Considerations on the Transformation of the Naval Electrical System of a Maritime Transport Ship into a Hybrid Naval Electrical System

Mircea PREDA and Gheorghe SAMOILESCU

***Abstract*—This article analyzes the viability of the solution of transforming the current electric power systems of maritime transport ships in operation, based exclusively on the use of fossil fuels as a basic source, into hybrid systems, by installing additional renewable energy conversion systems and an electricity storage system grouped into a new type of power plant, an ecological/green power plant. Starting from the technical data of the ship, we determined the size, type and configuration of the systems for generating electricity from renewable sources. Based on these, the structure of the green naval power plant was established as a component of the hybrid naval power system. The transformation of the classic naval power system into a hybrid naval power system entails the modification of the operating algorithms of the hybrid naval power system for managing the two component power plants in order to manage the available electrical power and prioritize the use of renewable energy sources.**

***Key words*—cyclonic flow, photovoltaic system, power plant, specific fuel oil consumption, wind system.**

I. 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 as well as the reduction of marine pollution by reducing the amount of waste water used in exhaust gas washing systems when using heavy fuel with a sulfur content greater than 0.5% and, last but not least, the reduction of costs per unit of cargo transported [1].

The transformation of the naval electrical system (NES) into a hybrid naval electrical system (NHS) is one of the countless solutions to reduce fossil fuel consumption, a solution applicable to new ships already in operation or to ships that will be built according to the same principles and designs as those recently put into operation. Taking into account the number of ships in operation and their potential operating life, any solution proposed by the current study is one to be considered. At a global level, there is a constant and consistent concern to find solutions to reduce fuel consumption. The majority of research projects on the use of renewable energy sources on board maritime ships are aimed at developing a new generation of ships, being at the concept stage for the production of zero-emission ships. On the other hand, these research directions are mainly focused on propulsion systems where the center of gravity of fuel consumption is actually located.

This study approaches research that is different from what is the dominant trend in current research through two aspects. The first aspect refers to the type of ships for which the solution is intended to be applied, and the second aspect is the naval system that is the object of the research, this system being the electrical one and not the propulsion one as in the case of the main research trend. In support of the statement made previously regarding the important research direction, we present some examples of research projects underway at different stages of execution and with different degrees of applicability. We start with the ship Planet Solar, a ship that in 2012 travelled around the world using only energy produced by solar panels [2]. From our point of view, this project has the great merit of demonstrating that it is possible for a ship to travel using only solar energy. On the other hand, this solution has too many limitations in order to achieve the same effect regarding cargo ships. Other projects still in the concept stage or during certain phases of model testing are: the NYK Super Eco Ship 2050 project [3] a project that involves the combined use of photovoltaic solar energy with wind energy by using soft retractable sails, Oceanbird [4] – a research program supported by the European Union using propulsion by rigid telescopic sails, the Germanischer Lloyd’s and DNV project [5] the concept of a 1000 TEU container ship powered by hydrogen fuel cells. The ship would be used in the North Sea and the Baltic Sea and the hydrogen supply would come from off-shore hydrogen production stations, ReVolt DNV research project for an autonomous battery-powered transport ship [6].

Another research direction was that of wind-assisted propulsion with various systems installed on board ships. Our

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research has a point in common with these studies because they are focused on improving the performance of ships currently in operation, however the difference is that as the name of the research topic says, it is focused only on propulsion systems.

Research into the application of the “Magnuson effect” for wind-assisted propulsion has resulted in the installation of Fletner rotors on several ships of different categories. The Fletner rotors have determined a reduction in fuel consumption, depending on the type of ship and the number of rotors, in percentages ranging from 1.8% on the Viking Grace ferry equipped with one rotor, to peaks of 40% on the E-Ship 1, a ship specially built for such propulsion equipped with four rotors [7].

II. The Naval Electric Power System

The NES includes all electricity sources, electricity converters, switchboards, electrical networks and electricity consumers brought together in the process of electricity generation, transport, distribution, and consumption on board the ship [8].

A. *NES Classification*:

In the specialized literature, the most common classification shows that naval electrical systems can be [9]:

a) Autonomous
b) With energy recovery from propulsion installations
c) Joined with propulsion installations

a) Autonomous NES [9] – These are electricity generation 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 engines, forming a group called Diesel-generator. In turn, autonomous NES can have different configurations: NES with one or more main naval power plants (MNPP) or with a MNPP and an emergency power plant (EPP)

b) NES with energy recovery or transfer from propulsion installations [9] – These are systems that include electrical power generation units whose mechanical energy comes from the propulsion system.
   - Turbo-generators (generators driven by steam turbines) use the energy recovered by the exhaust gas boiler from the exhaust gases of the combustion engine of the propulsion system
   - Shaft generators use part of the energy of the propulsion system to drive an electric generator coupled to the propeller shaft.

c) NES combined with propulsion systems [9] – Where the ship is propelled using electric motors regardless of the design, axial line, POD system, AZIPOD system, or any other design, it is recommended that the NES be combined with the propulsion system. The ship's power plant(s) simultaneously provide electricity for the ship's propulsion and for other consumers.

Oil/chemical product carriers and bulk cargo carriers of the current generation of ships have an autonomous NES

B. *Components of the Autonomous Naval Electrical System*

The NES of a 50.000-dwt oil/chemical tanker ship (ships that were the subject of the research) is composed of the following elements:

a) Main naval power plant (MNPP) – represents the set of main sources of electricity together with the main switch board (MSB).
   - MSB performs the synchronization and parallel connection of the main energy sources as well as their connection to the distribution network.
   - Energy sources (ES) – the sources of electricity on the ship, alternating current generators driven by four-stroke diesel engines that operate on heavy liquid fuel (fuel oil) or light fuel (diesel/similar) are used. The MNPP of the analyzed ship is composed of three diesel-generators (DG). The power of the generators is established when designing the ship by various calculation methods, the most common being the method of the ship's energy balance calculated for different operating modes. [8]. Another category of electricity sources is represented by batteries for communication equipment and batteries for general use.

b) Emergency naval power plant (EPP) – represents the assembly formed by the emergency generator and the emergency switch board (EBD). The emergency transformer is connected to the emergency distribution board.

c) The ship's electrical network – represents the assembly of electricity transmission lines on board the ship and the distribution boards (DB). DBs are nodal devices/equipment components of the electricity distribution network interconnected by means of power transmission lines, intended for the distribution of electricity in the network sections and the connection of consumers.

d) Static converters – Equipment used for the conversion of electricity parameters. Voltage-raising transformers or voltage-lowering transformers, rectifiers, inverters and frequency converters.

The elements and structure of the naval electrical system are presented in Fig. 1.

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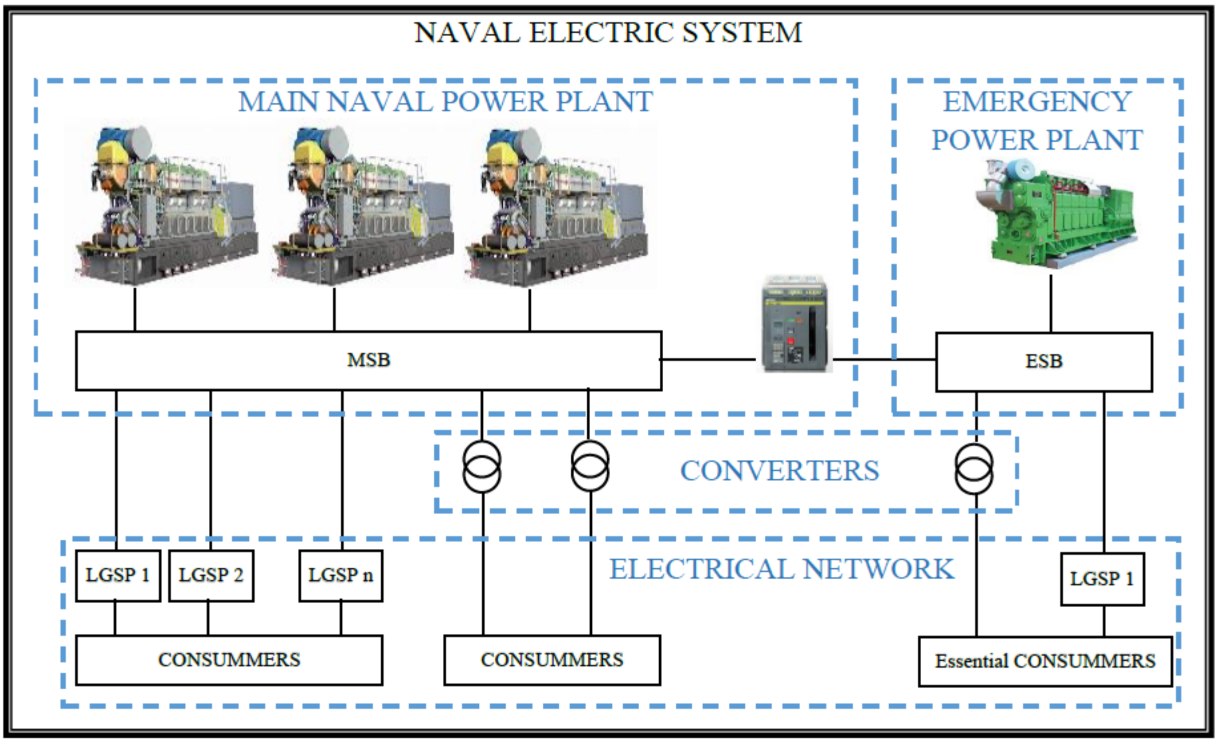

Figure 1. The elements and structure of the naval electrical system

C. Operation of the Autonomous Naval Electrical System

In normal sailing or anchoring mode of the ship, the entire electrical system of the ship is powered by a single generator, its power being more than sufficient for such situations. In navigation maneuvering mode for the safety of the ship and when the ship is in loading or unloading operation, two or even all three main generators operate in parallel.

In the event of a power supply interruption from the MNPP (black-out), the entry into operation of the EPP with power from the Emcy D/G is made with a delay of forty seconds. Thirty seconds from the moment of power interruption and the moment of starting the Emcy D/G engine, the time required to carry out the sequences of restoring the power supply of the NES from the main generators, and the other ten seconds are for stabilizing the parameters of the combustion engine before connecting the generator to the load

$t_0 = time\ of\ black - out$

$$\Delta t_1 = t_0 + t_{p1} + t_{c1} \quad (1)$$

where:

Δt_1 *is the connection time of the first standby stsrt generator*

$t_{p1} = 10\,\text{sec} - start - up\ and\ stabilization\ time\ of\ idle\ speed$

$t_{c1} = 5\,\text{sec} - stabilization\ time\ of\ electrical\ parameters\ and\ connection\ of\ ACB$

$$\Delta t_1 = 0 + 10 + 5 \quad (2)$$

$\Delta t_1 = 15\ \text{s}$

If the first diesel-generator has not restored the power supply, the automatic start-up sequence will continue with the second generator in standby.

$$\Delta t_2 = \Delta t_1 + t_{p2} + t_{c2} \quad (3)$$

where:

Δt_2 *is the connection time of the second generator in standby*

$t_{p2} = 10\,\text{sec} - start - up\ and\ stabilization\ time\ of\ idle\ speed$

$t_{c2} = 5\,\text{sec} - stabilization\ time\ of\ electrical\ parameters\ and\ connection\ of\ the\ ACB$

$$\Delta t_2 = 0 + 10 + 5 \quad (4)$$

$\Delta t_2 = 15\ \text{s}$

If the second diesel generator has not restored the power supply, the automatic start sequence within the main power plant will be exhausted and the emergency generator will be expected to start

$$\Delta t_{cu} = \Delta t_p + t_{cu} \quad (5)$$

where:

Δt_{cu} *is the connection time of the emergency generator*

$\Delta t_p = 30\,\text{sec} - initiation\ time\ of\ the\ emergency\ D\ /\ G\ engine$

$t_{cu} = 10\,\text{sec} - stabilization\ time\ of\ the\ engine\ speed\ and\ electrical\ parameters\ and\ ACB\ connection$

$$\Delta t_{cu} = 30 + 10 \quad (6)$$

$\Delta t_{cu} = 40$

III. Hybrid Naval Electric Power System

The transformation of the current NES into a hybrid system is achieved by installing additional systems and equipment designed to generate electricity from renewable sources, store the energy that exceeds the current consumption and achieve efficient management of the available electricity. This equipment and the conversion, storage and command-control systems are grouped together and form a third power plant on board the ship that we will call the green naval power plant (GNPP), which means that the new electro energetic system will have three power plants in its structure, as in Fig. 2:

Main power plant
Emergency power plant
Ecological power plant

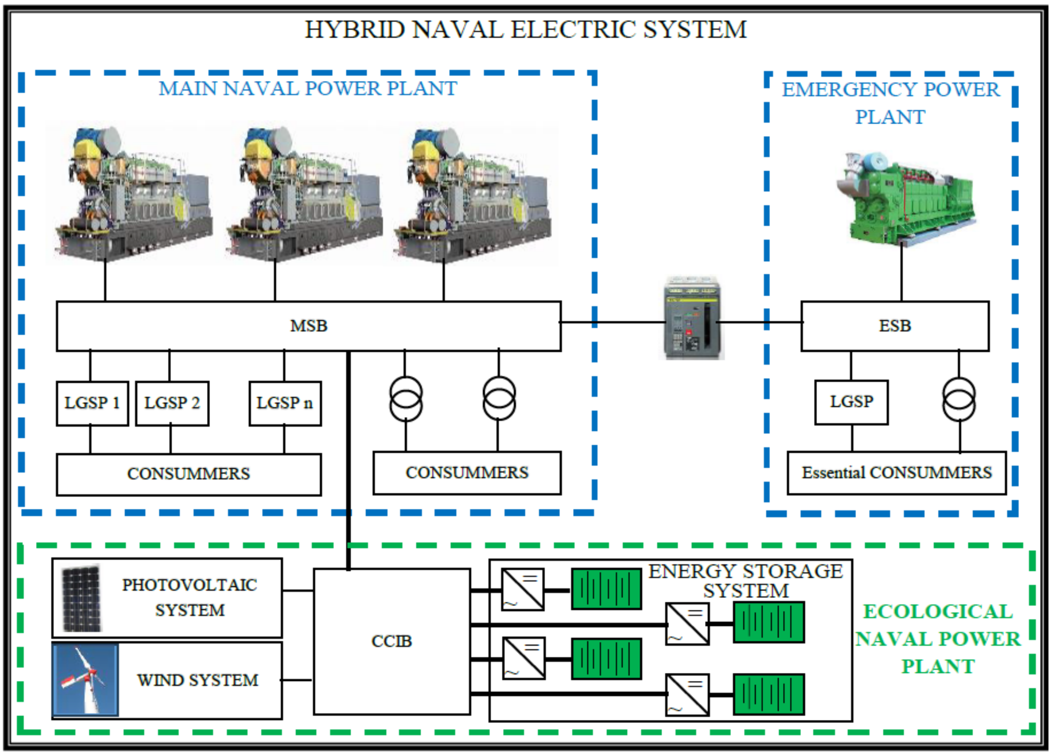

Figure 2. The elements and structure of the hybrid naval electrical system

A. *Green naval power plant*

The structure of the green naval power plant is determined by its functions within the HNES. The fact that the installation site of this plant is a maritime transport vessel imposes a series of limitations that must be taken into account and certain conditions that must be met.

Limitations:

- The ship is a means of transport of certain dimensions, which determines that the spaces available for the installation of new equipment are limited
- New installations must fit within the dimensions of the ship
- Renewable energy capture systems are sized according to the available spaces and not the energy requirement.
- The location of the systems must not affect visibility

Conditions:

- The location of the equipment must be established without affecting the stability of the ship
- The location of the new systems must not affect the operating flow of the ship
- The safety conditions on board the ship must not be affected
- The equipment in the composition of the power plant must meet specific corrosion resistance requirements

The limitations and conditions listed, corroborated with the fact that renewable energy sources do not have a constant level, with large variations from day to night, from one day to the next, from one region to another, require the creation of a renewable energy conversion system that integrates photovoltaic, wind, electricity storage equipment and equipment for interconnection, command and control of the systems.

Under the stated conditions, the NEPP will have the following structure:

1. photovoltaic system
2. wind system
3. electricity storage system
4. control and interconnection panel

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 [10, 11]:

1. Increased resistance to corrosion caused by increased humidity and salinity;
2. High degree of protection corresponding to the type of ship and the characteristics of the cargo transported;
3. Increased mechanical resistance to mitigate the effects of wind and water from breaking waves.

The requirements set out in points 1 and 2 are of a constructive nature and are met during the procurement process. The mechanical resistance requirements are taken into account and achieved from the design phase of the system of the panels on board ships.

The danger of mechanical overloads is determined by the appearance of significant amounts of water on the main deck of the ship following the breaking of waves against the ship's hull. In order to meet the requirement for 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 dimensions and configuration of the main deck of a 50.000 dwt tanker allowed the identification of available spaces for the installation of photovoltaic panels with a total area of 3,450 square meters. In order to meet the installation conditions, set out earlier, the installation of a photovoltaic field with an area (Ss) of 3,000 square meters was taken into account.

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The National Renewable Energy Laboratory of the United States of America, through its annual report published in 2024, shows the progress made in the development of high-efficiency photovoltaic cells. Analyzing the progress graph, it can be seen that since 2018, monocrystalline silicon cells have recorded an efficiency of 26.1% and [12]. Depending on the manufacturer, the declared efficiency for photovoltaic panels with monocrystalline cells is between 22% and 24%.

The average value of solar energy reaching a flat collector is considered to be at a level of 1000 Wh/m^2 [13].

Knowing the average level of solar radiation, the total surface area of the photovoltaic panels and considering that they have an efficiency of 20%, we can find out the average electricity generation capacity of the photovoltaic system that can be installed on board the ship.

Capacity:

$$C_s = S_s * AL_s * \eta_c \quad (7)$$

$$C_s = 3000\ m^2 * 1000\ Wh/m^2 * \frac{20}{100} \quad (8)$$

$$C_s = 600000\ Wh \quad (9)$$

Power:

$$P_s = 600\ kW \quad (10)$$

The daily electricity production potential of the photovoltaic system (Pot_{sfv}).

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

2) Wind system

To configure the wind energy conversion system that can be installed on board a shipping vessel with a displacement of 50.000 dwt, several types of wind turbines were studied. Both vertical axis wind turbines and horizontal axis wind turbines were taken into account, each with its advantages and disadvantages. I had the pleasant surprise of discovering the patent application filed by Adriano Pelegri for a wind turbine with cyclonic flow and wind collector. Leaving aside the fact that it promises a power coefficient close to the Betz limit, its operating principle, namely the fact that this turbine changes the direction of the flow lines of moving air masses from the horizontal plane to the vertical plane [14], schematized in Fig. 3, made us consider that this type of wind turbine is the most suitable for configuring a wind system.

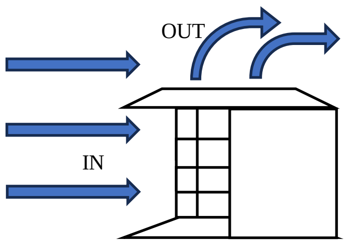

Figure 3. Changing the direction of the flow lines of air masses in the wind turbine

Starting on the one hand from the constructive dimensions of the ship and the fact that the wind energy conversion system will work together with a photovoltaic system, and on the other hand having the desire to use the capabilities of the wind system to the fullest, we were able to establish its configuration. The wind turbine with cyclonic flow and wind collector, chosen for the construction of the wind system, is a vertical axis wind turbine (VAWT) which, by changing the direction of the flow lines of air masses, practically operates on the principle of horizontal axis wind turbines (HAWT). In order to use the effect of this special trait of the wind turbine, we came to the conclusion that the wind system will consist of 12 (twelve) wind turbines arranged in three rows, the lower row being shifted towards the bow by a distance equal to 3 R from the upper row, the latter being arranged near the castle wall, Fig. 4.

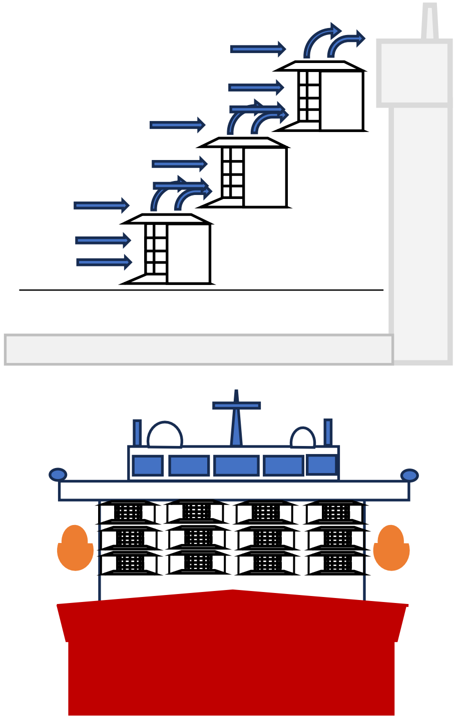

Figure 4. Wind system layout

Based on the dimensions of the hull of a 50.000-dwt tanker, the space allocated to a turbine has a width of L = 6 m and a height of H = 3.5 m [16].

For the installation of vertical axis cyclone turbines and wind collectors, it is necessary that 10% of the space allocated to the turbine be left free for their spacing. Following the turbine sizing calculations [14], these values result:

$$R = 1.35\ m \text{ and } D = 0.7\ m \quad (11)$$

$$Total\ turbine\ diameter = 5.4\ m \quad (12)$$

$$Stator\ height = 4D = 2.8\ m \quad (13)$$

The maximum available power of a turbine at a wind speed of v = 10 m/s

Denoting with v_e the wind speed and with $\rho = 1.25 \frac{kg}{m^3}$ the air density, the total available power P_e^{max} is expressed by the (14):

$$P_e^{max} = \frac{1}{2}\rho A_e v^3 = 4(\sqrt{6}+\sqrt{2})\rho D^2 v_e^3 \quad (14)$$

We introduce the data D = 0.7 m and v = 10 m/s in (2) and the maximum available power results:

$$P_e^{max} = 4(\sqrt{6}+\sqrt{2}) \cdot 1.25 \cdot 0.7^2 \cdot 10^3 = 9466\ W \quad (14)$$

The power coefficient declared by A. Pelegri determined following CFD simulation for wind speed $v = 8\ m/s$ is $C_p = 0.54$ [15]

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To calculate the power at different wind values we will take into account a decreasing power coefficient $\boldsymbol{C_p = 0.53}$

$$P_{tnv} = P_e^{max} * C_p \quad (15)$$

$$P_{tvn} = 9466\,W * 0.53 = 5016.98\,W \quad (16)$$

TABLE I. WIND SYSTEM POWER DEPENDING ON WIND SPEED

Wind speed	m/s	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of turbine	pc.	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Turbine power	kW	5.17	6.68	8.67	11	13.8	16.9	20.5	24.6	29.3	34.4	40.1	46.5	53.4	61	69.4	78.4
Total power	kW	60.2	80.1	104	132	165	203	247	296	351	413	482	558	641	733	832	941

As for the special requirements that must be met by wind turbines installed on board, they are similar to those applicable to wind turbines installed in offshore wind farms [17].

3) *Electricity storage equipment (batteries)*

For the optimal operation of the NEPP, it is necessary to have an electricity storage component in its composition [18], [19]. It is necessary to install at least two battery groups, with a minimum capacity equal to double to the maximum nominal power of a main generator.

The dimensioning of the battery capacity is carried out according to the daily consumption requirement and energy autonomy.

The current situation is a little different. In addition to the photovoltaic system as energy sources, we have the wind system and the ship's main generators. At the same time, the required consumption on the basis of which the storage system capacity is determined is analyzed under several aspects, depending on the ship's operating modes.

Capacity calculation based on the normal operating time of the ship in cruising mode, without production from renewable sources

$$T_{op} = \frac{C_{ss}}{P_{avr}} \quad (17)$$

$$C_{ss} = T_{op} * P_{avr} \quad (18)$$

where: T_{op} – operating time with power from the storage system (batteries); C_{ss} – storage system capacity; P_{avr} – average power that must be provided to cover consumption.

The basic functions of battery groups are the following:

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

- Storage of excess electricity produced by the main diesel generators during operation at a load regime appropriate to optimize specific fuel consumption [20].
- Ensuring the necessary power reserve during the start-up sequence of high-power electrical consumers
- Avoiding black-outs by ensuring the supply of electricity to all consumers during the time when the sources of electricity generation are unavailable.
- Ensuring the necessary electricity consumption during the temporary decrease in production from renewable energy conversion systems due to short-term cloudiness or low wind speeds
- Compensates for short-term consumption peaks in order to maintain electricity parameters during the operation of diesel generators and avoids automatic preferential disconnections of some consumers.

4) *Command-control and interconnection panel*

The command-control and interconnection panel (CCIP) represents a central and very important part in the NEPP structure, having the role of ensuring the following functions:

- Connecting and synchronizing the green sources of electricity within the NEPP and the storage system;
- Managing the consumption of electricity from renewable sources by commanding, controlling and switching the energy sources within the NEPP;
- Prioritizing the usage of electricity produced from renewable sources while ensuring the power reserve;
- Interconnecting and synchronizing with the Main Power Plant (MNPP) of the ship. The parameters of the electric current from the green power plant will be monitored and permanently synchronized with the parameters of the electric current from the main power plant. When consumption is covered entirely from renewable energy sources and the main generators are stopped, the parameters of the used electricity are maintained within the parameters imposed by the power management module (PMM) from the CCIP structure.
- The green electricity parameters will be those that follow the electricity parameters in the MNPP due to the much higher reaction speed of the static electronic components of the NEPP compared to the reaction speed of the mechanical systems (diesel engine) in the MNPP. However, there is an exception to this rule, which is applied at the end of the sequence in which consumption was fully provided from renewable sources, when the NEPP sends the power demand signal to the MNPP. After starting the generator located first in the start sequence, its synchronization and connection will be done by running the classic synchronization process performed by the PM3 power management system in the MSB.

IV. OPERATION OF THE HYBRID NAVAL POWER SYSTEM

By integrating renewable energy sources into the NES and transforming it into the HNES, the aim is to ensure that the electricity consumption is provided from renewable energy sources as much as possible. Depending on the navigation region and weather conditions, the level of renewable energy sources varies significantly during a voyage. It is possible to go from very high solar radiation conditions, approximately 2.5 times higher than the average annual solar radiation level, a level recorded in the summer in the tropics, to values located somewhere just above half of the average value [13]. The same

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is true for wind speed. From high-speed wind, favorable for wind energy production, to areas with wind speeds equal to or even below the starting limit of the wind turbine. These large variations in the level of renewable energy sources impose on the one hand the structure of the HNES presented and determine its operation under different regimes depending on the momentary potential of each energy source and the level of electrical power available in the storage system.

When the level of electricity production from renewable sources summed with the level available in the storage system is sufficient to ensure current consumption and power reserve, the NEPP will manage the process of production and consumption of electricity on board the ship.

The MNPP and the NEPP will be interconnected for the transfer of electricity on the power circuit as well as on low-current circuits for the transfer of data necessary for the development of the power management process in the ship's electrical system.

The operating principle of the NES is to cover the consumption of electricity. The production level is dictated by the consumption level. The power produced is equal to the power consumed

$$P_{pr} = P_c \tag{19}$$

The operating principle of the HNES is completely different. If the operation of NES is only related to ensuring electricity consumption, HNES will have a complex operating regime. Starting from the same the required electrical power in the system P_{nec} but this time with the possibility of providing it from different sources. The operating regime of HNES will be determined by the value and structure of the available power P_{dis}. In addition to ensuring the current consumption of electricity, the main objective is to prioritize the consumption of electricity produced from renewable sources and maximize the potential of renewable energy sources. The available power in HNES represents the sum of the powers in the production systems and the usable power in the storage system.

$$P_{dis} = P_{dg} + P_{eol} + P_{fv} + P_{ub} \tag{20}$$

where: P_{dg} - diesel-generator power; P_{eol} - wind system power; P_{fv} - photovoltaic system power; P_{ub}- usable power from the storage system.

The usable power from the storage system P_{ub} represents the difference between the total power available in the rechargeable batteries P_{tb} and the power required for emergency operation P_{av}, when all the main electricity production systems are inoperative

$$P_{ub} = P_{tb} - P_{av} \tag{21}$$

The total power of the batteries represents 98% of their maximum nominal capacity. For a good and long-lasting state of health (SOH) of the batteries [21], their charging will be limited to a *SOC* = 98% and discharging to a *SOC* = 5%. For this HNES, a storage system with two battery groups is chosen, each with a maximum capacity of 2.4 MW

$$P_{tb} = \frac{P_{maxb} * 98}{100} \tag{22}$$

$$P_{tb} = \frac{2400 * 98}{100} = 2352\ kW \tag{23}$$

Considering a two-hour interval as sufficient time to remedy the deficiencies that cause a temporary inoperability of the main diesel generators, we will be able to determine the value of the power required to cover the ship's consumption for this interval. Based on the hourly consumption recorded in the 24-time intervals of a day, we determine the average value of the hourly consumption that will form the basis for the calculation of P_{av} for ships built in 2019 or by dividing by 24 the daily consumption recorded in the system of ships built in 2021

$$C_{mo} = \frac{\sum_1^{24} C_o}{24} \quad \text{or} \tag{24}$$

$$C_{mo} = \frac{C_z}{24} \tag{25}$$

$$P_{av} = C_{mo} * 2 \tag{26}$$

Knowing the P_{av} value, the minimum *SOC* to which one of the battery groups can be discharged is determined in order to preserve this power reserve and not reach below 5%, the safe battery discharge limit

$$SOC_{av} = \frac{P_{av}}{Q_{gb}} * 100 + 5 \tag{27}$$

Research conducted on the four ships revealed an average hourly consumption during the journey between 300 kWh and 395 kWh, depending on the navigation area, for the two ships built in 2019 and an average hourly consumption between 450 kWh and 580 kWh for the ships built in 2021.

For the analysis of the operation of HNES, data collected from ships built in 2019 will be used. The average value of the hourly consumption that will be introduced into the calculations will be the maximum recorded value, 395 kWh. With this value, (26) becomes:

$$P_{av} = 395\ kW * 2 = 790\ kW \tag{28}$$

and (27) will have the following result:

$$SOC_{av} = \frac{790}{2400} * 100 + 5 \tag{29}$$

$$SOC_{av} = 38\% \tag{30}$$

Table II shows the solar radiation level values for 04.08.2025. Table III shows the wind speed values for the same date, and Table IV shows the consumption data and potential production data resulting from using the renewable energy level values from 04.08.2025 when the ship was underway in the Madagascar Island area.

TABEL II. SOLAR RADIATION LEVEL VALUES FOR 04. AUG. 2025

Time slot	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Solar radiation level	0	0	0	0	0	0	0	81.24	550.28	1108.2	15.91.97	1945.42
Time slot	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
Solar radiation level	2136.41	2155.81	2002.47	1683.9	1223.43	667.82	137.2	0	0	0	0	0

TABEL III. WIND SPEED VALUES FOR 04. AUG. 2025

Time slot	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
Wind speed	5.5	5.02	3.5	5.04	7.31	8.53	9.1	10.2	10.2	8.91	11.8	13.8
Time slot	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
Wind speed	14.6	15.3	16.3	17.5	18	17.4	17.9	17.9	17.8	17.9	17.4	17.4

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TABEL IV. POTENTIAL PRODUCTION

Hour	01.00	02.00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Cav	350	360	355	350	345	380	370	380	420	470	440	490
PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.75	330.17	664.90	955.20	1167.25
Wind	10.02	10.57	0	9.48	24.40	38.29	46.88	63.89	65.79	45.37	101.45	161.69
D/G	0	0	0	0	0	0	0	0	0	0	0	0
Dif	-339.98	-349.43	-353.21	-340.52	-320.60	-341.71	-323.12	-267.36	-24.04	240.27	616.65	838.94
SOC 1	98	98	98	98	98	98	92.31	81.17	80.17	90.18	98	98
Pb1	2352	2352	2352	2352	2352	2352	2215	1948	1924	2164	2352	2352
SOC 2	83.83	69.27	54.56	40.37	27.01	12.77	5.00	5.00	5.00	5.00	22.87	57.83
Pb2	2012.02	1662.59	1309.38	968.86	648.26	306.55	120.00	120.00	120.00	120.00	548.95	1387.89
Hour	13:00	14:00	15:00	16:00	17:00	18:00	19.00	20:00	21:00	22:00	23:00	24:00
Cav	400	470	470	430	460	380	380	375	370	350	350	350
PV	1282	1293.5	1201.5	1010	734	401	82	0	0	0	0	0
Wind	187.37	215.63	265.56	322.66	357	322.66	351.12	351.12	345.3	345.3	322.22	322.66
D/G	0	0	0	0	0	0	0	0	0	0	0	0
Dif	1069.37	1039.13	997.06	902.66	631	343.66	53.12	-23.88	-24.7	-4.7	-27.78	-27.34
SOC 1	98	98	98	98	98	98	98	98	98	98	98	98
Pb1	2352	2352	2352	2352	2352	2352	2352	2352	2352	2352	2352	2352
SOC 2	98	98	98	98	98	98	98	97.005	95.9758	95.78	94.6225	93.4833
Pb2	2352	2352	2352	2352	2352	2352	2352	2328.12	2303.42	2298.72	2270.94	2243.60

From the study of the resulting values presented in Table III, we can observe that on that day the electricity consumption was covered entirely from renewable sources. This was under the conditions of a normal day of sailing with normal ship maintenance activities. At the same time, from Table I it can be deduced that it was a clear day with a good level of solar radiation and from Table II we see that the wind had directions and speeds that allowed the recording of an average and above average production potential from wind sources starting with 11 am, and even between 7:00 pm and 11:59 pm the wind production system ensured over 90% of the ship's electricity consumption. It is easy to understand that this situation is not encountered permanently. There are numerous moments when the speed and/or direction of the wind are not favorable to generation or the level of solar radiation is low due to the overcast sky. These variations determine changes in the operating mode of the HNES with transitions from one generation system to another and covering the consumption from different sources. Depending on the nature of the available power, we distinguish several operating modes. These will be determined by analyzing the data in Table IV.

Time interval 00:00 - 02:00 Green energy production is very low, almost zero $P_{eol} > 0$; $P_{fv} = 0$. Battery state of charge (*SOC*) [22] for group no. 1 SOC_1 = 98%, for group no. 2 SOC_2 = 98%. The battery state of charge allows covering consumption from the batteries. Consumption is covered by group 2 of batteries with a contribution of less than 3% of wind energy. The respective operating mode is called MOD 1 and is characterized by:

MOD 1:

$$P_c > P_{eol} + P_{fv} \quad (31)$$

$$P_c < P_{ub} \quad (32)$$

a. Consumption covered one part (2.5%) from green energy and the other part (97.5%) from batteries
b. Main generators off $P_{dg} = 0$

Time interval 02:00 - 03:00 Green energy production is zero P_{eol} = 0; P_{fv} = 0. Battery state of charge (*SOC*) [22] for group no. 1 SOC_1 = 98%, for group no. 2 SOC_2 = 69.27%. Battery state of charge allows consumption coverage from batteries. Consumption is covered from group 2 of batteries. This operating mode is called MOD 2 and is characterized by:

MOD 2:

$$P_c > P_{eol} + P_{fv} \quad (33)$$

$$P_c < P_{ub} \quad (34)$$

a. Consumption fully covered (100%) from batteries
b. Main generators stopped $P_{dg} = 0$

Time interval 03:00 - 09:00 Green energy production is low, but increasing $P_{eol} \geq 0$; $P_{fv} \geq 0$. Battery state of charge (*SOC*) for group no. 1 SOC_1 = 98%, for group no. 2 SOC_2 =54.56%. Battery state of charge allows coverage of consumption from batteries. Consumption is covered from group 2 of batteries until 06:20 when this group reaches minimum *SOC* level (5%) and consumption from group 1 begins, down to a *SOC* level of 80.17%. Consumption is covered jointly from batteries with a contribution for the entire interval between 9% - 94% of green energy production. The operating mode is MOD 1

Time interval 09:00 - 13:00 Green energy production is very good, $P_{eol} > 0$; $P_{fv} \gg 0$. Charging of battery groups begins. The state of charge of batteries in group 1 goes from SOC_1 = 80.17% to a *SOC*1 = 98% at 10:25, and for group no. 2 from SOC_2 = 5% at 10:25 to a SOC_2 = 98% at 13:00. Consumption is fully ensured from the production of wind and photovoltaic systems. The electricity excess is stored in the batteries. The respective operating mode is called MOD 3 and is characterized by:

MOD 3:

$$P_c < P_{eol} + P_{fv} \quad (35)$$

$$P_c + P_{inc} = P_{eol} + P_{fv} \quad (36)$$

a. Consumption fully covered by green energy
b. Surplus green energy is stored in batteries
c. Main generators stopped $P_{dg} = 0$

Time interval 13:00 - 19:00 Green energy production is very good, $P_{eol} > 0$; $P_{fv} \gg 0$. The state of charge of the batteries is at maximum level, SOC_1 = 98%, SOC_2 = 98%. Consumption is fully covered by the production of the wind and photovoltaic systems. The production of electricity of the wind system is stopped by braking the turbines and the production of the photovoltaic system is limited to the value of consumption. The respective operating mode is called MOD 4 and is characterized by:

$$P_{eol} = 0 \quad (37)$$

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$$P_c = P_{fv} \quad (38)$$

a. Consumption fully covered by green photovoltaic energy
b. Main generators stopped $P_{dg} = 0$

Time interval 19:00 - 23:59 – HNES operates in MODE 1

In addition to the four operating modes identified and presented in which only NEPP is in operation, other operating modes can be distinguished that involve the joint operation of the two power plants, MNPP and NEPP.

When the NES operates in MODE 1 and the *SOC* level of the battery groups approaches the lower limit set for them, the CCIP of the NEPP will transmit a power request signal to the MNPP. The PMS of the MNPP initiates the synchronization start-up sequence and connection of the generator chosen to be the first in standby. After connecting the generator, the two plants will work in parallel. The respective working mode is MOD 5 and is characterized by:

$$P_{eol} \geq 0\ ;\ P_{fv} \geq 0 \quad (39)$$

$$SOC_1 = 38\%,\ SOC_2 = 5\% \quad (40)$$

One of the main generators in operation is at a load regime of 75% of its maximum power P_{maxdg} for optimal value of specific fuel consumption (SFOC) expressed in g/kWh [20].

Consumption is covered by electricity produced from renewable energy sources and electricity produced by the diesel-generator.

The excess electricity produced by the diesel-generator will be used to charge the batteries up to SOC_1 = 98% and SOC_2 = 98%

$$\begin{cases} P_{dg} = 80\% * P_{maxdg} \\ P_{nec} = P_{dg} + P_{fv} + P_{eol} - (P_{inc1} + P_{inc2}) \end{cases} \quad (41)$$

Due to the total lack of green energy production, the MOD 5 working mode will become the MOD 6 working mode characterized by:

MOD 6:

$$P_{eol} = 0\ ;\ P_{fv} = 0 \quad (42)$$

$$SOC_1 = 38\%,\ SOC_2 = 5\% \quad (43)$$

a. One of the main generators is in operation at a load regime of 75% of its maximum power P_{maxdg} for an optimal value of its specific fuel consumption (SFOC).
b. Consumption is covered entirely by electricity from the diesel generator
c. The excess electricity produced by the diesel generator will be used to charge the batteries up to *SOC*1 = 98% and *SOC*2 = 98%

$$\begin{cases} P_{dg} = 80\% * P_{maxdg} \\ P_{nec} = P_{dg} - (P_{inc1} + P_{inc2}) \end{cases} \quad (44)$$

The seventh mode is a completely exceptional one in the case of HNES when NEPP and MNPP are unable to produce electricity and both battery groups are at minimum *SOC*. MODE 7 is characterized by the following relationships:

MOD 7:

$$P_{eol} = 0\ ;\ P_{fv} = 0 \quad (45)$$

$$SOC_1 = 5\%,\ SOC_2 = 5\% \quad (46)$$

$$P_{gen} = 0 \quad (47)$$

Black out

Emergency generator starts and is connected, powering essential consumers.

V. Management Of Electricity Production and Consumption in the HNES

A. Electricity Management in the Nes

In the current NES of the ship, the management of electricity production and consumption is carried out by the PMS (Power Management System), a system consisting of the three programmable logic controllers (PLC) of the three interconnected generators. The information necessary for the operation of the system is collected from generators and high-power consumers and is applied to the terminals of digital or analog inputs depending on their nature. The information is processed, and through the programmable outputs the commands are transmitted to the execution elements of the generators or consumers.

B. Classic Electricity Management in the HNES

The command-control section of the CCIP can operate according to the same principle using PLC and a similar power management system. The CCIP has to manage the NEPP elements and consumption coverage, and for this the data that normally reaches the MNPP PMS is replicated to the CCIP PMS. During the parallel operation of the MNPP and the NEPP, the management of the electric power will be carried out by the CCIP PMS.

C. Electricity Management in the HNES Using Artificial Intelligence.

The best option for implementing HNES management is to implement artificial intelligence in the HNES management process. A power management system equipped with artificial intelligence that must manage electricity and prioritize the consumption of electricity produced from renewable sources will have capabilities for interpreting and processing data received from the HNES and the navigation equipment, records from databases with the level of solar radiation recorded in previous years at points on the travel route, data received through weather forecasts and many other data that can form an information architecture useful for the process of managing electricity production and consumption. Interpreting weather data in conjunction with information from databases and the characteristics of renewable energy conversion systems can provide reports with the production potential and the degree of consumption coverage based on production from renewable sources. The use of artificial intelligence for achieving electrical power management offers efficient solutions with minimal human effort. It provides potential reports and can provide suggestions for using electricity. By using artificial intelligence, the HNES will adapt and respond very quickly to rapid fluctuations that may occur in the current level of renewable energy sources, being very flexible and at the same time safe in operation.

VI. Conclusions

The presented proposal for the transformation of the naval electrical power system into a hybrid naval electrical power system envisaged the implementation of this process without making any changes to the existing installations through

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structural or positioning changes. The placement on the deck or in the engine room of the systems intended to transform a NES into a HNES is done in the spaces identified as available and without affecting the stability of the ship.

The results of the calculations carried out based on the collected data demonstrate that the solution for transforming a NES into a HNES is a viable one. The production of electricity from renewable energy sources can partially or completely cover the ship's consumption needs. The analysis carried out by interpreting the data recorded on August 04, 2025 during a journey in the Pacific Ocean shows how the production of the photovoltaic system combines and complements the production of electricity from the wind system. The analysis was made taking into account the upper limit of the average hourly consumption of one of the ships built in 2019 to establish the minimum emergency charge state of a battery group and the data recorded on that day to calculate the total electricity consumption for the 24 hours. The consumption was 9495 kWh (C_{mo} = 395 kWh) and the production potential had a calculated level of 13458.5 kWh. far exceeding the level of consumption.

For ships built in 2021 that have an average hourly consumption of 580 kWh, the resulting daily consumption of 13920 kWh exceeds the production potential of the green systems by 461.5 kWh. This difference in consumption must be covered from the electricity produced by the diesel-generator which will have to operate for approximately 35 minutes. The fuel consumption used for electricity production in the case of the HNES is reduced by 100% for ships built in 2019 and by 97.1% for ships built in 2021.

The advantages of transforming the NES into a HNES consist in reducing the fuel consumption necessary for electricity generation by significant percentages, sometimes even by 100%, with beneficial environmental effects. Considering the percentage represented by the fuel consumption of diesel generators in total fuel consumption, transforming NES into HNES would represent a very important step in achieving the 2030 objective of reducing carbon emissions in the naval sector.

The significant reduction in the operating time of diesel generators determines a reduction in their wear and tear and, implicitly, a significant reduction in expenses related to the maintenance process.

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