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OPTIMIZATION OF THE LOCAL MARINE ENERGY SYSTEM WITH DIESEL-GENERATORS

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Abstract. Maritime shipping sources 3% of global greenhouse gas emissions and heavily depends on fossil fuels. Decarbonizing this sector requires a joint approach involving the global shipping industry, governments, and international organizations. A diesel generator is the main source of electricity for marine installations. The cost of electricity in local systems for maritime shipping and sea floating platforms equipped with diesel generators depends primarily on the cost of primary fuel for diesel generators. An algorithm for the optimal redistribution of generators operating in parallel with different rated power and consumption curves of specific fuel consumption B from power P was developed. It was suggested to specify fuel consumption taking into account a non-linear curve and divided into several subintervals. An algorithm for optimizing the operation of two generators are presents. A program in the Matlab programming language was developed based on it. The specific fuel consumption for the considered local system was 0,2-1,63% when using the optimal distribution algorithm relative to the uniform power distribution. The developed algorithm can be used for the following purposes: evaluation and research of optimal energy generation; carrying out preliminary calculations of fuel consumption of diesel generators. From an environmental point of view, the use of optimization algorithms reduces fuel consumption and leads to a reduction in CO₂ emissions.

Keywords: Specific fuel consumption, local system, diesel-generator, non-linear programming

I. INTRODUCTION

Maritime shipping sources 3% of global greenhouse gas emissions and heavily depends on fossil fuels. The maritime sector, which accounts for more than 90% of world trade, is regarded as the basis of the global economy. Emissions are expected to increase further as this business expands. Coordinated and comprehensive actions are essential if the shipping industry tends to move towards zero emissions. Decarbonizing this sector requires a joint approach involving the global shipping industry, governments, and international organizations [1].

Optimal planning of generation of available generators to minimize total fuel consumption while meeting load demand and operational constraints in power consumption of offshore drilling rigs plays an essential role in improving specific power and oil rig efficiency.

Local systems based on diesel generators provide electricity. Such a local system is a multi-purpose system dealing with technical, economic, and environmental issues.

The main goals of local system control systems are optimization of operation, power supply planning, and system reliability.

A diesel generator is the main source of electricity for marine installations. The specific fuel consumption of marine engines ranges from 155 to 200 g/kWh at optimum load settings, typically around 85% of the maximum continuous load (MCL). Specific fuel consumption increases sharply when approaching at low power (30% P_{\max}) and especially at idle (7% P_{\max}).

Manufacturers do not recommend operating diesel generators at a load below 30-40% pu, at idle, as the generator may overheat. Fuel consumption of the diesel generator at idle entails economic inefficiency, as the cost of 1 kW of electricity will be quite high.

Incorrectly calculated power consumption can cause the diesel engine to work either with an overload (diesel machine manufacturers, as a rule, stipulate permissible short-term overloads within the range of 110% during 1 hour) or remain underloaded. In the first case, the engine life will reduce along with a decrease in efficiency (up to 20%). In the second case, the diesel generator operates in non-optimal modes, and its main components wear out quickly.

The total fuel consumed by the local maritime shipping assurance system based on diesel generators shall be minimized as the main target function.

II. LITERATURE ANALYSIS

Obtaining the equity of load capacities and power generation is a problem of nonlinear optimization [2-5].

Accurate simulation of specific fuel consumption is an urgent task for the optimal planning of generator operation when fuel consumption is the optimized function.

The study [2] features a nonlinear curve of the dependence of fuel consumption on power with polynomial functions of the third degree for diesel engines. This study suggests dividing the dependence into several intervals, which are described by different functions, to approximate fuel consumption to real rates.

Simulation of specific fuel consumption is usually carried out using polynomials of the second and higher orders, which, in turn, results in a higher error percentage. The study [3] suggests the use of cubic spline interpolation, which allows accurate simulation of the curve with minimal error.

Improving the energy efficiency of a local system based on diesel generators requires solving the issue of optimizing operating modes using the reduction of primary fuel consumption of diesel generators as an optimization criterion [4].

Algorithms for controlling the operation of diesel generators are based on the equation of maintaining the system energy balance.

General algorithms and methods used to manage the energy of local systems can be classified into two main categories: classical methods (methods of linear and non-linear programming) and AI methods (methods of fuzzy logic and neural networks). Besides, control algorithms can be a combined form of these methods [4,5].

An algorithm rapid change in the generator power level and power consumption power in to increase energy efficiency when powered by one DG is suggested in 1.

The need for parallel operation of several generators is essential to increase power, ensure increased power supply reliability, uninterrupted power supply for the main power source maintenance period, and compensate for the increase in power consumption by the connected load.

II. OBJECT, SUBJECT, AND METHODS OF RESEARCH

Object primary fuel consumption in diesel-generator.

Subject local maritime system.

Methods of research: mathematical methods for approximating characteristics, methods of theoretical foundations of electrical engineering, non-linear programming method for optimization.

IV. RESULTS

Accurate modeling of SFC is an important issue in the optimal scheduling of diesel-generators with fuel consumption as optimization function. Table 1 shows the specific fuel consumption as a part of the total power of the considered generator (Wärtsilä 16V26A (P=5200 kW), Wärtsilä 8V26A(P=3900kW)) [2,3].

Table 1 shows that there are no specific fuel consumption data for starting the generator (0% of the nominal load of the diesel generator).

Table 1 – Specific Fuel Consumption for Diesel Generators at Different Loads

Load (pu)	Specific Fuel Consumption, (g/kWh)
	Wärtsilä 16V26A
0	289
0,25	233,12
0,50	201,00
0,75	192,98
0,85	195,20
0,90	195,51
1,00	196,55

The value of missing data can be determined by extrapolation. Missing data can be extrapolated using 2nd- and 5th-degree polynomials, cubic spline function, and data from Table 1. In reality, a diesel generator's specific fuel consumption curve shows a maximum specific fuel consumption at the start. Therefore, polynomials of higher degrees cannot be used for extrapolation. At the same time, the use of polynomials of lower degrees will result in a more significant error. Using a cubic spline function makes it possible to avoid this.

The specific fuel consumption at zero load or diesel generator start, calculated using a cubic spline, is

Mathematical equations (1) - (7) can be used to calculate the numerical value of the specific fuel consumption at any given load of the diesel generator [2,3]:

I subinterval for $0 \leq p_j < 0,25$

$$B(p_j) = 2,9512(p_j)^3 + 187,866(p_j)^2 + 270,67 p_j + 289 \quad (1)$$

II subinterval for $0,25 \leq p_j < 0,5$

$$B(p_j) = 2,9512(p_j - 0,25)^3 + 190,08(p_j - 0,25)^2 - 176,184(p_j - 0,25) + 233,12 \quad (2)$$

III subinterval for $0,5 \leq p_j < 0,75$

$$B(p_j) = 7,0041(p_j - 0,5)^3 + 192,293(p_j - 0,5)^2 - 80,591(p_j - 0,5) + 201 \quad (3)$$

IV subinterval for $0,75 \leq p_j < 0,85$

$$B(p_j) = -1442,4(p_j - 0,75)^3 + 197,546(p_j - 0,75)^2 + 16,869(p_j - 0,75) + 192,98 \quad (4)$$

V subinterval for $0,85 \leq p_j < 0,9$

$$B(p_j) = 1940,1(p_j - 0,85)^3 + 235,158(p_j - 0,85)^2 + 13,10(p_j - 0,85) + 195,2 \quad (5)$$

VI subinterval for $0,9 \leq p_j < 1$

$$B(p_j) = 67,134(p_j - 0,9)^3 + 55,8598(p_j - 0,9)^2 + 4,1427(p_j - 0,9) + 195,51 \quad (6)$$

VII subinterval for $1,0 \leq p_j < 1,1$

$$B(p_j) = 67,134(p_j - 1)^3 + 76(p_j - 1)^2 + 17,328(p_j - 1) + 196,55 \quad (7)$$

A fuel consumption curve (Fig. 1), showing how much fuel is consumed to generate a specific power value using a Wärtsilä 16V26A diesel generator, was constructed based on expressions 1-7.

The algorithm suggested in [6] was improved to optimize the local system based on diesel generators for the marine sector (offshore drilling rigs). In this algorithm, generator power graphs were described by a single function over the entire power variation interval. It was suggested to specify fuel consumption taking into account expressions (1-7).

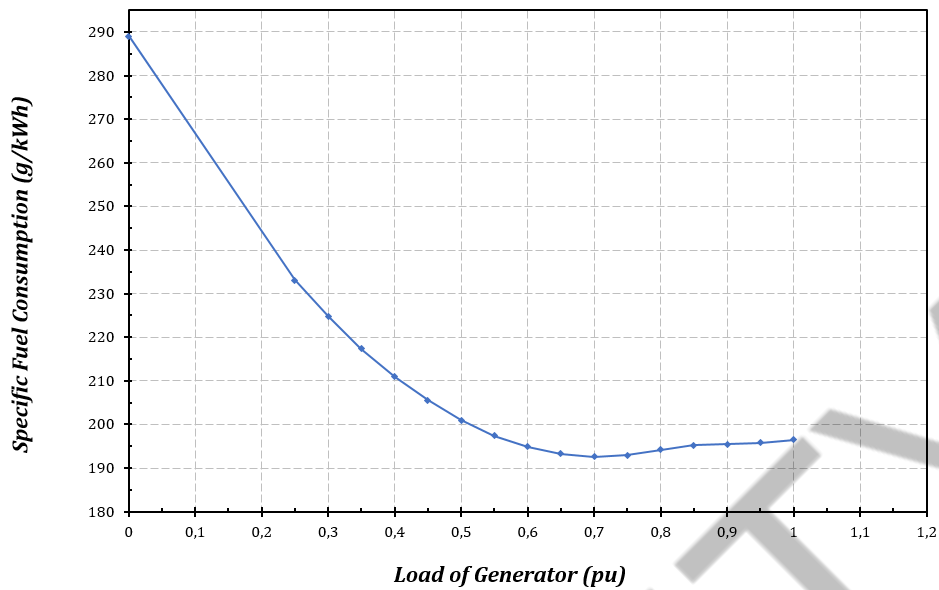


Fig. 1. Specific fuel consumption B of the diesel generator at P_{load} different loads.

This algorithm sets the required values of diesel generator capacities at each time interval taking into account the previous values of generator capacities to ensure the current P_H value.

The scheme of the local system is shown in fig. 2. It consists of two generators and load.

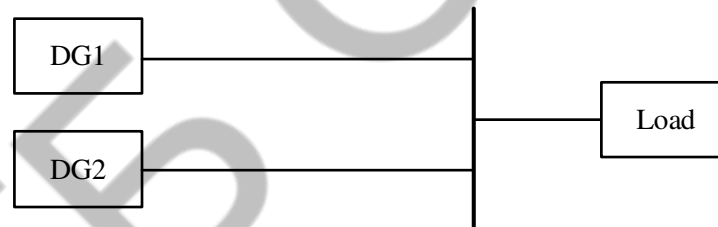


Fig. 2. Scheme local energy system

As shown in the figure, a tidal turbine installation, diesel generators and energy storage battery are used to power the offshore drilling rig in stand-alone mode of operation. The specific fuel consumption of diesel engines is usually simulated using polynomials of the second and higher order.

When the load changes at each time interval, the i function of finding the minimum is the sum of primary fuel consumption:

$$B_{i \min} = B_1(P_{1(i-1)} + \Delta p_{1i}) + B_2(P_{2(i-1)} + \Delta p_{2i}) \quad (8)$$

where $\Delta p_{1i}, \Delta p_{2i}$ are power values by which the power of each generator shall be changed (increased or decreased).

Algorithm for optimizing the operation of two generators

Step 1. Set initial conditions:

- curves of consumption of primary fuel B from power P for each generator separately $B_1(P)$, $B_2(P)$ in the form of a continuous function
- expressions that describe the dependence of $B_1(P)$, $B_2(P)$ on different intervals for revised calculations.
- initial power values of each generator P_{10} , P_{20} . In relative units.

Step 2. Set the current value of the load power of P_{loadi} of i interval.

Step 3. Calculate the required value of the load power change relative to the previous one:

$$\Delta P_i = P_{loadi} - (P_{1(i-1)} + P_{2(i-1)}).$$

Step 4. Condition check:

$$\Delta P_i = 0$$

if **Yes**, then the calculation goes to **Step 2**; if **No**, then the calculation shall be performed further.

Step 5. Calling the subroutine to calculate the minimum value of primary fuel consumption (8).

Calculate the function under the following limitations:

- the sum of power by which the power of the generators changes shall be equal to the load change calculated at **Step 2**.

$$\Delta p_{1i} + \Delta p_{2i} = \Delta P_i$$

- the power change of each generator shall be within the following limits

$$-\Delta P_i \leq \Delta p_{1i} \leq \Delta P_i$$

$$-\Delta P_i \leq \Delta p_{2i} \leq \Delta P_i$$

- the power of the generator shall not exceed its maximum power

$$(\Delta p_{1i} + P_{1(i-1)}) \leq P_{1\max}$$

$$(\Delta p_{2i} + P_{2(i-1)}) \leq P_{2\max}$$

Step 6. Calculation of power that shall be installed to obtain minimum consumption:

$$P_{1i} = P_{1(i-1)} + \Delta p_{1i},$$

$$P_{2i} = P_{2(i-1)} + \Delta p_{2i}.$$

Step 7. Clarify fuel consumption. Determine the value of the fuel using the specified functions (1-7), taking into account the power obtained in **Step 6**.

Step 8. Set initial conditions for the next calculation. The obtained power values are the initial conditions for calculations during the next interval.

Repeat the calculation from **Step 2**.

At the same time, the function shall be calculated under the following limitations:

$$\begin{cases} \Delta p_{1i} + \Delta p_{2i} = \Delta P_{loadi} \\ -\Delta P_{loadi} \leq \Delta p_{Gi} \leq \Delta P_{loadi} \\ (\Delta p_{Gi} + P_{G(i-1)}) \leq P_{G \max} \end{cases}$$

where $\Delta P_{loadi} = P_{load(i-1)} - P_{loadi}$ – change of load power, Δp_{Gi} – power increase of a single generator.

Wärtsilä 8V26A was chosen as the second diesel generator. Its consumption curve is shown in Fig. 3 in relative units from the Wärtsilä 16V26A maximum power.

$B1(p)$ and $B2(p)$ are represented as polynomials:

$$B1(p) = -68,584p^3 + 271,13p^2 - 294,03p + 289,58$$

$$B2(p) = 155p^3 + 129,93p^2 - 37,8p + 225,63$$

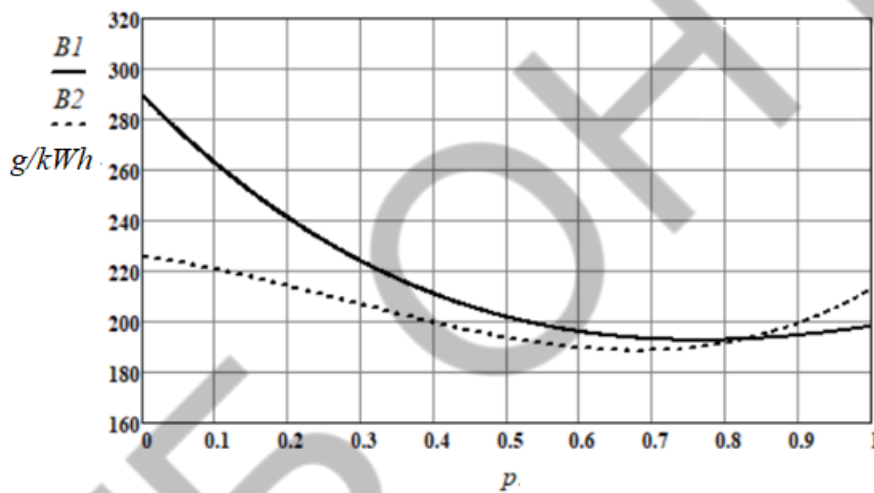


Fig. 3. The power load P_{load} (pu)

Consider for the daily load diagram presented in the form of a step graph during 12 T intervals (every 2-hour) (Fig. 4).

Calculations of primary fuel consumption of diesel generators were carried out according to the algorithm developed by the program in the Matlab programming language.

Figure 5 shows the fuel consumption $B1(p)$ for the graph in Fig.3 and $B11(p)$ for the graph in Fig.1. Fuel consumption is shown in Fig. 6. Power distribution diagrams for each generator are shown in Fig. 7-8.

Determining the final consumption, the cost of fuel is calculated using functions (1-7).

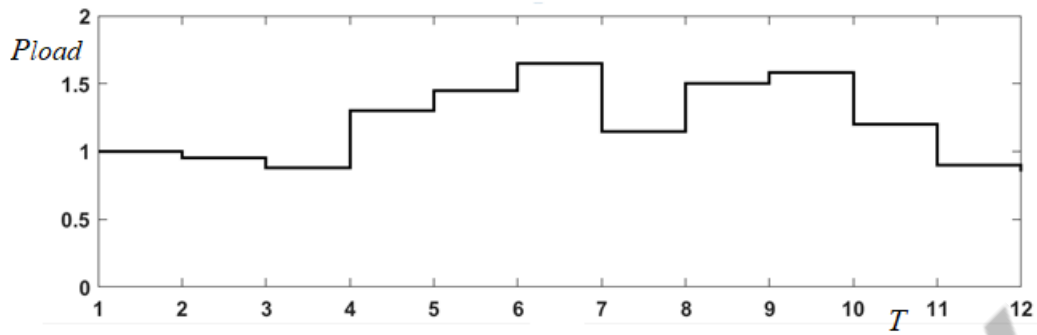


Fig. 4. The power load P_{load} (pu)

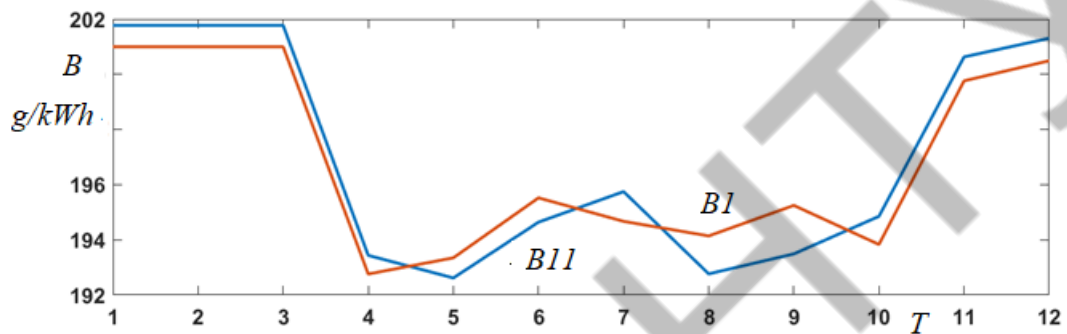


Fig. 5. Fuel consumption

A curve in Fig. 6 was constructed to evaluate the optimization. It corresponds to the consumption of primary fuel with a uniform distribution of power according to the following expression:

$$B_{neopt} = \sum_i^n B_i \left(\frac{P_{Hi}}{n} \right)$$

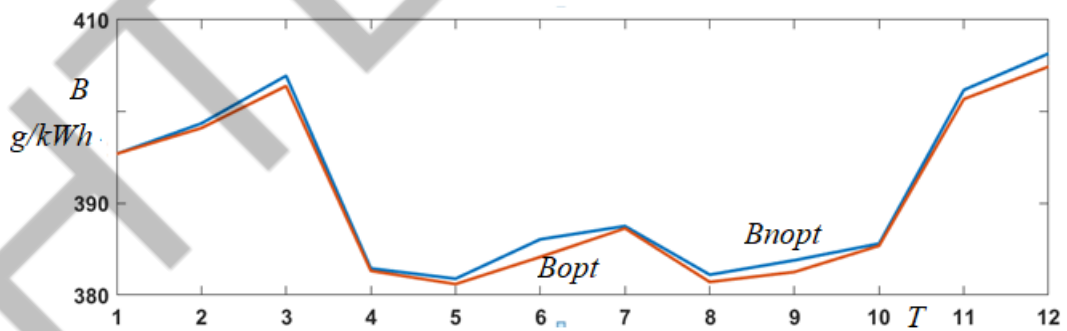


Fig. 6. Total specific fuel consumption

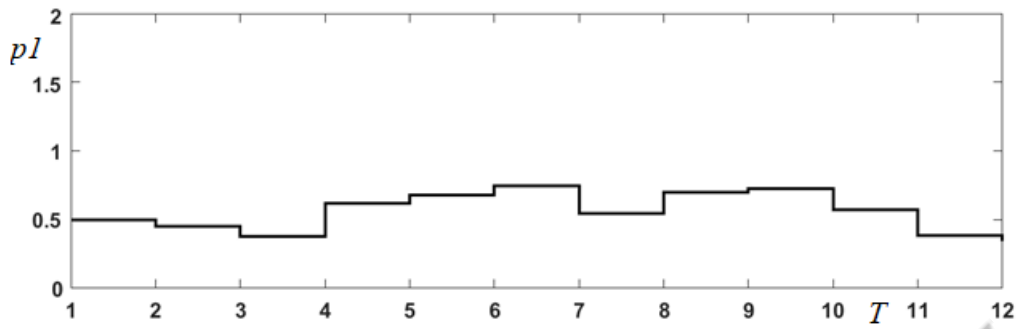


Fig. 7. Optimal power distribution for I generators

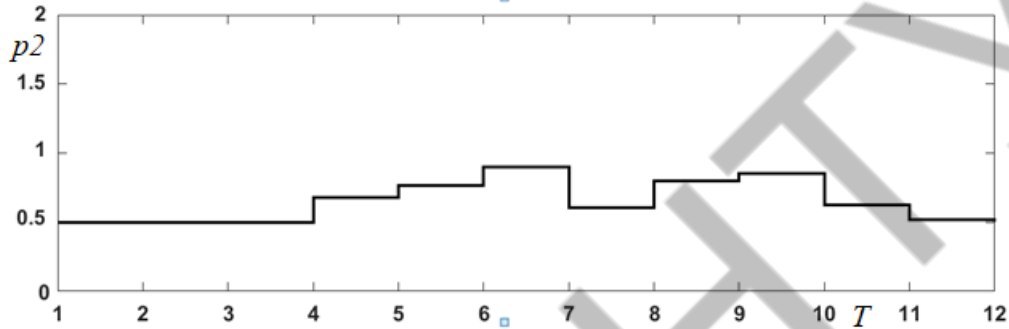


Fig. 8. Optimal power distribution for II generators

A comparison of the results of the algorithm taken as a basis with the approximated revised information was performed.

The results were entered into Table 2 for two options for load power curves (fig.1 fig.9 a and b). $B_{\%}, \%$ – percent of fuel consumption reduction, Mean values B_{nopt} and B_{opt}

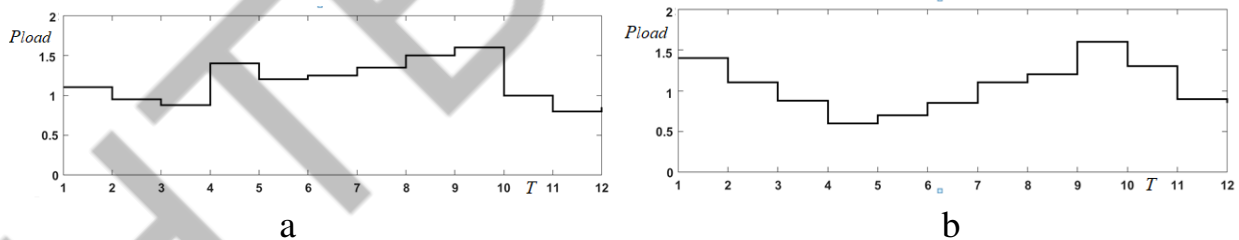


Fig. 9. The power load P_{load} (pu)

Table 2. Optimization results

№	fig	$B_{nopt}, g/kWh$	$B_{opt} g/kWh$	$B_{\%}, \%$
1	(fig.1)	4696	4687	0,2
2	(fig.9a)	4783	4705	1,63
3	(fig.9b)	4792	4752	0,85

When using the optimal algorithm into account a non-linear curve and divided into several subintervals., the average value of $B_{\%}$ is 0.2% – 1,6% (depends on load schedules) relative to the uniform power distribution.

The use of the algorithm and the program based on it will allow for the following:

- to reduce the cost of electricity for offshore drilling rigs by lowering the costs of fuel purchase and delivery;
- performing preliminary calculations of diesel generator fuel consumption as part of local systems for given load capacity diagrams.

V. CONCLUSIONS

The optimization algorithm and a program for analyzing and optimizing primary fuel consumption when distributing power between diesel generators based on it with revised calculations of fuel consumption made it possible to obtain more accurate consumption values. The economic impact of implementing optimization can be achieved by reducing the current fuel consumption and costs for its delivery. From a technological perspective, there is a reduction of the expenses for the use and delivery of primary fuel and losses during the production, transmission, and redistribution of energy. From an environmental perspective, the application of optimized algorithms and the use of renewable energy sources leads to a reduction in CO₂ emissions and the decarbonization of the marine sector.

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