ANALYSIS AND IMPROVEMENT OF ENERGY EFFICIENCY OF SHIP POWER SYSTEM

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Abstract: The purpose of this paper is to present a methodology for analysis and optimization of energy efficiency of Ship Power System and to show potential measures for energy savings. Environmental protection, energy efficiency and optimized use of resources are key concerns for scientist all over the world due to global economic growth and increased energy consumption. The greatest potential for conserving resources and lowering energy costs lies in the efficient use of energy.

Key words: energy efficiency, optimization, energy savings

1. Introduction

The ship as a complex energy system includes Ship Power System and Ship Propulsion System. The greatest amount of energy on the ship is consumed for propulsion. Electrical loads are second in energy consumption. These are the main areas for implementation of energy saving measures. Energy efficiency improvement could be achieved by applying an integrated approach. The ship energy system could be divided mainly into three subsystems - sources of energy; devices for transfer, transmission and distribution of energy; and consumers. (Fig.1.) For evaluation of energy efficiency, it is necessary to undertake a study of distribution and sizes of the energy flows in the system. Optimization of different parts of this system could provide overall efficiency improvement.

The tools that could be applied for evaluation of the effectiveness of the system are "Sankey" diagrams (Fig.2.). These charts visualize the size and distribution of energy flow in the energy system.

The incoming energy flow to the ship is divided into three parts - energy consumed by the main engine, auxiliary engines and auxiliary boiler. The energy (chemical) of the fuel is converted into three types of energies – electrical, mechanical and thermal. Through these charts it is easier to assess consumption, determine the areas with the greatest losses and the resulting optimization of energy efficiency. Fuel (energy) economy improvements will provide efficiency in maritime transport - reduction of costs and greenhouse gases.

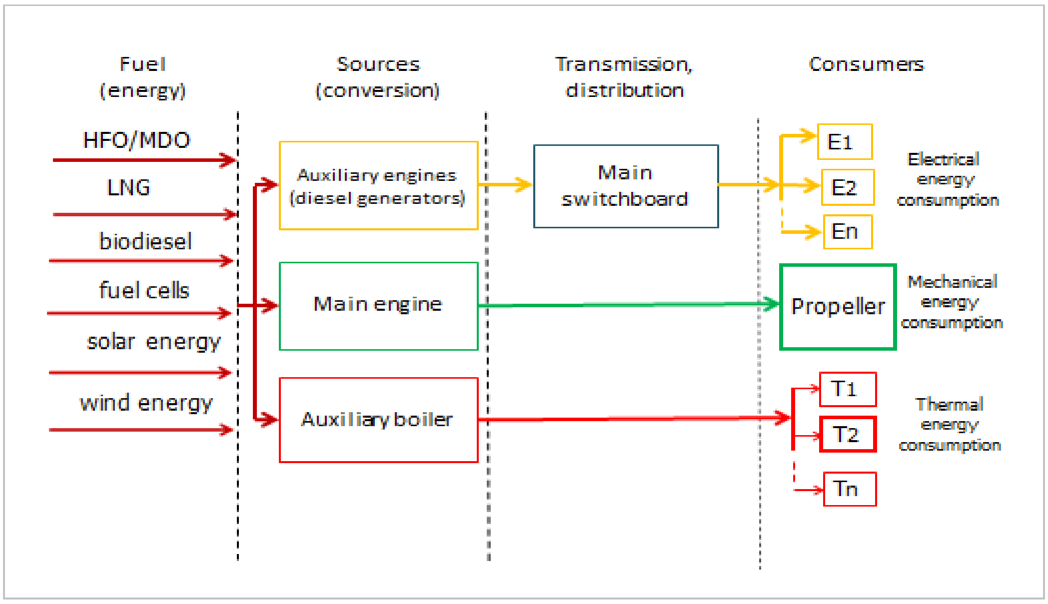

Fig.1. Ship energy system

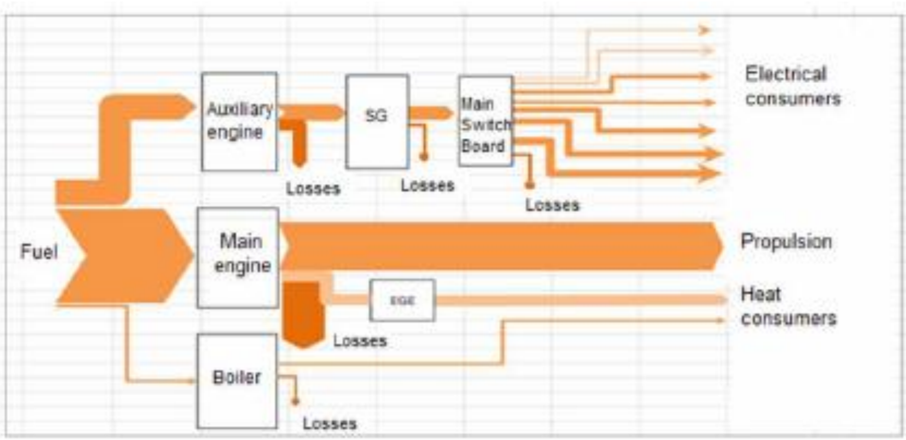

Fig.2. "Sankey" diagram of ship energy flows

2. Analysis and improvement of Ship Power System energy efficiency

A great amount of the fuel consumed on the ship is for electricity generation. The proposed methodology for optimization of energy efficiency of Ship Power System includes four main stages: determine baseline data of the system; analysis and assessment; identify and implement the most appropriate measures and practices for improvement and the final stage conclusions for improvement. To achieve energy efficiency optimization, it is necessary to undertake analysis of the distribution and size of the energy flow in subsystems - from the source through the devices for power transmission to consumers.

2.1 Analysis of the energy flow through the auxiliary engines (diesel generators)

For assessment of the effectiveness of auxiliary engines the thermal efficiency is calculated. In the example considered, the ship (Container carrier „Jaguar Max“2,200 TEU) has: Diesel generator (DG) – 4pcs. - YANMAR 6N280L-EN 1470 kW, 720 RPM, Generator type: FEK 55B-10, 1837 kVA, 2358A, 450V AC, 60Hz, cosφ = 0.8.

We study one of the main modes - **Sailing with working refrigeration equipment**.

In this mode it is necessary to use three diesel generators and the power of auxiliary engines (AE) is: **P** = 4410 kW. For calculation of daily fuel consumption of AE we use Power consumption in this mode: $\mathbf{P_{AE}}$ = 3982 kW

Daily fuel consumption of AE: $FOC_{AE/S} = \dfrac{P_{AE} \times SFC \times h}{g/t} = \dfrac{3982 \times 200 \times 24}{1000000} = 19,1[t/day]$,

where SFC_{AE} = 200 g/kWh - specific fuel consumption of AE
h = 24 - transit hours for day;
g/t = 1000000 - grams per metric ton;

For evaluation of the thermal efficiency of AE, first is determined the amount of fuel consumed per second *mf [kg/s]* and heat flow $Q_f = m_f \times C.V.$ emitted in engine during combustion.

The fuel consumption per second: $m_f = \dfrac{19,1}{24 \times 3600} \times 1000 = 0,221 kg/s$

C.V. (calorific value) is the thermal energy released during combustion of 1kg of fuel [kJ/kg].
C.V. for AE is 42720 kJ/kg (10200 kcal/kg)
The heat flow in engine is: $Q_f = m_f \times C.V. = 0,221 \times 42720 = 9441,12 kW$

The resulting thermal efficiency AE is: $\eta_{BTh} = \dfrac{P_B}{Q_f} = \dfrac{3982}{9441,12} = 0,42$,

where P_B = 3982 kW is the output shaft power in this mode.

The total energy received from AE for a year in this mode (292 days) has value[1]:

$$E_{AE} = 9441,12 \times 24 \times 292 = 66163,4 MWh$$

The useful energy has value: $E_{AE/S} = 3982 \times 24 \times 292 = 27905{,}8 MWh$

- **Energy losses in AE**

The losses can be calculated by total energy E_{AE} received from AE and useful energy $E_{AE/S}$:

$$E_{AE_S/loss} = E_{AE} - E_{AE/S} = 66163{,}4 - 27905{,}8 = 38257{,}6 MWh$$

$$(Q_{loss} = Q - Q_E = 9441{,}12 - 3982 = 5459{,}12 kW;$$

$$E_{loss} = 5459{,}12 \times 24 \times 292 = 38257{,}5 MWh)$$

- **Energy efficiency improvement of AE**

Thermal energy losses from exhaust gases and cooling systems represent a significant part of the energy flow through the diesel engine. Part of this energy can be recovered (Waste Heat Recovery System) to save money and reduce emissions, which will increase the efficiency of the system. [3]

The exhaust gas flow from the auxiliary diesel engine can be calculated [2]:

$$\left(\frac{\text{Exhaust Temp. }(^{\circ}\text{F}) + 460}{540}\right) \times \text{Intake Airflow (CFM)} = \text{Exhaust Flow}$$

For the survey vessel, the auxiliary engine is the Diesel 4-Cycle Turbo type and the temperature is 900 ^{0}F. Input airflow (CFM) data is provided by the manufacturer and, if missing, it is calculated by multiplying the power (h.p.) by 2.5. The engine tested has a power of 2200 hp. And the incoming airflow has a value: CFM = 4966.5 (at load 90.3%)

The flow of exhaust gases obtained is:

$$\text{Exhaust flow} = \frac{900^0 F + 460}{540} \times 4966{,}5 = 12508{,}22 \text{ kg/h}$$

Cp = 1,014 kJ / kg is the specific thermal capacity of the exhaust gases (http://www.dieselnet.com);

The exhaust gas temperature at full load is 400 ^{0}C, the output temperature from the turbocharger is 500 ^{0}C, and therefore the thermal energy of the exhaust gases is [4]:

$$Q_{us,g} = m_g . c_p . (T_{in} - T_{out}) = \frac{12508{,}22}{3600} . 1{,}014 . (500 - 400) = 352{,}3 kW$$

The amount of additional thermal energy obtained can be increased depending on the operating mode and the number of working DGs.

Energy from the auxiliary engines as waste heat could be used to obtain the necessary amount of steam for consumers when sailing or staying in a port. This will provide a reduction in emissions, the steam (energy) obtained will be at a low cost and the payback period of the investment short.

For energy savings is recommended using one diesel generator (DG) running at nominal mode (load 80% of rated power) when sailing. When consumption is higher (operation of deck machinery, refrigeration containers, pumps and compressors) it is necessary to use several DGs working in parallel.

Fuel consumption varies depending on the load of the diesel – generator. For the studied auxiliary diesel engine 6N280L-EN x 1470kW it is shown in Table 1.

Table 1.

Load factor, %	25	50	75	100	110
Fuel oil consumption (FOC), kg/kWh	250,3	221,1	217,1	211	215,9

A comparison can be made and the resulting savings can be calculated by increasing the load on the engine. For the auxiliary diesel engine 6N280L-EN x 1470kW according to data of test trials, at 50% load, the fuel oil consumption is: FOC = 221 kg/kWh, and at load 75%, fuel consumption has value: FOC = 217 kg/kWh. For sailing with duration of 6 months (180 days), 24 hours a day, 983kW power consumption for sailing mode (without refrigeration).

- **at 50% load,** the fuel consumption is: $FOC = 180 \times 24 \times 221 \times 983 = 938,5t$

- **at 75% load**, the fuel consumption is: $FOC = 180 \times 24 \times 217 \times 983 = 921,5t$

Fuel saved for sailing mode (without refrigeration) is **17t**. At a cost of $ 600, the value of the expected savings (for 6 months) is: 17t x $ 600 = $ 10200

Fuel savings will provide efficiency improvement and reduction of greenhouse gases:

$$\Delta CO_2 = C_F \times \Delta FOC = 3,206 \times 17t = 54,5\ tCO_2\ ,$$

where ΔCO_2 is the amount of carbon emissions saved; ΔFOC – fuel saved; C_F = 3,206 (t-CO_2/t-Fuel) for Diesel/Gas Oil is the conversion factor of emissions CO_2.

2.2 Analysis and energy efficiency improvement of the devices for power transmission and electrical loads

For evaluation of energy efficiency we study distribution and size of the energy flow through the devices for power transmission to consumers.

If we consider the most typical mode - ***Sailing with operation of refrigeration equipment***

The energy generated by AE per day is: $E_{AE/S} = P \times h = 4410 \times 24 = 105840\ kWh$

$P = 4410\ kW$ - full power of auxiliary engines;

h = 24 - transit hours per day;

The energy generated by AE per year (292 days):

$$E_{AE,year/S} = 4410 \times 24 \times 292 = 30905,3 MWh$$

In this mode of sailing, the load factor of auxiliary engines is 90.3%; efficiency of AE is η_{AE} = 96,2%, and the efficiency on the main switchboard is η = 98%. The amount of energy flow (for 1 year) through the elements of the system is shown in the table below:

Table 2.

	Incoming energy flow	Efficiency	Outgoing energy flow	losses
Electric power generated by the AE	30905,3 MWh	96,2%	29730,9 MWh	1174,4 MWh
Main switchboard	29730,9 MWh	98,%	29136,3 MWh	594,6 MWh

The distribution of energy flow to electrical loads in mode ***sailing with operation of refrigeration equipment*** is presented in Table 3.

Table 3.

	Consumers	Power consumption	Incoming energy flow	Energy %
1.	Pumps and Separators	373,1 kW	2614,7 MWh	9,4%
2.	Compressors, fans and other consumers in the engine room	138,9 kW	973,4 MWh	3,5%
3.	Deck machinery and cargo fans	331,1 kW	2320,35 MWh	8,3%
4.	Refrigeration plants (Reefer container)	2949,3 kW	20668,7 MWh	74%
5.	Household consumers	118 kW	826,94 MWh	3%
6.	Lighting, commun. and nav. equipment	28,8 kW	201,83 MWh	0,7%
7.	Periodically working consumers	43 kW	301,34 MWh	1,1%
	Full power consumption	**3982,2 kW**	**27907,3 MWh**	**100%**

Essential part of the electrical energy is consumed by refrigeration equipment, drive systems of pumps and fans. These consumers are the most common, they provide proper operation of ship systems and mechanisms and good working conditions for the crew.

In order to identify areas of the system that need to be optimized we could use a Sankey diagram of Fig.3. This chart describes the distribution and size of the energy flow from the source of electrical energy through the devices for power transmission and distribution to electrical loads and energy losses.

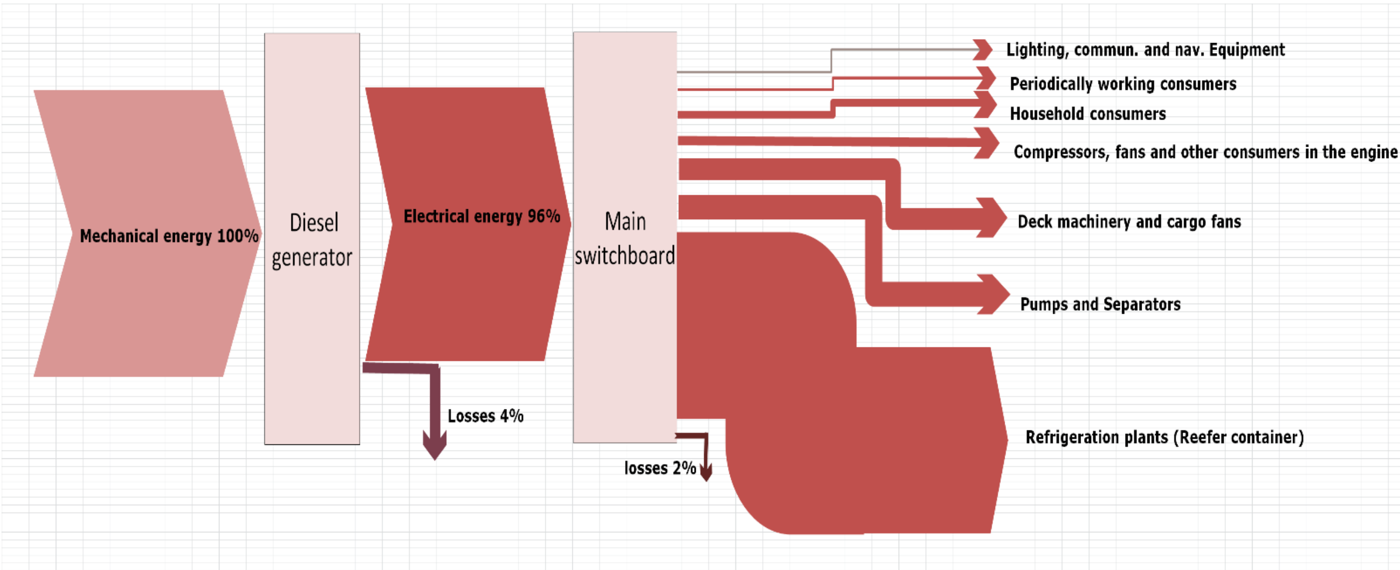

Fig.3. "Sankey"diagram of the energy flows in the Ship Power System

The size of the flows in the chart corresponds to the amount of energy flowing through the subsystems. This diagram also identifies key consumers whose performance needs to be optimized. The most significant impact on the workload of ship power plant have continually working consumers - the mechanisms of the main engine, refrigeration systems, deck machinery, fans and pumps. As this motor driven systems are the largest energy consumer on the ship optimization of the performance of these systems will provide greatest energy savings.

The main optimization activities include:

- Proper selection of mechanisms and motors to ensure optimal load of electric drive;
- Implementation of high efficient electric motors and power converters;
- Improved operation;
- Effective management and operation of electric drives - flow control by variable frequency drive.

In the example considered, the ship has 58 number of pumps - cooling, ballast, fire, fuel feed, oil-pumping, etc.; 9 compressors – cargo, conditioner and DG; 66 number of fans - in different locations on the ship. To obtain the most efficient optimization is to adjust the speed of the electric drive. ($P_2/P_1 = (n_2/n_1)^3$).

Flow control by variable frequency drive provides energy savings, lower fuel consumption and reduction of emissions CO_2.

As an example we may consider the application of the variable frequency drive (VFD) for the seawater cooling pumps (M.Cool.S.W.P.). For comparison of the different methods for control we could apply software calculators (Pump Save, PSAT). They are used to determine the amount of savings and the investment payback period. Comparison between throttle and frequency control and bypass with frequency control was made.

The characteristics of the considered system are as follows:

Density of seawater:	ρ = 1 kg / dm3
Nominal volume flow:	Qn = 1200 m3 / h
Nominal pump head:	Hn = 20 m
Maximum head:	Hmax = 30 m
Static head:	Hst = 1 m
Nominal pump efficiency:	ηp = 80%
Nominal motor power:	P_1n = 90 kW
Voltage:	400V
Nominal motor efficiency:	ηm = 94%
Nominal efficiency of the VFD:	η_{VFD} = 98%
Working time for 1 year:	5400 h
Electricity price (per kWh):	0.144 $ / kWh
Cost of the investment costs:	25000 $

Working time of pump at different loads:

60% * Q = 10%

70% * Q = 20%

80% * Q = 50%

100% * Q = 20%

Savings when replacing a throttle with VFD:

Required pump power:	81.8 kW
Energy (throttle control):	441 MWh
Energy (VFD):	278 MWh
Energy saved in a year:	163 MWh
Annual energy costs saved:	23 472 $
Value of the initial investment:	25 000 $
Payback time:	1.1 Years

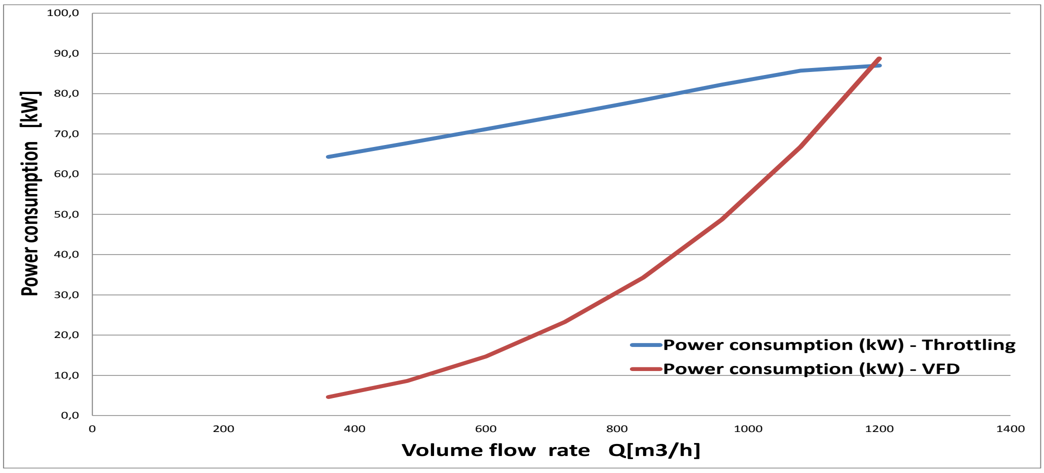

Fig.4. Specified values of the power consumption at throttle and VFD

Replacement of bypass control with variable frequency drive:

Required pump power:	83.4 kW
Energy (bypass control):	489 MWh
Energy (VFD):	283 MWh
Energy saved for a year:	206 MWh
Annual energy costs saved:	29 703 $
Value of the initial investment:	25 000 $
Payback time:	0.8 Years

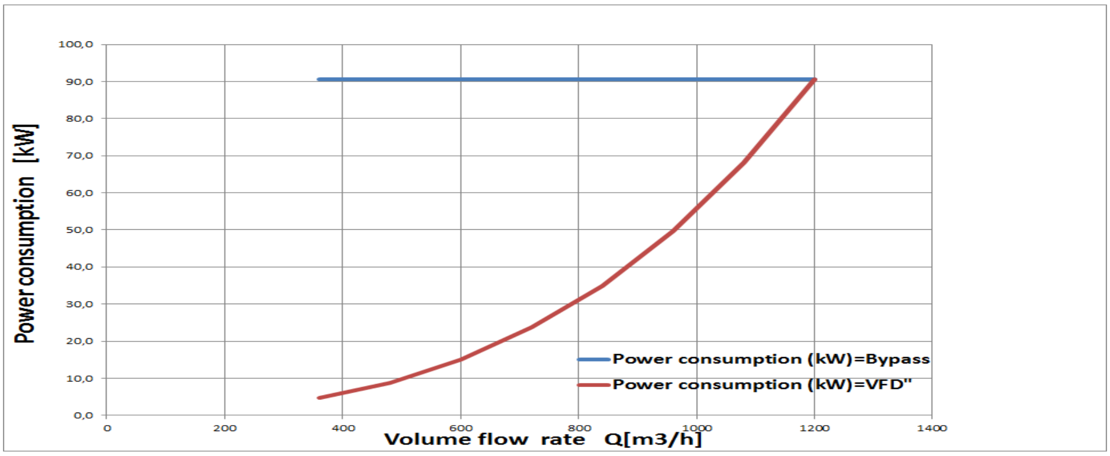

Fig.5. Replacement of bypass control with VFD resulting in greater power savings.

As an example we may consider the application of the VFD for the fans in the engine room.

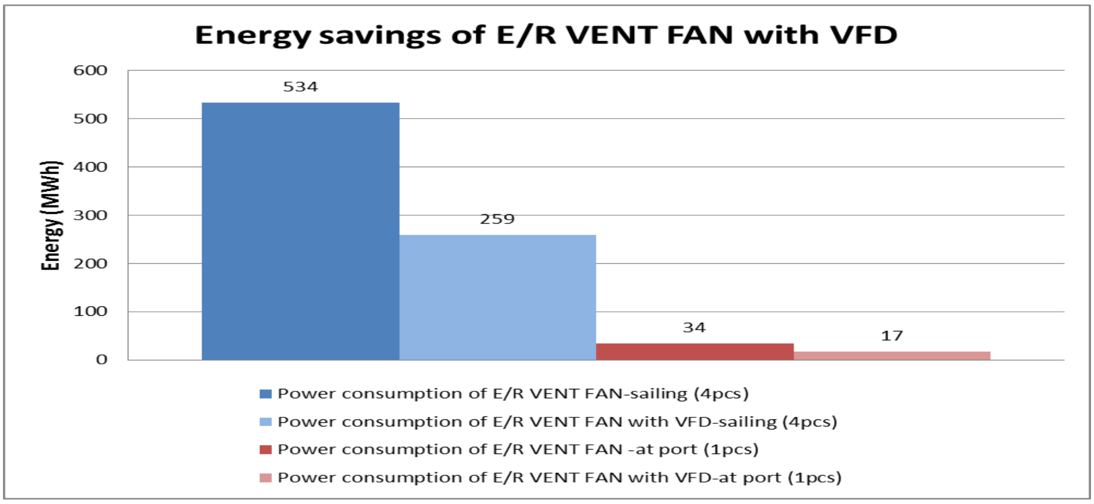

Fig.6. Energy savings when use variable frequency drives for fans in engine room

In this considered **container carrier** (2200 TEU) for the fans in the engine compartment (E/R VENT FAN - 4 pcs work at sailing mode) it is assumed that the motors in 80% of the time operate with 70% of the nominal speed (power 22 kW, efficiency 89%, Pk = 98,9 kW at 5400 hours). When using a variable frequency drives (efficiency = 98%), the energy at part load is:

$$\mathbf{E_1 = 98{,}9 \times (0{,}7)^3 \times 5400 \times 1/0{,}98 \times 0{,}8 = 150\ MWh}$$

For the rest 20% of the time, the energy at full load is calculated:

$$\mathbf{E_2 = 98{,}9 \times (1{,}0)^3 \times 5400 \times 1/0{,}98 \times 0{,}2 = 109\ MWh}$$

Energy consumption when using variable frequency drives is:

$$\mathbf{E_{vfd} = 150 + 109 = 259\ MWh}$$

Power consumption without using a frequency drive is: **E = 98,9 x 5400 = 534 MWh**

Energy savings: $\mathbf{E_s = E - E_{vfd} = 275\ MWh}$

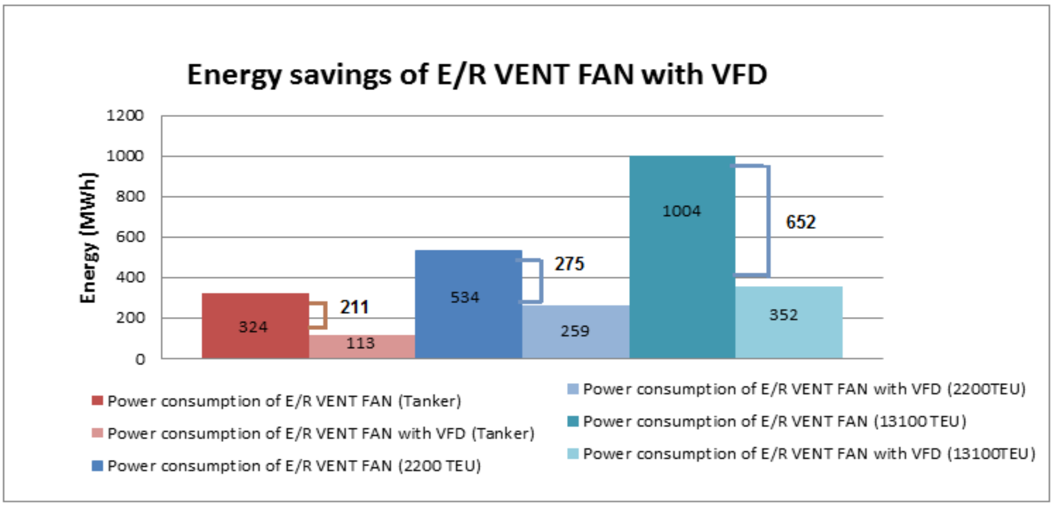

Fig.7. Savings when using VFD for fans in engine room for a different types and sizes of ships.

For comparison of savings for different ship size and types, were used data for tanker 164,000 DWT and container carrier 13,100 TEU **Tanker** - E / R VENT FAN - 4pcs: power 18.5kW; efficiency 78%; load factor 63%; at 5400 hours.

In the sailing mode - 4 pcs fans and the power consumption is Pk = 60 kW.

The energy consumed at full load is: **E = 60 x 5400 = 324 MWh.**

When using a variable frequency drives (efficiency = 98%), the energy at part load (70%) is:

$$\mathbf{Evfd = 60 \times 5400 \times (0.7)^3 \times 1/0.98 = 113\ MWh.}$$

The energy saved is: **Es = E - Evfd = 211 MWh.**

Container carrier (13100 TEU) - E/R VENT FAN - 3pcs: power 75 kW; efficiency 93%; load factor 77% at 5400 hours. In sailing mode work 3 pcs. Fans and power consumption is Pk = 186 kW.

The energy consumed at full load is: **E = 186 x 5400 = 1004 MWh**

When using a variable frequency drives (efficiency = 98%), the energy at part load (70%) is:

$$\mathbf{Evfd = 186 \times 5400 \times (0{,}7)^3 \times 1/0{,}98 = 352\ MWh.}$$

The energy saved is: **Es = E - Evfd = 652 MWh.**

3. Conclusions

Implementation of energy management strategy on the ship could reduce energy consumption and operational costs. By performing energy analysis and evaluation of energy flows on the ship it is easier to choose the most appropriate opportunities for energy savings. The methodology proposed in this paper for energy efficiency improvement consists of overall energy assessment and performance optimization of Ship Power System. Reduction of energy consumption and fuel saving would provide optimization of energy efficiency of ships and environmental protection.

4. References:

1. AECOM, URS, North Carolina Maritime Strategy, Vessel Size vs. Cost, May 31, 2012

2. Engine Exhaust Temperature & Flow Guide, www.donaldsonexhaust.com

3. MAN Diesel & Turbo SE, Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emission and EEDI, Copenhagen, Denmark, December 2012

4. Senčić T., Račić N., Franković B., Influence of Low-Speed Marine Diesel Engine Settings on Waste Heat Availability, Brodogradnja : časopis brodogradnje i brodograđevne industrije (0007-215X5X) 63 (2012), 4; 329-335, https://bib.irb.hr