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AGH Solar Boat –the analysis of energy and ecological parameters of the solar powered boat

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Abstract. Nowadays, aviation and maritime transportation produce 3% of world anthropogenic greenhouse gases emission. One of the main problems in maritime transportation is pollution emitted by traditional oil engines. It not only causes fish extinction but also produces CO_2. So, there is a strong need to change the way people consider maritime transportation. Fuel switching may be significant part of the implementation of the UN Sustainable Development Goals 2030 Agenda. The AGH Solar Boat is a project that connects sustainable development with innovative technologies. It represents the various aspect of engineering from construction, material engineering to electronics and photovoltaics. This paper presents the numerical analysis of the performance of the monocrystalline flexible solar panels (GSC 170+ and GSC 150+) and electric engine used in the first version of the boat. The results are compared with numerical results of the oil engine. Such comparison allows to show the difference in the emitted CO_2 as the saving in the air pollution. The importance of this research is significant for the future solution of solar powered engines in maritime transportation. There are great opportunities of using renewable energy in boats and ferries

1. Introduction

Nowadays, global demand for energy production constantly growing. Greenhouse (GHG) emissions, air and water pollution,global warming– there are examples of the negative anthropogenic impact on the planet Earth. Besides many other pollution sources, aviation and marine transportation combined are responsible for approximately 3% of globalGHG emissionand are among the fastest growing modes in the transportation sector [1]. One of the main problems in marine transportation is pollution emitted by traditional, oil engines. It not only causes fish extinction, but also produces e.g. carbon dioxide (CO_2)significantly contributing to air pollution around the world [2]. As it is shown in Fig. 1, international marine and aviation CO_2 emissionsstill increase and in 2015, it was responsible for production of 657.07 million tonnes of CO_2 [3]. Moreover, around 15% of global anthropogenic NO_x and 5–8% of global SO_x emissions are attributable to oceangoing ships [4]. Due to the fact, that nearly 70% of ship emissions are estimated to occur within 400 km of land, ships have the potential to contribute to air quality degradation in coastal areas [5]. For example, in European coastal areas, shipping emissions contribute with 1–7% of ambient air PM_{10} levels, 1–14% of $PM_{2.5}$, and at least 11% of PM_1 [6].

Taking into account above facts, there is a strong need to reduce the emissions generated by the ships. It may be realized by fuel switching, i.e. implementing renewable energy based systems. Among different available renewable energy sources (RES), solar radiation may be converted to electricity usingphotovoltaic (PV) panels. The large variety of PV applications allows for a range of different technologies to be used in the marine and aviation transportation sectors, including organic, thin film and crystalline silicon technologies. On the other hand, the main disadvantage of such solution is an inability to work continuously in every weather conditions. PV panels are able to provide electrical energy just in specified conditions and just only during the day. In recreational boats, or short distance ferries, we do not have to provide electrical energy continuously for a long time. In merchant navy there is no possibility to stop the vessel due to lack of energy in batteries. Despite of the great technological development, batteries are not able to compete with traditional, fossil fuels.

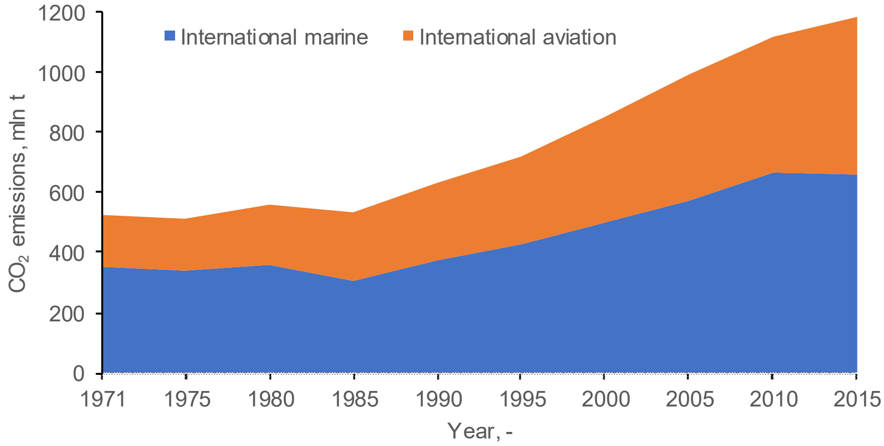

Figure 1. CO_2 emission from international marine and aviation.

Worldwide literature does not include many studies devoted to solar and electric powered boats. Among available works, a methodology to design a solar-powered boat with the aim to determine the size of a photovoltaic system with minimum cost was shown in [7]. A leisure passenger catamaran boat operated in Taiwan with 42 person capacity and total duration of cruising around 5 hours was chosen as a case study. 280 W_p Multi-crystalline PV module and 12 V 90 Ah Lead-Acid Battery were chosen for this case. Simulations have shown, that the optimal number of PV modules is 32 (8.9 kW_p), while the number of batteries is 32 (34.6 kWh_{el}). A novel method for optimally sizing a hybrid PV/diesel/energy storage system in a stand-alone ship was presented in [8]. Specifically, a proposal for an approach to generating power from PV arrays on the shipboard along typical navigation route from Dalian in China to Aden in Yemen was shown. Variations of the load under five conditions were modelled; regular cruising, full-speed sailing, docking, loading/unloading and anchoring. In [9] the large-scale PV system was introduced into the ocean-going green ship to modify the traditional structure of the ship's power grid: utilize the abundant solar resources on the ocean, reduce the ship's fuel consumption and pollutant emission. A novel structure of PV array based on the ship's illumination unit, ship's photovoltaic group, an operating point controlling device and batteries was proposed, and layout of the array on the ocean-going green ship was researched as well. In [10] the concept of a fully electrified ferry aimed to support and promote energy efficient, zero GHG emission and air pollution, free waterborne transportation for island communities, coastal zones and inland waterways in Europe and beyond were presented. The E-ferry concept differed from all other known projects e.g. by a record-breaking high charging power of up to 4 MW_{el} allowing for short port stays.

On the other hand, in the literature, there are some examples of developing and optimizing PV powered small boats. The relationship between the power generated with PV modules and the design of the propeller for the boat during a race was studied in [11]. The set of equations describing the energy generated while sailing a distance, and a model for a permanent magnet DC motor were made and the power flows from PV module hull resistance in the water was considered. As a consequence of performed optimization was an increase of 15% in efficiency (determined to compare monitoring data from a race for PV-powered boats from 2012 with a similar race in 2014). Another research, presented in [12], was focused on the development of an electrical propulsion system for 4 m length boat model. The target of this development was attempting to design the electric drive which could reach up to

5 knots. The electricity of the propulsion system was supplied by 4 batteries providing 24 V of direct current, while the thrust of the vessel was delivered by 3-phases 2.2 kW_{el} squirrel cage induction motor. The on-site experiment was carried out in the open-sea at Sriracha Bay. The results indicated that the maximum speed of the system could reach 5 knots within 1 km distance.

This paper includes results obtained during implementation AGH Solar Boat project. This project is aimed at the construction of the novel, solar-powered boat, and links sustainable development with innovative technologies. The project represents various aspect of engineering from construction, material engineering to electronics and photovoltaics. Below presented tests include numerical analysis of the performance of the monocrystalline flexible PV panels and electric engine used in the first version of the developed boat. The results are compared with the numerical results of the oil engine. Such comparison allows showing the difference in the emitted CO_2 as the saving in the air pollution.

2. Materials and methods

The boat was equipped with 6 light-weight, flexible photovoltaic panels with nominal power 1003.4W_p (including 5 panels GSC 170+ and 1 panel GSC 150+). The panels are made of techno-polymers which give them a higher efficiency and a weight of about 1/8 compared to the traditional glass panels. The implementation of innovative GWire technology allows to prevent “micro-cracks” and “hot spots” by increasing the number of wires in the cell. The location of the PV panels on the boat’s deck is shown in Figure 2.

Figure 2. The view of the deck with installed PV panels.

The PV panels are normally connected to the battery via battery management system (BMS). Generated energy may be stored in the battery with 1420.8 Wh_{el} capacity and used to power brushless electric engine. This engine has a rated power of 3.3 kW_{el} with the possibility of temporarily overloading up to 4.5 kW_{el}. The efficiency of the engine characteristic stays at the level of 90.0% in the speed range $n = 2000 \div 5000$ min^{-1}. This type of engine was chosen because of its low mass, easy adjustment and high efficiency.The basic parameters of the used photovoltaic modules are shown in Table 1.

Table 1. Basic parameters of the used photovoltaic modules.

Parameter	GSC 170+	GSC 150+
Maximum power (P_{MPP}), W_{el}	170.4	151.5
Voltage at maximum power (V_{MPP}), V	20.9	18.6
Current at maximum power (I_{MPP}), A	8.4	8.5
Open circuit voltage (V_{oc}), V	23.4	20.8
Short circuit current (I_{sc}), A	8.8	8.8
Cells efficiency (η), %	21.0	21.0
Dimensions (*H x L x D*), mm	1530 x 680 x 1.5	1375 x 680 x 1.5
Weight, kg	2.6	2.3

2.1. TRNSYS component used for simulations photovoltaic system
It is crucial to identify the performance of the PV modulesfrom the standpoint of competitions in solar boats races. For this purpose, dynamic simulations in TRNSYS (Transient System Simulation Tool) software were conducted. The operation of photovoltaic panels was represented by the Type 94 (component, which uses a four parameter equivalent circuit model to determine the current and power of the PV array at a specified voltage as well as current and voltage at the maximum power point [13]). The equivalent circuit diagram, which is the basis for the considering model, is shown in Figure 3.

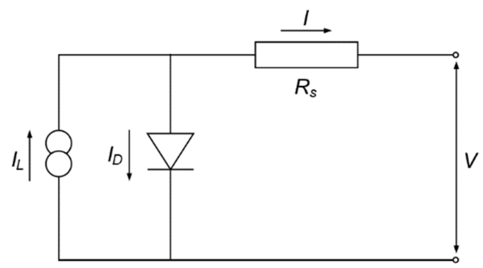

Figure 3. Equivalent electrical circuit of PV module used in TRNSYS simulations.

The model determines the I-V curve and thus the power delivered to the load using four parameters: the PV module photocurrent at reference conditions $I_{L,ref}$, the diode reverse saturation current at reference conditions $I_{o,ref}$, the series resistance R_s, and the empirical PV curve-fitting parameter γ. The current-voltage equation of circuit shown in Figure 3 is as follows:

$$I = I_L - I_o \left[\exp(\frac{q}{\gamma k T_C}(V + IR_s) - 1 \right] \tag{1}$$

where:
I_L - module photocurrent, A
I_o - diode reverse saturation current, A
q - electron charge constant, C
γ - empirical PV curve-fitting parameter, -
k - Boltzmann constant, J/K
T_c - module temperature, K
V - voltage, V
I - current, A
R_s - module series resistance, Ω

The series resistance R_s and the empirical PV curve-fitting parameter γ are constants. The photocurrent I_L depends linearly on incident radiation:

$$I_L = I_{L,ref} \frac{G_T}{G_{T,ref}} \tag{2}$$

where:
$I_{L,ref}$ - module photocurrent at reference conditions, A
G_T - total radiation incident on PV array, W/m^2
$G_{T,ref}$ - incident radiation at reference conditions, W/m^2

The reference insolation $G_{T,ref}$ is defined as 1000 W/m^2. The diode reverse saturation current I_o is a temperature dependent quantity:

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 \tag{3}$$

where:
$I_{o,ref}$ - diode reverse saturation current at reference conditions, A
T_c - module temperature, K
$T_{c,ref}$ - module temperature at reference conditions, K

Eq. 1 gives the current implicit as a function of voltage. Once I_o and I_L are found from Eq. 2 and Eq. 3, Newton's method is employed to calculate the PV current. In addition, an iterative search routine finds the current (I_{MPP}) and voltage (V_{MPP}) at the point of maximum power along the IV curve.

Power generated in PV panels has to be conditioned using regulator (which distributes DC power from panels to and from a battery) and inverter (converts the DC power to AC and sends it to the load and/or feeds it back to the utility). Type 48 models both the regulator and inverter and it was used in the model.

Power conditioned in the regulator was stored in the battery (represented by Type 47, which specifies how the battery state of charge varies over time, given the rate of charge or discharge). The load is given by schedule (Type 14) and weather is taken from Meteonorm database (via Type 15). Due to the fact, that there is no data for Monaco, the data for Nice was used instead (Nice is a French city situated about 20 km from Monaco).

3. Results and discussion

Below presented results include the results of dynamic simulations. Power generated in the PV modules and its usage by electrical engine were calculated for 11-16 July (time corresponding to the date of Monaco Solar & Electric Boat Challenge, edition 2017 and 2018, supplemented by one day before and one day after competitions). Such calculations allow assessing the scenario the boat operation during the races. Dynamic simulations are supplemented by comparison of the emitted CO_2 in case of using the electric engine and sample oil engine typically used in boats (calculations were made for typical 5 horsepower electric motor installed on a sample recreational boat).

3.1. Dynamic simulations in TRNSYS

Figure 4 shows the variations in power generation in the considered photovoltaic system (including five GSC 170+ panels and one GSC150+ panel) for above mentioned days. It can be observed, that maximum reached power value is about 92.6% of the nominal power of the tested panels (929.4 W_{el} compared to 1003.4 W_p). Such a value is achieved between 12.00 PM and 2.00 PM, while in the rest time of competitions (i.e. from 10.00 AM to 5.00 PM) generated power typically exceeds 500-600 W_{el}. On the other hand, during cloudy days, this value significantly decreases, and may be as low as ~210 W_{el} (14 July, 12.00 PM). It shows, that high efficient generation and storage systems are required to provide proper operation of the boat and consequently various race scenarios have to be considered before competitions. On the other hand, real weather conditions differ from statistical ones.

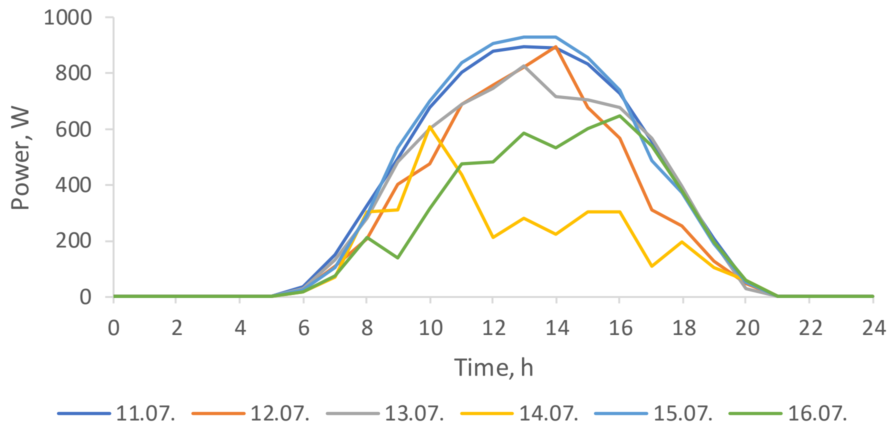

Figure 4. The power generation in the PV panels for selected days in the year (Nice, France).

Energy generated in the photovoltaic panels is conditioned in a battery management system and used to load the battery. Then, energy is used to power an electric engine. Both the efficiency of loading battery and engine's operation was assumed at a constant level of 90%. Another one approximation was connected with the fact, that shading effect of skipper was not included in calculations (this effect is negligible because skipper sits low in the cockpit). The effect of heating PV modules by electrical components located under the deck and the impact of seawater on the operation of the module were also not included. Finally, in case of the first-day of Monaco Solar & Electric Boat Challenge, the energy is consumed for Endurance Fleet Race (2 hours long race starting at 10.00 AM), parade (3.00 PM) and Speed Record competition (4.00 PM). The energy flow for such a races schedule was shown in Figure 5.

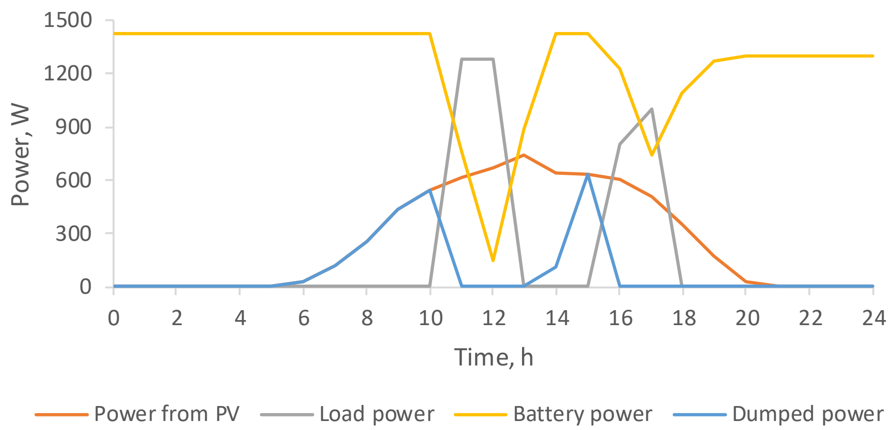

Figure 5. Variations in the power obtained from PV panels, load power, battery power and dumped power during the Endurance Fleet Race, Parade and Speed Record competition (on the example of weather conditions for 13 July).

It was assumed, that battery at the beginning of competition is fully charged (it was charged a day before) and it has not been discharged below 10% of its capacity during the races. For such assumptions, taking into account power generating in PV modules and transferred to the battery via BMS, the average level of power consumed during Endurance Fleet Race was calculated to 1280 W_{el} (42.7% of the nominal power of the electric engine). Time after this race has to be intended for charging the battery before further parts of the competitions. Parade and Speed Record competitions consume less energy,

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but due to the late time of ending the races (6.00 PM), the battery is not fully charged at the end of the day (~90.9%).

Considering the sunniest day (15 July according to Meteonorm database), the average power available to use during Endurance Fleet Race is higher – reaches a level of 1420 W_{el} (47.3% of the nominal power of the electric engine). Power consumed during other races stays at the same level. On the other hand, in the case of the most cloudy day (14 July according to Meteonorm database), the situation is significantly different: average power, available to use during Endurance Fleet Race, is only 920 W_{el} (30.7% of the nominal power of the electric engine) and power available to use during Parade and Speed Record competition is 500 and 600 W_{el} respectively. At the end of the day, the battery is charged only in 34%.

The second day of Monaco Solar & Electric Boat Challenge includes Slalom Race (10.00 AM) and One-On-One Race (3.00 PM). In this case, the scenario of power usage is quite different. During Slalom Race more power in shorten time is consumed in comparison to Endurance Fleet Race. Assuming the same conditions as in the first case (13 July), the maximum level of average power available during the Slalom Race is 1900 W_{el} (63.3% of the nominal power of the electric engine). On the other hand, in the case of One-On-One Race, average power usage may be at a level of 1200 W_{el} (see Figure 6).

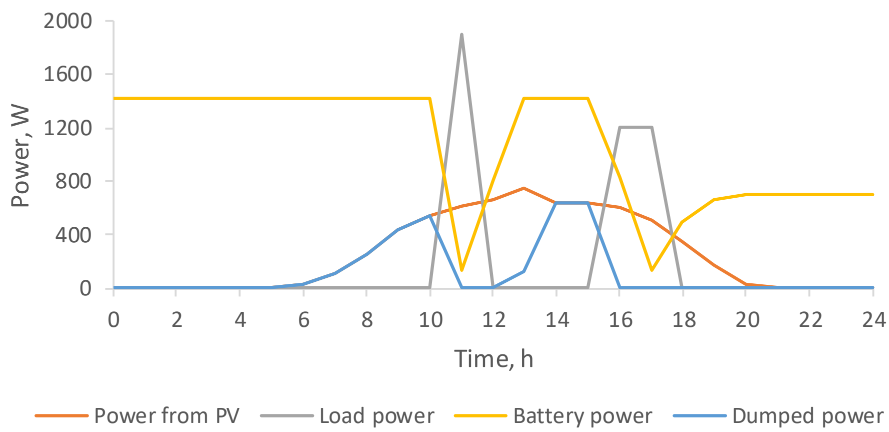

Figure 6. Variations in the power obtained from PV panels, load power, battery power and dumped power during the Slalom Race and One-On-One Race (on the example of weather conditions for 13 July).

Energy consumed by the electric engine during Monaco Solar & Electric Boat Challenge (calculated for the given weather conditions) is about 8.7 kWh_{el}, while theoretically available power is a bit higher (see the level of dumped power in Figure 5 and Figure 6). Comparing operation of the used electric engine with operation ofexemplary gasoline engine, the theoretically avoided CO_2 emission is around 10 kg. Of course, the analysed boat is developed for the competition in the races, and its construction differs from typical recreational boats. Such a type of boat was used to carry out the comparison of ecological parameters connected with the use of electric and oil engines.

3.2. Ecological analysis of the usage of electric engine installed ona recreational boat

In this part, the fast simulation for typical 5 horsepower (~3.7 kW_{el}) electric motor installed on a recreational boat was conducted. Assuming that there are no batteries, and the vessel will be used for half an hour relying only on power supplied by PV panels, the theoretical surface covered by photovoltaic cells should be equal to 16.4 m^2 (without any space between each cell). The cost of such amount of Sun-power cells are about 5 000 US dollars, while gasoline for a working hour costs about 3 US dollars (assuming that in Wide Open Throttle (WOT) conditions modern, 5 horsepower gasoline engine burns ~2 l for a working hour). It is a just theoretical calculation, but it shows how much surface is required to provide a sufficient amount of energy for 5 horsepower electric engine. Despite the fact, that electric engines have many advantages, the main problem is connected to their power supply. In the case when the vessel is used occasionally, or have a continued access to an external power supply (i.e. charging station in the harbour), there are no contraindications to provide power to the electric engine with batteries assisted by photovoltaic panels. Such a solution is environmentally friendly because of the zero emission of dangerous gases and low noise emission while working. Considering the same conditions as assumed earlier, gasoline motor emits about 3 kg of CO_2 for each working hour. Assuming that electric engine is working with 100% of power, panels are generating power at a level of 929.4 W (as calculated before) and batteries are fully charged at the beginning, total operating time of the vessel is approximately 33.6 minutes. So, even when using full throttle, the vessel can be used for half an hour without emitting CO_2.

4. Conclusion

Results of the currently conducted study show important aspects of operation of the solar powered boat – both from the standpoint of power generation and its consumption during races and from the standpoint of reduction of CO_2 emission. Presented analysis were carried out for the first version of the boat, realized under AGH Solar Boat Project.

The use of dynamic simulations allows preparing various race scenarios, depending on the weather conditions. The significant difference in the power available from PV panels during the sunny and cloudy day was shown. Taking into account an example of Endurance Fleet Race, the average level of power consumed by electric engine varying from 920.0 W_{el} in the cloudy day to 1420.0 W_{el} in the sunny day (assuming, that battery at the beginning of competition is fully charged). Such situation is similar for other competitions. So, predicting the conditions of the race may be an important part of strategy.

From the standpoint of non-races solar powered vessels, they may be used especially in the short distance transport, bringing tremendous improvement of air quality in coastal areas and, generally, in rapidly developing countries. Introducing this clean technology can also help to reduce water pollution in lakes, rivers and in further time affect seas and oceans.

Unfortunately, using even latest available technologies, it is still not possible to provide a sufficient amount of electric energy for a long time constant. It excludes the use of electric motors in large commercial vessels.

Acknowledgements

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