ENERGY BALANCE ANALYSIS OF SOLAR-POWERED CATAMARAN

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Abstract. In the last decade, alternative energy is being used in various vehicles due to the depletion of fossil energy resources. One of the kinds of alternative energy is electricity. Electric drive can be used in land vehicles, aircraft and watercraft. To identify the possibility of using electric watercraft and the technical parameters, an experiment was conducted in real navigation conditions in the territory of Jelgava city on the Driksa canal on a 1.62 km long route. The experiment used a data logger to take measurements of parameters of the motor and the solar cell, as well as of solar intensity. The experiment was done with a rebuilt pedal-powered catamaran equipped with a 445 W solar panel, a 40 Ah lithium-ion battery and a Minn Kota Endura C2 34 electric motor. The experimental data were processed to identify the power and energy generated and consumed parameters for the electric motor, the solar panel and the battery of the watercraft. On the day of the experiment at a solar intensity of 500-600 $W \cdot m^{-2}$, the catamaran could cover an unlimited distance at power settings 3 to 5 at a speed of 2.73 km h^{-1} to 3.79 km h^{-1}. At power setting 5, the electric motor consumed a power input of 320-330 W – a power output generated by the solar cell in sunny weather. If the battery is discharged, the solar cell charges it when the watercraft is anchored in the port, as well as when moving in case the solar cell generates more energy than the motor consumes at a particular power setting. According to the results of the experiment, low-speed electric-drive watercraft equipped with solar cells can be operated without additional battery charging at all power settings at geographical latitudes up to 57º and solar altitudes up to 35º-56º.

Keywords: solar catamaran, energy, experimental route, solar intensity, voltage, current.

Introduction

As energy resources are depleted in the world, non-fossil energy sources are sought. Therefore, at the beginning of this century, constructors and scientists sought for a possibility of using electricity in several transport industries. Currently, electric drive is used not only in land vehicles – various automobiles, tractors and trucks – but also in aircraft and watercraft. The use of electric drive in watercraft is relatively simple. Solar energy is easier to use in watercraft than in land vehicles because the horizontal surface areas of watercraft are usually larger than those of land vehicles.

Initially, electric watercraft stored energy in batteries. With the development of solar cell technology, solar cells began to serve as an additional source of energy for watercraft, which could provide a longer range per charge and battery charging when anchored in the port. Over the last 10 years in the world, several kinds of solar-powered watercraft of various sizes and capacities have been exploited both in the tourism industry and in commercial transport [1].

Rosa Zuloeta Bonilla et al. have simulated the use of solar-powered boats in the Amazon basin and compared them with internal combustion engine boats. The research involved a 12 m long twelve-seater boat and a 10 m long twenty-seater catamaran. The results showed that on calm water, a 3-kW motor was sufficient for the boat, whereas in a river with a current, the power should be increased to 10 kW. The simulation found that the average speed of the catamaran was 2.8-3.9 $m \cdot s^{-1}$, which could be achieved by a motor with a power output in the range of 1.4-5.4 kW [2; 3].

There are available several prototypes of autonomous watercraft [4]. It is easier to robotize an electric solar-powered boat than a conventional internal combustion-powered watercraft. There have been developed prototypes of autonomous solar-powered taxis as well [5; 6]. The development of such prototypes considers the fact that less traffic and lower speeds are on water than on land.

Lapko A. has researched the possibilities of using an electric-drive boat. The motorboat batteries were charged on shore, similarly to an electric car. If the weight of a watercraft is 3-10 t, it needs a motor with a power output of 3.5 to 20 kW. Batteries with a capacity of 10-60 kWh are required to operate such a watercraft for 3-4 hours [7].

Safak Hengirmen Tercan et al. have found that if switching from internal combustion-powered tourist boats to ones running on alternative energy sources and being equipped with 60 kWh batteries, the payback period is 9 years, while for the boats equipped with batteries twice as capacious, it is 13 years [8]. For a light-duty watercraft, matching the power output of its solar panels with that of the motor can significantly reduce the cost of the watercraft, yet in this case the watercraft achieves a lower speed.

For light-duty watercraft, the recommended type of hull is a catamaran, as this allows the solar cells of a larger area to be placed in the most convenient way [9]. The possibilities of using not only solar energy but also wind and wave energy are being researched and simulated for watercraft. Wave energy is exploited when a watercraft is not moving [10; 11]. The popularity of solar and electric watercraft is evidenced by the French Electric Boats Association founded in 1994, which currently has more than 60 members [12].

It is believed that solar energy is too insignificant to be used for full propulsion in mobile technology, especially at latitudes more than 40º. An original prototype of a watercraft was developed to identify the possibility of using solar energy in watercraft, and an experiment was done with it to measure the electrical parameters. The present research aims to identify the power and energy parameters of the solar-powered catamaran at different power settings based on experimental data.

Materials and methods

The technical parameters of the solar-powered catamaran were identified during experimental trips. The experimental trips were made on the Driksa canal in Jelgava city. For experimental purposes, a prototype of a solar-powered catamaran with a special mounting frame for a solar cell and a motor was developed based on a standard pedal-powered catamaran (Figure 1).

Fig.1. **Prototype of the solar-powered catamaran**

The catamaran was equipped with a standard Minn Kota Endura C2 34 electric motor and a 445 W solar photovoltaic panel. The motor has 5 power settings for forward movement and 3 power settings for reverse movement. The 3rd, 4th and 5th electric motor standard power settings were used for the experiments. The electrical system of the catamaran was adapted to operate the electric motor, and the catamaran was equipped with a 12 V 40 Ah Lithium-ion battery. The battery could ensure the autonomy of the catamaran without using the solar cell for about 90 minutes. The weight of the prototype was 112.6 kg, and its carrying capacity was 300 kg. Solar cell, battery charging and motor control were provided by a standard MPPT charge controller PW·M VS3024AU. The controller ensured a nominal battery voltage of 14.6 V and a cut-off voltage of 11.1 V. The solar panel Longi LR4-72HIH-445M supplied a voltage of 41.3 V at maximum power. The current of the solar panel at maximum power was 10.78 A.

A Graphtec midi Logger GL220 was used to record electrical data during the experiment. The data were saved 10 times per second. The logger was powered by a separate 12 V battery. Four data logger channels were used to record the electric motor and battery current and voltage. The fifth channel was used to record the pyranometer voltage. A pyranometer Apogee SP-500 was employed to measure the intensity of solar radiation. The experiment used an adjustment factor of 18.37 to record the solar intensity by the pyranometer. A Garmin Edge 830 GPS logger was used to record route data – the speed of the catamaran. A circuit diagram for the experimental equipment is shown in Figure 2.

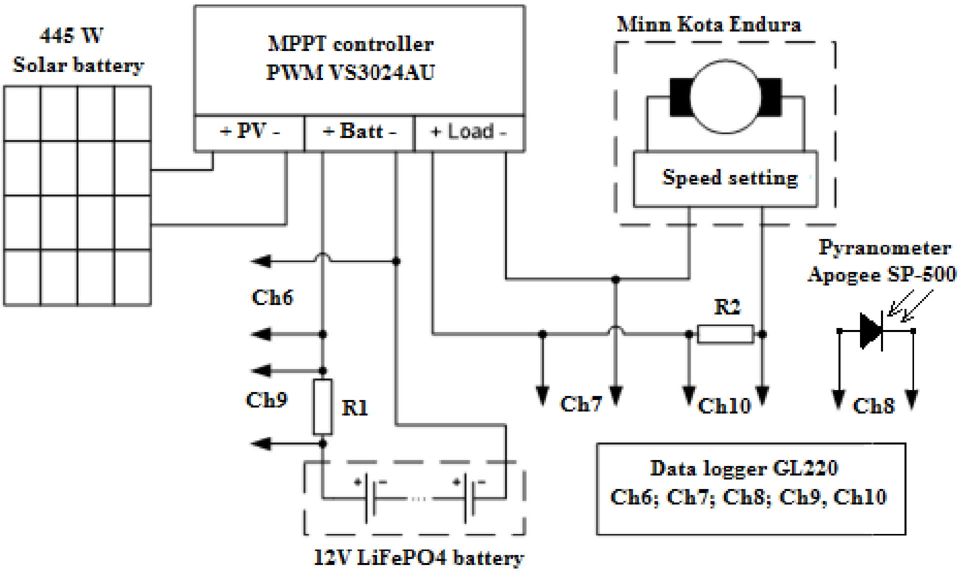

Fig.2. **Circuit diagram for the experimental equipment:** Ch 6 – battery voltage; Ch7 – motor voltage; Ch8 – pyranometer voltage; Ch9 – battery current; Ch10 – motor current

The experiment was conducted on 5 July 2022, on the Driksa canal in Jelgava city, between the mouth of the canal and the pedestrian bridge. The experiment was carried out from 10.00 to 18.00. The coordinates of the route were latitude 56.65º and longitude 23.73º. The experiment was done at power settings 3 to 5 and had three replications on a 1620 m long section of the canal, which represented a round-trip route. The water current and wind speed did not exceed 0.2 $m \cdot s^{-1}$. Two operators participated in the experiment. The experimental trip was started immediately after all data storage devices were turned on. The devices were turned off immediately after the catamaran stopped. After the experiment, the data were transferred to the computer and were processed.

Results and discussion

Based on the experimental data, the power output consumed by the motor or supplied by the battery was calculated from the current and voltage values recorded. The instantaneous power output of the solar cell was calculated from data on the power of the battery and the motor. Based on the values calculated, the corresponding energy values were identified for the solar cell, the motor and the battery for a particular time interval. The values calculated for the battery for a particular time interval could be both positive and negative, depending on whether the battery was charged or the battery's energy was used to run the motor at times when the solar energy was not sufficient to run the motor.

Data from one replication of the experiment at power setting 5 are presented in Figure 3. During the experimental trips, the solar intensity (S_{in}) reached 600 $W \cdot m^{-2}$ for the most period. At periods when the intensity of solar radiation decreased because the sun went behind clouds, the motor was powered by the battery. At that moment, there was also a slight decrease in the motor power (P_{mot}), on average from 325 W to 275 W at the 10940th second of the experiment. At sufficient solar intensity, the power output of the solar cell ($P_{solar\ cell}$) was usually equal to or slightly higher than the power input required to run the motor. The analysis of the trip revealed that battery charging was necessary only in the final part of the experiment after a longer period of low solar radiation intensity. At this stage, after the 12260th second of the experiment, the power output of the solar cell was on average 13.7% higher than the power input consumed by the motor. During the battery charging (P_{akb}), it is observed that the controller did not provide the same motor power as it did with a fully charged battery. During the battery charging, the motor power was on average 4.9% lower than that at the stages of the experiment when the battery was not being charged.

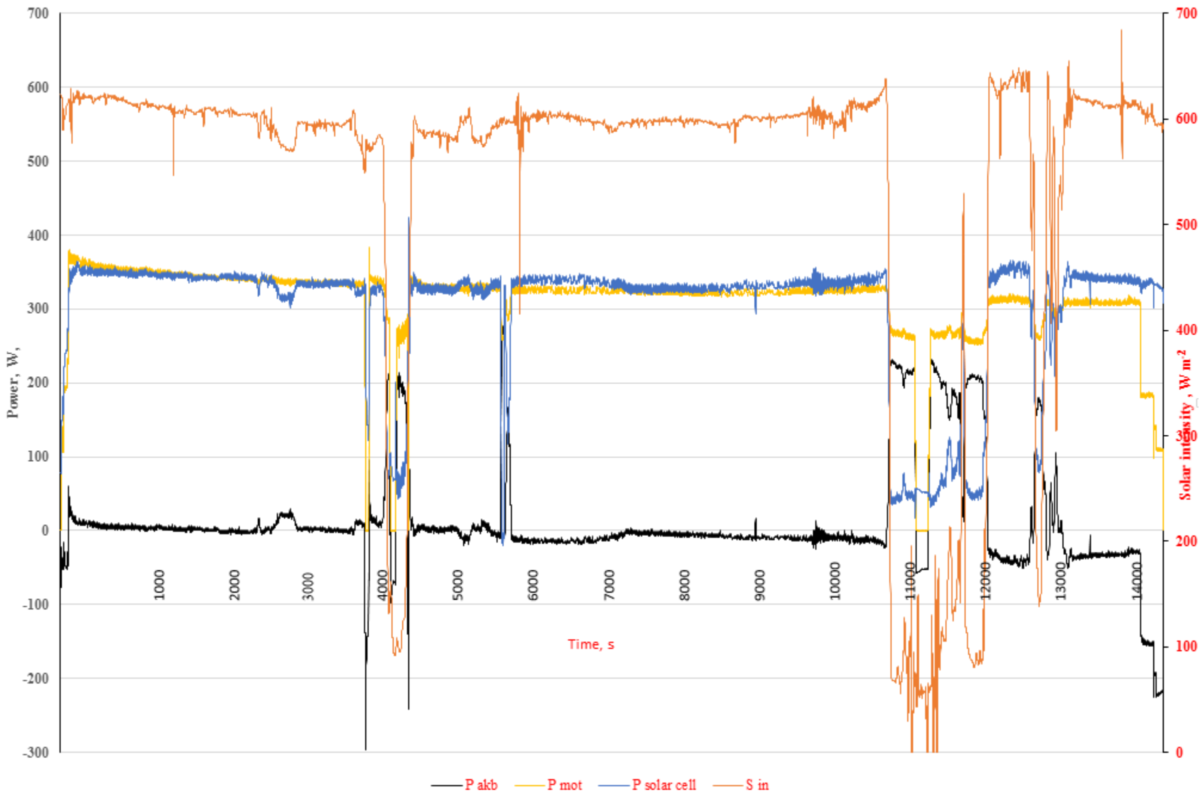

Fig.3. **Power parameter measurements at power setting 5**

The energy balance of the catamaran and the average values of solar intensity during the experiment are presented in Figure 4.

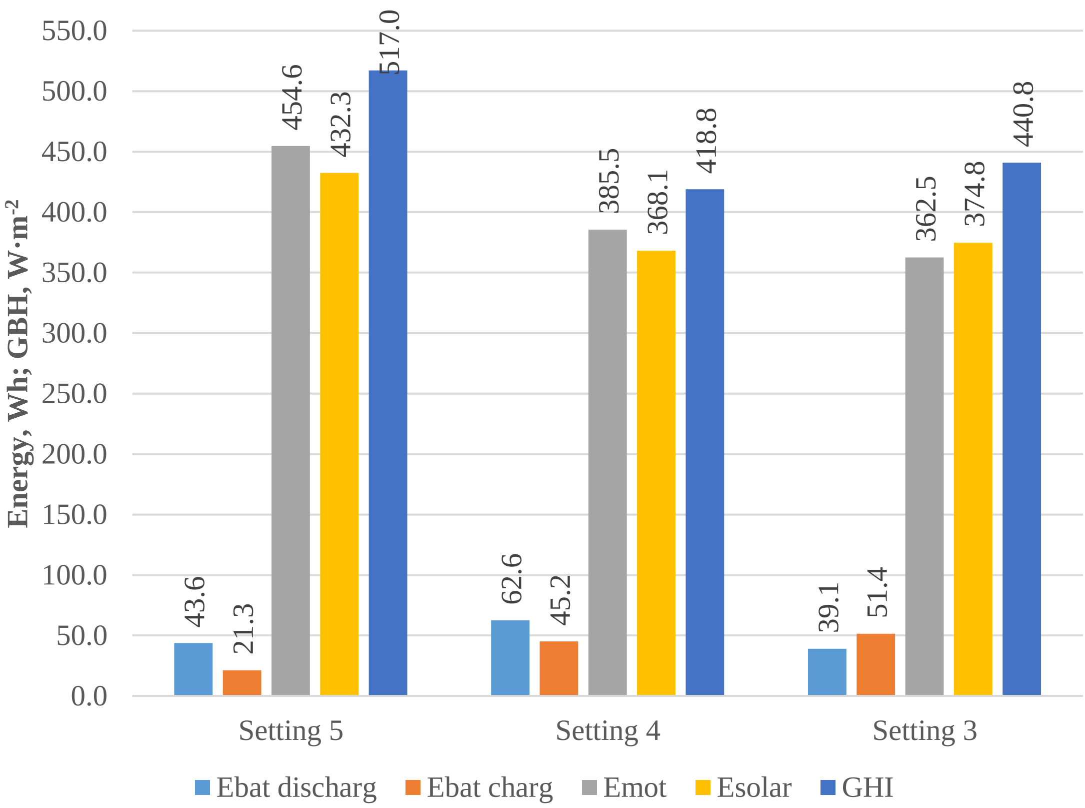

Fig.4. **Energy parameters of the catamaran during the experimental trips**

During the experimental trips, the highest value of solar intensity was observed at power setting 5, reaching 517.0 W·m^{-2}, whereas the lowest value was at power setting 4, which was 19% lower. The solar panel was capable of providing most of the energy required for the motor. At power setting 5, only 6.9% of the energy required by the motor was consumed from the battery, while at power setting 4.0-5.5%. Covering the energy deficit was necessary at periods when the intensity of solar radiation decreased due to the appearance of clouds. At power setting 3, the energy generated by solar radiation was 3.4% more than that required to run the motor. The energy was used to charge the battery, reaching 51.4 Wh, which was the highest value during the experiment. The highest battery discharge energy, 62.6 Wh, was achieved at power setting 4, which could be explained by a lower solar radiation intensity than that observed at other power settings. Due to the low intensity of solar radiation at power setting 4, the amount of energy required to run the motor was supplied from the battery. At periods when the intensity of solar radiation increased and the energy generated was more than that required to run the motor, the battery was charged. At power setting 5, the motor consumed an average of 454.6 Wh, which was the highest energy consumption during the experiment. At power setting 4, 15.2% less energy and at power setting 3, 20.3% less energy was consumed than that at power setting 5. When solar intensity is lower than 450 W·m^{-2} and it is necessary to cover a relatively long distance autonomously, it is recommended to use power settings 3 or 4 because the speed of the catamaran decreases only from 3.8 km·h^{-1} to 3.1 km·h^{-1} (at power setting 4) or 2.7 km·h^{-1} (at power setting 3), yet at the same time a significant energy saving is made, which allows the distance covered autonomously to be increased without additionally charging the battery.

The power parameters of the experimental catamaran at different power settings are shown in Figure 5.

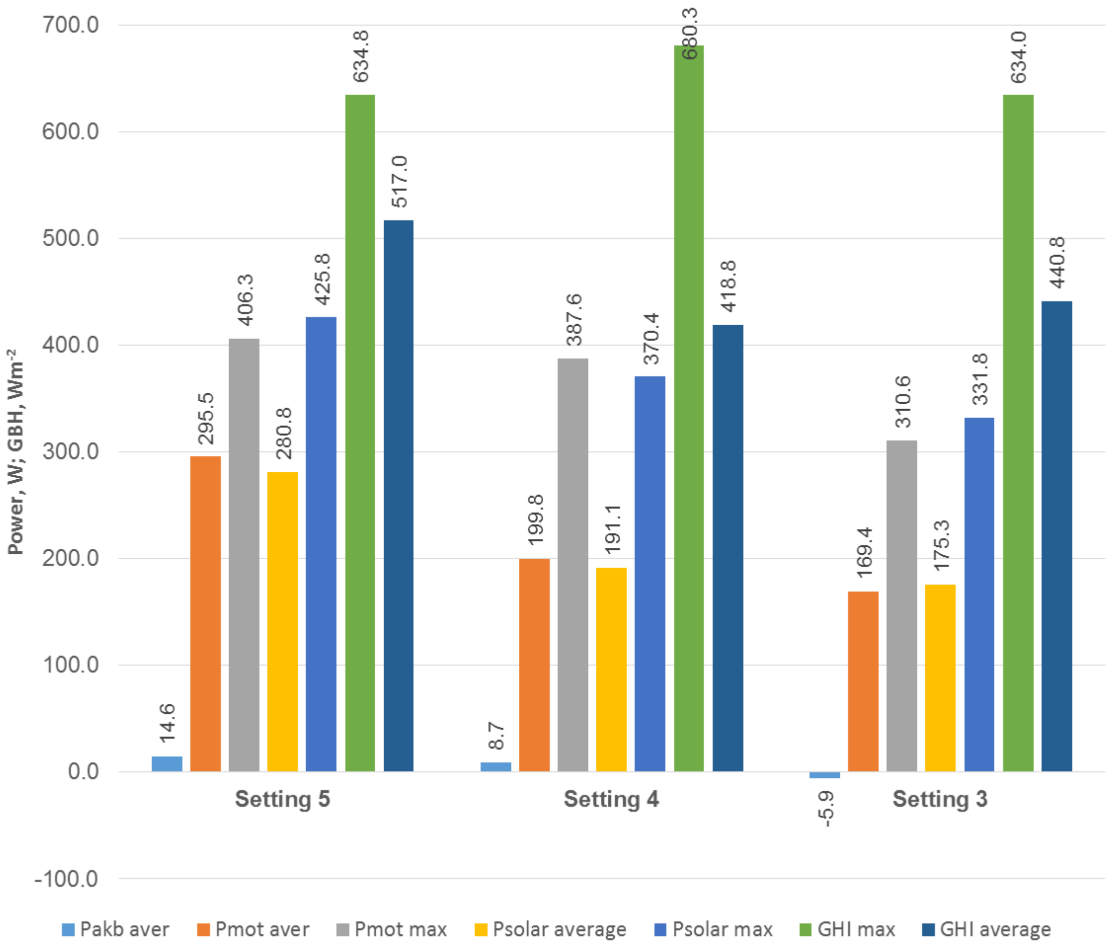

Fig.5. **Average power parameters of the catamaran during the experimental trips**

The maximum values of various parameters are usually very short-lived, for example, the maximum motor power values were observed at the moment of switching power settings when the instantaneous load on the propeller increased, for example, reaching 406.3 W at power setting 5. In steady movement, a power output of 295.5 W was obtained at this power setting. The MPPT solar controller adjusted the power output of the solar cell to the power input consumed by the motor and battery charging, which was evidenced by a decrease in the average power output of the solar cell in proportion to a decrease in the motor power at lower power settings. The average battery discharge power values were low, yet at power setting 3, the average battery charging power was 5.9 W. The average power output of the motor at power setting 4 was 32.4% lower than that at power setting 5, and 42.7% lower than that at power setting 3. Such a significant decrease in power at lower power settings could be explained by a decrease in the hydrodynamic resistance of the experimental watercraft, as the speed of it decreased. The highest solar intensity value was obtained at power setting 4, reaching 680.3 $W \cdot m^{-2}$.

Conclusions

1. Over the last decade, electric powered watercraft have been used in tourism and passenger transport. Electric batteries as well as hydrogen cells can be used as the main energy source to power the electric motor.
2. The use of solar cells in electric watercraft significantly reduces pollution, reduces noise caused by the engine and also makes economic savings during a longer period of operation. Solar energy is easier to use in watercraft than in land vehicles because the horizontal surface areas of watercraft are usually larger than those of land vehicles.
3. At an average solar intensity of 450-520 $W \cdot m^{-2}$, the experimental watercraft could move at all power settings without additionally charging the battery. When the intensity of solar radiation decreased, it was necessary to shift to power setting 4 or 3.
4. The prototype of a solar-powered catamaran could be charged even when anchored in the port, which facilitated the operation process, as there was no need to use the charging infrastructure of the port.
5. During the experimental trips on a 1.62 km section of the canal, the highest energy consumption of 454.6 Wh by the catamaran was observed at power setting 5, the solar cell at this setting generated 432.3 Wh of energy or 95.1% of the energy required for running the catamaran.
6. During the experiment, in case of excess solar energy, the battery was charged. If the energy generated by the solar cell was larger than what was needed to charge the battery and move, the controller performed energy absorption.
7. Solar panels of sufficient efficiency can be used in watercraft at latitudes up to 57º and solar altitudes up to 35º-56.14º without additional battery charging at all power settings.
8. The maximum power values of the motor and the battery were observed for a very short period, which did not exceed one second. After the movement of the catamaran or solar intensity stabilized, the power values approached the nominal values again.
9. A higher output power of the motor was achieved when using the solar cell as the main energy source than when powering the motor from the battery. This could be explained by the potentially higher voltage supplied from the solar cell.
10. As the intensity of solar radiation decreased and the power source for the motor was switched to the battery, the speed of the catamaran also decreased by 8-9% at power setting 5.

Author contributions

D. B.: Conceptualization, methodology, validation, experiment, visualization, writing. I. J.: formal analysis, literature analysis, data analysis, project administration, writing – review and editing. J. L. B.: prototype development, testing the prototype, experiment design. All authors have read and agreed to the published version of the manuscript.

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