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DETERMINANTS OF THE ELECTROMOBILITY DEVELOPMENT SECTOR ON WATER

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Purpose: The aim of the article is to identify selected factors of the development of electromobility in water tourism.
Design/methodology/approach: The subject of the conducted analyses was to determine the demand for energy to propel tourist vessels, possible gains from energy generated in photovoltaic panels installed on yachts and the condition of the tourist infrastructure necessary to support electromobility on water.
Findings: The conducted analysis allowed to determine the energy consumption graph for the tested unit and the real energy yield from PV panels.
Research limitations/implications: Energy consumption for propulsion depends to a large extent on the type, weight and speed of the yacht. Further research should focus on optimizing the hull shape, the type and systems of PV panel installation. It is also necessary to analyze the even distribution and modernization of existing infrastructure and indicate directions of development and good practices in the management of inland ports.
Practical implications: The research conducted indicates the validity of using ecological electric drives in water tourism.
Social implications: Lack of awareness of the benefits of using ecological propulsion on vessels and the inadequacy of existing infrastructure limits the possibilities of developing electromobility.
Originality/value: The conducted research provided results of energy consumption and possible yields from installed PV panels during normal operation of the vessel. The results may contribute to the popularization of the use of electric drives.
Keywords: Ecomobility on water, PV panel efficiency, inland waterways, tourist infrastructure.
Category of the paper: Research paper.

1. Introduction

Waterways have been used for economic purposes since ancient times. The extensive system of lakes and rivers constituted natural connections used for the transport of commercial cargo and promoted the development of adjacent areas. In different periods, these roads gained or lost their importance, but they always played a key role in the development of the local economy. Inland waterway transport is considered more environmentally friendly and economically justified compared to road transport (Chrysty et al., 2020; Barros et al., 2022; Calderón -Rivera et al., 2024; Erceg, 2019) . Studies conducted in many places around the world indicate the benefits of using inland waterway transport (Calderón-Rivera et al., 2024b; Cheranchery, 2024; Kader, Olanrewaju, 1AD; Kenc, Szostak, 2022; Plotnikova et al., 2022a; Rohács, Simongáti, 2007; van Lier, Macharis, 2014; Xie, 2021). The most important advantages include financial benefits resulting from reduced logistics costs (Nachtmann et al., 2015, p. 46), and reduced negative environmental impacts (Jurkovič et al., 2021, p. 250; Barros et al., 2022; Calderón-Rivera et al., 2024a; Kader, Olanrewaju , 1AD; Kenc, Szostak , 2022; Maloberti et al., 2022). The waterway network in Europe is well developed. Despite numerous environmental benefits, in many regions, such as Spain, France, the Czech Republic, Serbia, Belgium and England, there is a noticeable decline in the importance of inland waterway transport (Erceg, 2019). However, it should be noted that there are countries, such as Bulgaria and Hungary, where an increase in the volume of cargo transport was noted (UN, 2022, p. 127).

In the face of the green transformation and the assumptions adopted by world leaders to reduce CO2 emissions, an increase in interest in developing inland transport networks should be expected (Bielawa, Cywiński, 2024, p. 6; Calderón-Rivera et al., 2024a; Erceg, 2019; Kader, Olanrewaju , 1AD; Kenc, Szostak, 2022; Plotnikova et al., 2022b; van Lier, Macharis, 2014).

Inland waterways and unclassified waters suitable for navigation are also an attractive tourist area with high natural values and great development potential. The need to expand infrastructure enabling safe operation of navigation can be used to develop water tourism, including the increase in the use of vessels powered by electric engines. The development of electromobility on water, due to the specificity of using yachts with ecological drive, will have a positive impact on the state of the natural environment (Barros et al., 2022; Calderón-Rivera et al., 2024a; Rohács, Simongáti, 2007; Xie, 2021). Determining the real energy consumption necessary to drive electric yachts, and therefore their range, and identifying requirements for the equipment of marinas and ports will allow for the popularization and development of ecological water tourism.

In planning and modernizing tourist infrastructure related to the service of users using vessels on inland waterways, special attention should be paid to compliance with the principles of sustainable development, taking into account the possibilities of technical progress and the directions of changes in European legislation. The development potential of the electromobility sector on water depends on a number of factors (Kramarz et al., 2024, p. 49), which include, among others, the condition of tourist infrastructure, economic and technical barriers related to the acquisition and storage of energy to drive small vessels

2. Waterways in Poland

Waterways in Poland constitute an extensive network of connections including regulated navigable rivers – 65.6% (2522 km), canalized sections – 17.8% (656 km), canals – 9.4% (355 km) and navigable lakes – 7.2% (255 km) (GUS, 2023). The hydrotechnical infrastructure, managed by the State Water Management Polish Waters, includes locks and slipways, which enable safe movement of vessels. Currently, 94.2% of navigable routes are available for use, which is 3549 km.

Detailed operating parameters of inland waterways are specified in the regulation of the Council of Ministers on their classification (Rozporządzenie…, 2002). The document specifies the minimum navigation parameters for selected waterways. The regulation also specifies the maximum parameters of vessels for individual classes of waterways. According to Annex 1 to the regulation, vessels with a maximum length of 24 meters, width of 3.5 meters and a draft of up to 1 meter may sail on waterways of regional importance (class Ia, Ib, II and III). The total length of routes of classes I, II and III is 3561.5 km (GUS, 2023). Access to water bodies in Poland is not formally limited, but violations of the regulations, such as blocking access to the coastline, often occur (Jóźwiak, 2024, p. 39).

Despite favourable infrastructural conditions and structural support, there has been a clear decline in interest in water transport in Poland, which is also visible in the aging rolling stock (Kenc, Szostak, 2022; Zielińska, 2018, p. 838).

Many years of neglecting investments in maintaining proper navigation parameters of waterways resulted in 90% of domestic cargo transport taking place on local sections of the Oder (Deja et al., 2017, p. 87).

Taking into account the parameters of vessels used in recreational navigation, there are no practical restrictions on their use on classified waterways, even with the lowest parameters, provided that the current hydrological conditions and the specific nature of the route are taken into account.

3. Determination of energy demand for the propulsion of vessels

Economic analyses show that inland waterway transport is definitely the cheapest and more environmentally friendly. This is mainly due to the amount of power required to move a given mass of cargo. Road transport requires 8-10 kW of power per ton of cargo, rail transport 0.8-1.0 kW, while inland waterway transport only 0.2-0.4 kW of energy (Winter, Kulczyk, 2003, p. 13).

Table 1.
Energy consumption and pollutant emissions in different means of transport (German data)

Means of transport	Energy consumption kJ / tkm	Pollution, g/ tkm			
		CO2	CH4	NOx	WHAT
Rail	677	41	0.06	0.2	0.05
Shipping	584	42	0.06	0.5	0.17
Car	2889	207	0.3	3.6	2.4
Plane	15800	1106	1.5	5.3	1.4

Source: Kulczyk, Winter, 2003.

The development of hybrid yachts powered by energy from photovoltaic (PV) panels and diesel fuel can significantly reduce fuel consumption and CO2 emissions (Kenc, Szostak, 2022). In the case of 70% coverage of energy from PV, CO2 production drops to 2.1 tons per year, while fuel savings mean that the payback period for this type of boat can be achieved after 12 years (Kurniawan, 2016, p. 5).

A yacht equipped with a purely electric drive is a solution that can result in a complete reduction of CO2, NOx and SOx, which are dangerous to the ecosystem. The return on high investment costs is estimated at 10 years (Kurniawan, 2016, p. 6). Yachts powered exclusively by electricity, which is mainly obtained from PV panels, are small recreational vessels and fishing boats. Depending on the purpose and conditions in which they are to be used, they are designed using the latest technologies to optimize its technical parameters, including resistance, weight and possible areas for PV panel installations (Pencheva et al., 2019; Xie, 2021; Kurniawan, 2016, p. 2).

A houseboat-type motor yacht built on the hull of a seagoing lifeboat was used to conduct tests of the drive’s energy consumption. The basic technical parameters of the unit are: total weight 3.5 t, length Lc-7.95 m, width Bc-3 m, draft T-0.6 m. The main drive was an INTO electric motor (induction, asynchronous) with a maximum power of 38 kW, powered by energy stored in 8 150 A 12 V AGM VRLA batteries, creating a 300 Ah power bank at 48 V. The yacht was equipped with devices enabling the recharging of electric energy based on the available basic technical infrastructure, most common on Polish waterways (Łapko, 2015).

Energy demand tests were conducted in conditions optimal for recreational sailing – wind up to 3 m/s, small waves, which corresponds to 2 on the Beaufort scale. Energy measurements were read from on-board devices Victron Energy Battery Monitor BMV 712 Smart 12/24/48V. Speed measurement was performed based on the NavShip application using GPS positioning.

The conducted research allowed to determine the real demand for energy necessary to move the unit. Graph 1 shows the relationship between the speed of sailing and the consumption of electricity stored in the batteries. Analyzing the presented graph, the unit used 1-1.4 kWh of energy at a speed of 6-6.5 km per hour. Considering that the speed limit in the channels is usually 6 km/h, the achieved cruising speed of the yacht is acceptable. However, it should be noted that, as in the case of eco-driving, the adoption and adherence to the assumed rules regarding the style of driving the vehicle must be fully understood and accepted by the driver or helmsman.

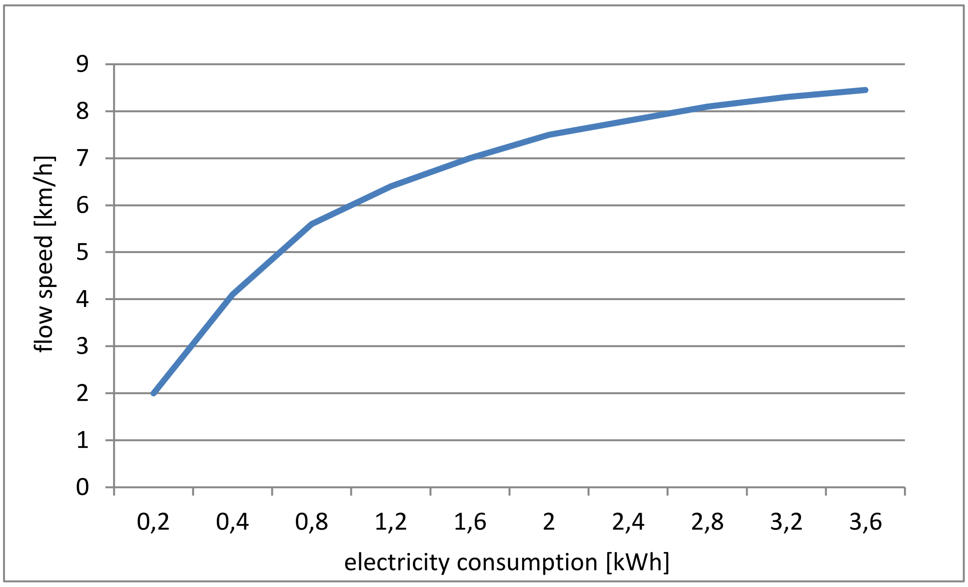

Figure 1. Relationship between flow speed [km/h] and electricity consumption [kWh].
Source: own study.

It is also worth paying attention to the economics of sailing itself. In the case of using vessels equipped with a combustion engine (leaving aside the issues of noise and pollution resulting from exhaust emissions), pleasure yachts consume from 3 to 5 liters of fuel per hour. The cost of sailing for 5-7 hours is therefore PLN 100-220 per day. Even with maximum economical sailing on similar vessels and at the same speed, it is difficult to achieve a cost below PLN 60 per day.

During the measurements, the duration of the electric engine operation depended on the distance to be covered on a given day, and the average time of its use was 9.5 hours per day. On the Gdańsk-Iława route, energy consumption was 12-13 kWh per day. Energy consumption during sailing on the Iława-Ostróda-Zalewo route was an average of only 7 kWh per day.

The measurements carried out indicated a significant increase in the consumption of electric energy from the batteries at speeds above 6.5 km/h. Achieving higher speeds is possible, but not very economical and involves a significant limitation of range or the need to increase the battery capacity, and therefore an increase in the yacht's weight.

The batteries of the tested unit have 14.4 kWh of energy available. Taking into account the battery life, the maximum degree of energy use was assumed at 70%, which gives about 10 kWh of energy to be used. It should therefore be assumed that the energy stored in the batteries allows economical sailing for up to 8-10 hours, covering up to 60 kilometers.

An additional source of energy that increases the potential distance that can be covered are photovoltaic panels. Currently, photovoltaic panels are increasingly installed on vessels, where they support the power supply of on-board systems. The introduction of new solutions and technologies will allow for increased energy production and its use also for the propulsion of the unit (Pencheva et al., 2019; Xie, 2021).

4. Testing the efficiency of PV panels on a vessel

Analysis of the efficiency of photovoltaic panels has been conducted on the tested vessel since 2021. The aim of the analyses is to determine the amount of energy that can be obtained in real conditions, i.e. during standard use of the yacht.

The vessel was initially fitted with flexible photovoltaic panels, which are a popular solution on yachts due to their ability to adapt to the curves of the hull. For testing, eight flexible Green Cell photovoltaic panels (100 W, 12 V/18 V ETFE) with a total power of 800 W were fitted. The electricity generated during the voyage was directly used by the vessel's drive engine. During the stop, the energy generated by the panels was stored in batteries.

To determine the potential for energy yield in real conditions, weekly periods from July and August in 2021–2024 were analyzed, selecting those with the highest energy production. This approach corresponds to the length of a standard recreational cruise and allows for a reliable assessment of the system performance. The measurement results are presented in Table 2 and Table 3.

Table 2.
Performance study of flexible PV panels on a vessel in 2021-2023

Date	Energy yield (Wh)	Max PV power (W)	Max PV Voltage (V)	Min. battery voltage (V)	Max battery voltage (V)	Time in mode bulk (m)	Time in mode absorption (m)	Time in mode float (m)
18/07/2021	2710	624	85.57	48.98	56.9	858	2	128
17/07/2021	2880	568	78.62	46.58	54.78	988	0	0
16/07/2021	1680	512	85.33	48.27	56.73	904	1	91
15/07/2021	1840	564	80.68	50.07	56.66	526	71	390
14/07/2021	3790	479	80.05	49.89	55.93	1008	0	0
13/07/2021	3720	658	80.57	49.84	55.62	1009	0	0
12/07/2021	2620	592	86.55	49.25	56.91	849	1	148
Total 2021	19240							

Cont. table 2.

23/07/2022	1340	548	86.56	46.73	56.79	702	1	248
22/07/2022	2140	560	86.22	48.17	56.76	778	1	198
21/07/2022	3060	487	81.43	49.14	56.88	889	60	34
20/07/2022	2510	470	81.57	49.18	57.04	993	14	55
19/07/2022	1830	479	82.99	49.92	57.07	489	65	122
18/07/2022	1900	585	86.44	50.21	57.16	711	96	178
17/07/2022	1690	675	87.47	49.53	57.04	695	51	246
Total 2022	14470							
07/07/2023	770	209	88.05	49.04	56.94	939	1	86
07/06/2023	640	192	81.77	47.32	56.15	1009	0	0
07/05/2023	840	166	81.23	47.04	55.98	971	0	0
07/04/2023	970	213	78.36	48.17	52.99	1026	0	0
07/03/2023	660	175	81.82	51.6	53.88	1032	0	0
07/02/2023	810	355	80.2	51.7	54.3	1006	0	0
07/01/2023	760	277	81.16	51.75	53.66	1009	0	0
Total 2023	5450							

Source: own study.

In the most efficient weekly cycle in 2021, the PV panels produced a total of 19,240 Wh of energy, reaching a maximum instantaneous power of 658 W. Daily efficiency on July 13 and 14, 2021 exceeded 3.7 kWh, which significantly affected the yacht's range.

The 2022 results showed a decrease in energy yield of almost 5 kWh per week compared to the previous year. Nevertheless, daily maximum power values were comparable to the 2021 results. This decrease in efficiency raised suspicions about possible degradation of the flexible panels.

In 2023, a clear drop in the efficiency of flexible panels was noted - they produced 5450 Wh of energy in a week, and the maximum instantaneous power was only 355 W. These results confirmed the progressive decline in the efficiency of flexible panels, but the rate of degradation in a relatively short time remains surprising.

In connection with the above, a decision was made to dismantle the flexible panels in order to conduct detailed studies aimed at explaining the causes of premature loss of efficiency. The results obtained will contribute to the development of technology and deepening knowledge about the degradation processes of PV panels.

Table 3.

Performance testing of rigid PV panels on a vessel in 2024

Date	Energy yield (Wh)	Max PV power (W)	Max PV Voltage (V)	Min. battery voltage (V)	Max battery voltage (V)	Time in mode bulk (m)	Time in mode absorption (m)	Time in mode float (m)
7/19/24	840	195	79.29	51.99	56.95	260	21	739
7/18/24	1060	234	79.94	52.04	56.95	272	58	686
7/17/24	4630	651	76.74	50.62	56.77	770	107	141
7/16/24	3710	781	75.73	49.18	56.9	956	68	0
7/15/24	3330	657	75.93	50.26	56.92	827	65	119
7/14/24	4580	712	75.11	49.97	56.55	1038	0	0
7/13/24	1140	412	79.44	49.85	56.98	570	70	376
	19290							

Source: own study.

In July 2024, panels in a rigid aluminum frame were installed on the tested vessel - two JA SOLAR JAM60S20-HC MONO 385W MR modules, with a total power of 770 W. In the most efficient week in 2024, 19,290 Wh of energy was obtained, reaching a maximum instantaneous power of 781 W. Daily energy production exceeded 4.5 kWh twice, reaching values of 4580 Wh and 4630 Wh.

In 2024, in two cases, the daily energy yield was almost 1 kWh higher than the best results from 2021, despite the fact that rigid panels had 30W less nominal power than flexible panels. The disadvantage of rigid panels is the inability to adjust to the curves of the yacht's hull. However, on houseboats, the installation of rigid panels is possible and practical.

5. Adaptation of infrastructure to support electromobility on water

A key element of the development of electromobility on water is investing in infrastructure that enables battery charging on inland waterways. The results obtained indicate that the energy produced by PV panels can significantly extend the range of navigation. However, in houseboat -type vessels, most often used for recreational leisure, it is necessary to supplement the energy deficit.

In the case of using electric yachts, including those supported by energy obtained from PV panels, there is no need to use specialist electrical installations. The specificity of recreational inland navigation means that units most often spend the night in ports adapted for this purpose. The demand for energy and the scale of required security do not significantly affect the energy system. The vast majority of ports and marinas already have sufficient infrastructure or can easily adapt their installations to service yachts powered by electricity.

Development of electromobility sector on water, including the support and motivation system for recipients, can be compared to the development of electric road transport. The existing financial incentive systems for car users and for companies involved in the construction and operation of vehicle charging infrastructure are an important factor in the development of the sector (Kosiarz, 2021, p. 119).

The Act on Electromobility and Alternative Fuels specifies the principles for the development of infrastructure for electromobility on water, treating it on an equal footing with other transport segments (Act…, 2018).

The formal requirements specified in the Act (Act…, 2018), e.g. regarding the technical inspection of power supply points by the Transport Technical Supervision, mean that in Poland there is probably no single point enabling the legal charging of large commercial vessels with electric drive currently. However, taking into account the specificity of charging tourist vessels, in almost every port there is sufficient infrastructure to replenish the energy in batteries.

In the unit used, the cost of replenishing the energy balance was around PLN 5-7 per day (if it was necessary to recharge the batteries) and it was included in the standard fee for staying at the marina.

6. Summary

Electric yachts may be the future of water tourism. Taking into account the specificity of using units with an electric engine, cruise routes should be designed based on the possible distance, time and possibilities of recharging batteries in ports adapted for this purpose. Apart from the main water tourism centres, such as the Great Masurian Lakes route, the infrastructure is poorly developed, which significantly limits the possibilities of developing water tourism based on electric yachts. Further research into the optimal development of waterway infrastructure, dissemination of research in this area and promotion of good practices will be conducive to the development of tourism using electric boats, positively affecting the state of the natural environment.

Research conducted in 2021-2024 showed the feasibility of installing an electric motor in houseboat yachts. The electric motor used together with a 300 Ah 48 V energy storage proved to be a sufficient source of propulsion, consuming an average of 1.2 kW of energy per hour. Additional energy obtained from PV panels improved the energy balance, significantly extending the time of recreational sailing.

Dynamic technical progress, mainly in the area of using capacious energy banks, results in increased possibilities of using electric energy to propel vessels. In addition to research on the capacity of energy banks and their charging speed, further research may focus on optimizing the shape of the hull and the type and systems of PV panel installation. The collected research results indicate a large potential for the development of tourism with electric yachts on inland waterways, but also the need for additional analyses in the area of even distribution and modernization of existing infrastructure.

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