No.	Wh/m^2	No.	Wh/m^2
1	17,384	12	1247	23	2214,6	34	2072,7	45	856,59
2	67,512	13	1369,4	24	2255,1	35	1997,7	46	723,63
3	142,86	14	1486,8	25	2285	36	1913,5	47	593
4	234,27	15	1598,3	26	2304,2	37	1820,8	48	467,46
5	341,53	16	1703,3	27	2312,6	38	1720	49	350,95
6	460,94	17	1800,9	28	2310,1	39	1611,9	50	245,83
7	588,79	18	1890,5	29	2296,8	40	1497	51	155,49
8	721,78	19	1971,7	30	2272,8	41	1376,4	52	78,548
9	857,22	20	2043,9	31	2238,2	42	1250,8	53	26,801
10	990,79	21	2106,7	32	2193,1	43	1121,5		
11	1120,4	22	2163,7	33	2138	44	989,64		

The recorded data for the level of solar radiation at the ship's point at an interval of 15 minutes were downloaded [14]. For the interval 06:45 – 07:00, was the first non-zero recording with a summed value of direct and diffuse radiation of 17.348 Wh/m^2, and the last non-zero value was recorded for the interval 19:45 – 20:00, with a value of 26.801 Wh/m^2, which shows that the system was subjected to solar radiation for 13 h and 15 min. The peak irradiance was reached in the interval 13:15 – 13:30 with a value of 2312.596 Wh/m^2. During the 13 hours and 15 minutes, a total of 53 recordings were made, corresponding to 53 each at 15 min intervals. Table 1 shows the 53 recorded values.

Total value of solar energy on 26.06.2021

$$E_{rs} = \left(\textstyle\sum_{n=1}^{n=53} a_n\right) : 4, \quad (11)$$

$$E_{rs} = 17654{,}18 \frac{\text{Wh}}{\text{m}^2}, \quad (12)$$

$$Pot_{sfv} = E_{rs} \cdot S_s \cdot \eta_{cv} = 17654{,}18 \cdot 3000 \cdot \frac{20}{100} =$$

$$= 10592508 \text{ Wh} = 10592{,}5\ k\text{Wh} \quad (13)$$

$$Pot_{sfv} = 10{,}592 \text{ MWh}. \quad (14)$$

As can be clearly seen, the difference between the results obtained by the two calculation variants is significant. The use of the average value of 1000W/m^2 provides good results for determining the annual photovoltaic potential of a location, at a fixed point. The different values from summer to winter determine an average value close to the recommended one of 1000 W/m^2.

For a mobile vehicle equipped with photovoltaic panels that travels on different maritime routes, the variant of using database records for certain periods of the year and navigation routes is the appropriate one, providing results as close as possible to reality [15].

The roll and pitch movements of the ship do not alter the data obtained from the presented calculations. The roll and pitch are periodic movements of sinusoidal type, which determine a partial compensation. This allows them to be ignored in the calculations of estimating the solar energy received by a flat photovoltaic collector arranged in a horizontal plane [16].

3.1.2 WIND SYSTEM

The wind energy conversion system is composed of a variable number of cyclonic wind turbines with wind capture. The number of turbines is directly proportional to the dimensions of the ship's accommodation. As special requirements to be met by wind turbines installed on board, they are like those applicable to wind turbines installed in offshore wind farms [17].

Based on the dimensions of the accommodation, the space allocated to a turbine has a width of L = 6 m and a height of H = 3.5 m [18].

For the installation of cyclonic turbines with a vertical axis and a wind collector, it is necessary that 10% of the space allocated to the turbine is left free for their spacing. Following the turbine sizing calculations [19], the following values result: the external radius - R = 1.35 m, scale factor D = 0.7 m, total turbine diameter = 5.4 m, stator height 2.8 m.

If one considers v_e the wind speed (the inlet speed) and $\rho = 1.25\ \text{Kg/m}^3$ the air density, the total available power P_e^{max} is expressed by the relation:

$$P_e^{max} = \frac{1}{2}\rho A_e v_e^3 = 4\left(\sqrt{6}+\sqrt{2}\right)\rho D^2 v_e^3. \quad (15)$$

We insert the values for the unknowns D = 0.7m and v_e= 10 m/s in eq. (1). The maximum available power is:

$$P_e^{max} = \frac{1}{2}\rho A_e v_e^3 = 4\left(\sqrt{6}+\sqrt{2}\right)\rho D^2 v_e^3 = 9466 \text{ W}. \quad (16)$$

The power coefficient declared by A. Pelegri determined following the CFD simulation for the wind speed $v = 8\text{m/s}$ is $C_p = 0.54$.

To calculate the power, we will consider a decreasing power coefficient $C_p = 0.53$.

The power of the wind subsystem, depending on the wind speed, is presented in Table 2.

Table 2

Wind turbine power depends on wind speed

Wind speed (m/s)	No. turbines (pieces)	Turbine power (kW)	Total Power (kW)	Wind speed m/s	No. turbines (pieces)	Turbine power (kW)	Total Power (kW)
10	12	5.02	60.2	16	12	20.5	247
11	12	6.68	80.1	17	12	24.6	296
12	12	8.67	104	18	12	29.3	351
13	12	11	132	19	12	34.4	413
14	12	13.8	165	20	12	40.1	482
15	12	16.9	203				

3.2 ELECTRICAL ENERGY STORAGE SYSTEM

For the optimal operation of the ENPP, it is necessary to have an electrical energy storage component [20], [21]. It is necessary to install at least two battery groups, with a minimum capacity equal to the maximum nominal power of a main generator.

The basic functions of the battery groups are the following:

- Storage of electrical energy produced from renewable energy sources when production exceeds consumption from the ship's electrical energy system.

- Storage of excess electrical energy produced by the main diesel generators during operation at a load regime appropriate to optimize specific fuel consumption [10].
- Ensuring the necessary power reserve during the start-up sequence of high-power electrical consumers.
- Avoiding blackouts by ensuring the supply of electrical energy to all consumers in the event of and during the time when the sources of electrical energy generation are unavailable.
- Ensuring the necessary electricity consumption during the temporary decrease in production from the photovoltaic system due to short-term cloudiness [22].

3.3 COMMAND-AND-CONTROL INTERCONNECTION BOARD

The command-and-control interconnection board (CCIB) represents the nodal and very important part in the ENPP structure, having the role of ensuring the following functions:

- Connecting and synchronizing the ecological sources of electricity production from the ENPP composition and the storage system.
- Managing the consumption of electricity from renewable sources by commanding, controlling and switching the energy sources from the ENPP composition.
- Prioritizing the consumption of electricity produced from renewable sources while ensuring the power reserve.
- Interconnecting and synchronizing with the Main Power Plant (NPP) of the ship.

4. THE OPERATING PRINCIPLE OF THE ECOLOGICAL NAVAL POWER PLANT

The main role of the ecological (auxiliary) naval power plant is to integrate renewable energy sources into the ship's electrical power system and, as a secondary role, to optimize the fuel consumption of the ship's main diesel generators.

The parameters of the electricity produced from renewable energy sources by the photovoltaic and wind systems are analyzed and synchronized by CCIB with the parameters of the electricity produced by the main diesel generators. The parameters of the "green" electricity will be those that will follow the parameters of the electricity in the NPP due to the much higher reaction speed of the static electronic components of the ENPP compared to the reaction speed of the mechanical systems (diesel engine) in the NPP.

Once the ENPP is installed, it will practically take over the management of the process of production and consumption of electricity on board the ship.

MSB and CCIB will be interconnected on the power circuit for the transfer of electricity between NPP and ENPP and on data circuits for the transfer of information necessary for the command-and-control synchronization process.

Starting from the analysis of the electrical power requirement P_{nec} and the value and structure of the available power P_{dis} in the production systems, as well as from the objective of prioritizing the consumption of green energy simultaneously with the existence of the power reserve P_{rez} one can identify 6 operating modes:

$$P_{dis} = P_{dg} + P_{eol} + P_{fv} + P_{b1} + P_{b2} - P_{rez} \quad (17)$$

where P_{dg} is the diesel generator power, P_{eol} is the wind system power, P_{fv} is the photovoltaic system power, P_{b1} is the battery group power no.1, P_{b2} is the battery group power no.2, P_{rez} is the power reserve.

Operating mode 1

Green energy production $P_{eol} > 0$; $P_{fv} > 0$

The required power is significantly lower than the production power of the wind and photovoltaic systems summed $P_{nec} \ll P_{eol} + P_{fv}$. Battery state of charge (SOC) [23] for group no. 1 SOC1 ≥ 80%, for group no. 2 SOC2 < SOC1

Determines:

a. 100% assured consumption of green energy

b. Excess green energy to be stored in batteries P_{inc}

c. Main generators stopped $P_{dg} = 0$

$$P_{eol} + P_{fv} = P_{nec} + P_{inc} \quad (18)$$

Operating mode 2

Green energy production $P_{eol} > 0$; $P_{fv} > 0$

The required power is approximately equal to the production power of the wind and photovoltaic systems summed $P_{nec} \cong P_{eol} + P_{fv}$, with oscillations above and below its value. Battery state of charge (SOC) for group no. 1 SOC1 ≥ 80%, for group no. 2 SOC2 < SOC1.

Determines:

a. 100% assured consumption of green energy

b. Temporary excess of green energy will be stored in batteries (group no 2) P_{inc}

c. Peaks of consumption above the production power of the wind and photovoltaic systems ensured from group 1 of batteries up to a SOC1 = 40%

d. Main generators stopped $P_{dg} = 0$

$$\begin{cases} P_{nec} = P_{eol} + P_{fv} \\ P_{nec} = P_{eol} + P_{fv} - P_{inc2} \\ P_{nec} = P_{eol} + P_{fv} + P_{des1} \end{cases} \quad (19)$$

Operating mode 3

Green energy production $P_{eol} > 0$; $P_{fv} > 0$

The required power is greater than the production power of the wind and photovoltaic systems combined $P_{nec} \geq P_{eol} + P_{fv}$. Battery state of charge (SOC) for group no. 1 SOC1 ≥ 80%, for group no. 2 SOC2 < SOC1.

Determines:

a. 100% assured consumption of green energy (solar, wind, and battery)

b. The difference in consumption and production power of the wind and photovoltaic systems ensured from group 1 of batteries to a SOC1 = 40%, and from group two to a SOC2 = 20%

c. Main generators stopped $P_{dg} = 0$

$$P_{nec} = P_{eol} + P_{fv} + P_{des1} + P_{des2} \quad (20)$$

Operating mode 4

No green energy production $P_{eol} = 0, P_{fv} = 0$,SOC1 ≥ 40%, SOC2 ≥ 20%

Determine:

a. assured consumption from batteries group 1 up to SOC1 = 40% and from group two up to SOC1 = 20%

b. Main generators off $P_{dg} = 0$

$$P_{nec} = P_{des1} + P_{des2} \quad (21)$$

Operating mode 5

No green energy production $P_{eol} = 0, P_{fv} = 0$,SOC1 ≤

40%, SOC2 ≤ 20%

Determine:

a. One of the main generators in operation at a load regime of 75% - 80% of its maximum power P_{maxdg} for an optimal value of specific fuel oil consumption (SFOC) expressed in gr/kWh.

b. Assured consumption 100% of the energy produced by the diesel-generator

c. The excess electrical energy produced by the diesel-generator will be used to charge the batteries up to a SOC1 = 95% and SOC2 = 95%

$$\begin{cases} P_{dg} = 80\% * P_{maxdg} \\ P_{nec} = P_{dg} - (P_{inc1} + P_{inc2}) \end{cases} \quad (22)$$

Operating mode 6

Green energy production $P_{eol} > 0$; $P_{fv} > 0$.

Determine:

a. One of the main generators in operation at a load regime of 75% - 80% of its maximum power P_{maxdg} for optimal value of specific fuel consumption (SFOC).

b. Consumption ensured from the mixed production of electricity, produced by diesel generators and renewable energy conversion systems

c. The excess electricity produced will be used to charge the batteries up to SOC1 = 95%, and SOC2 = 95%

$$\begin{cases} P_{dg} = 80\% * P_{maxdg} \\ P_{nec} = P_{dg} + P_{eol} + P_{fv} - (P_{inc1} + P_{inc2}) \end{cases} \quad (23)$$

The command-control section of the CCIB monitors the value of electrical energy consumption in the ship's electrical system, analyzes the capacity of the ENPP energy sources and the level of electrical energy stored in the accumulator batteries, and transmits commands and switches the electrical system created by interconnecting the NPP with the ENPP into one of the presented Operating Modes.

The operating modes were presented generically without going into details regarding the command, control, and switching of all ENPP and NPP components.

When the ship is operating for loading or unloading or in navigation maneuvers, the ENPP will operate alternating between mode 7 and mode 6 or 3, or 4, and the SOC level to which the batteries can be discharged will have an increased value of 50% and 30%, respectively compared to the normal regimes when the value is 40% and 20%. The SOC level of the battery groups to which they can be discharged will alternate periodically to balance the number of charge-discharge cycles of them[24].

The existing NPP on board will not undergo structural or functional changes. The only changes will be made to the power management system (PMS) software for communication with the ENPP.

5. DETERMINATION OF OPERATING MODE FOR PARAMETERS RECORDED

From the results of research carried out on board three chemical and oil tankers with a capacity of 50,000 dwt (years of construction 2019 and 2021, respectively), on different routes, we selected the results of calculations carried out on June 26, 2021. It is worth noting that on that date, low wind speeds were recorded, slightly above the turbine starting threshold, so we considered a zero-production power of the wind system P_{eol}= 0. The results are in Table 3.

Table 3

Level of electricity production

Time	P_{nec} (kWh)	P_{dg} (kWh)	P_{fv} (kWh)	SOC 1		SOC 2	
				(%)	(kWh)	(%)	(kWh)
01:00	350	900	0	86%	1030	20%	240
02:00	360	900	0	95%	1140	56%	670
03:00	355	825	0	95%	1140	95%	1140
04:00	350	0	0	66%	790	95%	1140
05:00	345	0	0	40%	480	92%	1105
06:00	380	0	0	40%	480	60%	725
07:00	370	0	3	40%	480	30%	358
08:00	380	0	118	28%	336	20%	240
09:00	420	0	394	26%	310	20%	240
10:00	470	0	709	46%	549	20%	240
11:00	440	0	988	91%	1097	20%	240
12:00	490	0	1202	95%	1140	76%	909
13:00	400	0	1338	95%	1140	95%	1140
14:00	470	0	1383	95%	1140	95%	1140
15:00	470	0	1326	95%	1140	95%	1140
16:00	430	0	1171	95%	1140	95%	1140
17:00	460	0	931	95%	1140	95%	1140
18:00	380	0	633	95%	1140	95%	1140
19:00	380	0	320	90%	1080	95%	1140
20:00	375	0	76	65%	781	95%	1140
21:00	370	0	0	40%	480	89%	1071
22:00	350	0	0	40%	480	60%	721
23:00	350	0	0	40%	480	31%	371
00:00	350	219	0	40%	480	20	240

We have considered a storage system with a maximum capacity of 2.4 MW (two battery groups, each with a storage capacity equal to the maximum power of a generator). Analyzing the consumption and production data in Table 2 and considering that at 00:01, the batteries are at a minimum accepted SOC of 40% one group, respectively 20% the other group.

Analyzing the data in Table 2, we will be able to see in which operating mode the ENPP, or better said, the entire ship's electrical energy production system, is in a certain time interval.

- Time interval 00:01 – 02:55 = operating mode 5
- Time interval 02:55 – 07:00 = operating mode 4
- Time interval 07:01 – 09:00 = operating mode 3
- Time interval 09:01 – 12:20 = operating mode 1
- Time interval 12:20 – 18:00 = operating mode 1
- The table shows the values of the production potential of the photovoltaic system; however, the production power P_{fv} will be limited to the consumption level, the batteries being already charged to the maximum established value (SOC=95%)
- Time interval 18:01 – 23:01 = operating mode 4
- Time interval 23:21 – 24:00 = operating mode 5

As can be seen, depending on the value of electricity production from renewable energy sources, the battery charge level, and the value of electricity consumption, the ecological naval power plant will automatically switch from one operating mode to another.

The situation presented is a general, somewhat ideal situation of photovoltaic system operation with few transitions from one operating mode to another. In daily operation, the dynamics can be much higher with frequent oscillations between operating modes 1, 2, and 3. A situation of this nature can occur following a short-term cloudiness that can determine the transition from operating mode 1 to operating mode 2.

6. ADVANTAGES OF IMPLEMENTING THE PROPOSED SOLUTION

The installation of ecological marine power plants ENPP on board maritime transport vessels brings with it a series of advantages, including:

a) Implementation of renewable energy sources and storage capacities in the electricity production system determines the reduction of fossil fuel consumption, both by reducing the operating time of diesel generators and by reducing their specific fuel oil consumption.

b) Stability in operation of the electrical system by maintaining a power reserve to compensate for short-term consumption peaks, a very common situation during maneuvers.

c) Operational safety by reducing or even eliminating the occurrence of a total blackout.

d) During full navigation, when electricity consumption is relatively constant, in addition to the significant reduction in fuel consumption, the number of operating hours of diesel generators is considerably reduced, which reduces engine wear and maintenance costs.

e) During the operation of the ship in ports for loading and unloading, a considerable part of the electrical energy consumed can be provided from renewable sources by ENPP.

f) Much higher reaction speed of ENPP components compared to that of diesel generators to load changes, and the existence of electrical energy storage capacities allows a single diesel generator to be used during ship maneuvers that operate with increased efficiency, compared to the current situation in which at least two diesel generators with a high specific consumption are used.

7. **CONCLUSIONS**

The ecological marine power plant is designed as an auxiliary element that can be installed on board maritime transport vessels without making structural or location changes to existing installations. The location of the renewable energy capture and conversion systems was designed without altering the deck or engine room installations and, importantly, without affecting the ship's stability.

Through the analysis presented, we were able to demonstrate that the idea of installing an ecological marine power plant on board maritime transport ships is viable. ENPP covers a large part of the consumption needs, or perhaps even entirely, from renewable energy sources. The analysis presented using data recorded on June 20, 2021, during a march in the Atlantic Ocean shows that on a clear summer day, the production of the photovoltaic system can provide 100% of the electricity needs. On June 20, 2021, the electricity consumption was 9.495 MWh, and the calculated production of the photovoltaic system was 10.590 MWh. A production potential that exceeds the consumption level by 1.095 MWh. From the calculations presented, it can be concluded that ensuring 100% consumption of "green" energy depends on the capacity of the storage systems. With a storage capacity of 2.4 MW at the ENPP level, we have an energy loss from the photovoltaic system of 3.941 MWh, as the storage system is charged to 95% SOC at 12:15 and the solar system production is limited to the consumption value. Therefore, a correct dimensioning of the storage capacity would create the possibility that, under favorable environmental conditions, the entire consumption of electricity from renewable sources can be ensured.

CREDIT AUTHORSHIP CONTRIBUTION

Conceptualization, M.P.; methodology, M.P. and GS; software, M.P.; validation, M.P. and G.S.; investigation, M.P.; resources, G.S.; data writing—original draft preparation, M.P.; writing—review and editing, M.P. and G.S. All authors have read and agreed to the published version of the manuscript.

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