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Review

Solar Energy-Powered Boats: State of the Art and Perspectives

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Abstract: This paper presents an examination of the primary applications of solar energy as the main power source in the maritime sector, focusing on recent developments. A comprehensive review of the existing literature, including journal articles, proceedings, and patents, is conducted to identify three prominent areas for advancing solar energy-powered boats: maritime drones, sporting boats, and short-range touristic vessels. Maritime drones primarily serve as small autonomous boats for research, conservation, or military operations. On the other hand, sporting boats include nautical and energy design competitions involving students and enthusiasts. In terms of commercial interest, there is a growing demand for environmentally friendly and low-noise boats suitable for tourist activities, particularly in protected areas. Furthermore, specific and illustrative cases are explored in a dedicated section. Lastly, potential future perspectives are discussed and elucidated.

Keywords: solar energy; photovoltaic panels; electric boats; autonomous naval vehicles; hydrofoils

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1. Introduction

The demand for enhanced transportation efficiency has gained significant importance due to the reliance on fossil fuel-powered (a progressively scarce energy source) vehicles, which result in the emission of substantial toxic pollutants that exacerbate the greenhouse effect. Within the automotive sector, there have been endeavors to develop vehicles that can serve as alternatives to combustion engine cars, such as electric vehicles and solar energy-powered vehicles [1]. This necessitates various interdisciplinary design activities [2] aimed at reducing weight, improving aerodynamics, and enhancing the functional features of solar vehicles [3–5].

Solar energy-powered boats have emerged as a noteworthy solution for environmentally friendly transportation, starting with Alan T. Freeman's pioneering solar boat called Solar Craft 1 in 1975 [6]. These boats have garnered increasing interest from esteemed boatyards, universities, and research centers worldwide, as they address the need for eco-friendly transportation (refer to [7] for a recent review on the life cycle assessment of PV panels).

Solar-powered boats offer a multitude of advantages detailed in [8]. Firstly, they boast the remarkable attribute of emitting zero greenhouse gases, thus making a substantial contribution towards combating the urgent global issue of climate change and safeguarding both human society and biodiversity. Moreover, these boats are entirely independent of fossil fuels, which are exhaustible energy sources, thereby providing a sustainable and resilient alternative. Another notable benefit lies in their remarkably low noise levels, courtesy of employing electric motors, enabling a quiet onboard environment. Furthermore, solar-powered boats exhibit reduced maintenance costs, owing to their simpler machinery and limited number of moving parts, facilitating straightforward operation and upkeep utilizing commonly available tools. Lastly, these boats ensure heightened safety by eliminating the need to carry substantial quantities of fuel and oil, effectively mitigating the potential risks of spills and fires. Collectively, solar-powered boats present an esteemed choice for a greener, quieter, and safer boating experience.

Compared to other solar vehicles, such as the car discussed in [2], solar boats possess greater potential for three main reasons: the first is related to the overall dimensions. The roof area of an automotive vehicle typically ranges from 5 to 6 m^2 for a car [9] and up to 34 m^2 for a truck [10], allowing for a peak PV power output in the range of 1 to 6 kW. However, this constitutes only a tiny fraction of the engine power, particularly for larger vehicles. Conversely, the designer enjoys substantial freedom in determining the shape and size of PV panels for boats. The second reason is related to the shape of the panels, which consists of lower aerodynamic requirements due to the generally limited speed of this kind of vessel. And finally, third, the boats spend most of their useful life directly exposed to the sunlight.

Nevertheless, the feasibility of a solar boat hinges on achieving the highest level of energy efficiency, which relies on various design and manufacturing aspects.

This work aims to offer a comprehensive review of how these factors have been embodied in different boat types in the past, mostly prototypes, to serve as the foundation for further developments for the design activities in the fields described in the following sections.

Although several recent reviews have been published on this subject [11–14], the perspectives of these authors differ, as they also encompass hybrid boats and other renewable energy sources and do not consider certain classes of solar maritime vehicles.

This paper focuses solely on boats that are primarily powered by solar energy and occasionally supplemented by wind or wave energy, thereby excluding boats equipped with internal combustion motors [15].

Therefore, attention will be directed towards the categories of boats where the practical significance of solar–electric propulsion has been established, namely, small autonomous boats, leisure vessels designed for slow and limited-range tours, and sporting boats.

The depicted powertrain configuration in Figure 1 represents the typical setup observed in the analyzed cases, including the solar panel with MPPT charge controller, the battery with the BMS system, DC converters, inverters, and the electric motor.

While selecting suitable PV systems is an area of significant interest [16], comprehensive details regarding the specific PV cell types employed are scarce in the reviewed literature. However, it is commonly noted that mono or polycrystalline silicon-based cells are utilized. Likewise, the discussion on motor configurations is not extensive but various options, such as brushless, asynchronous, or DC configurations, are encountered.

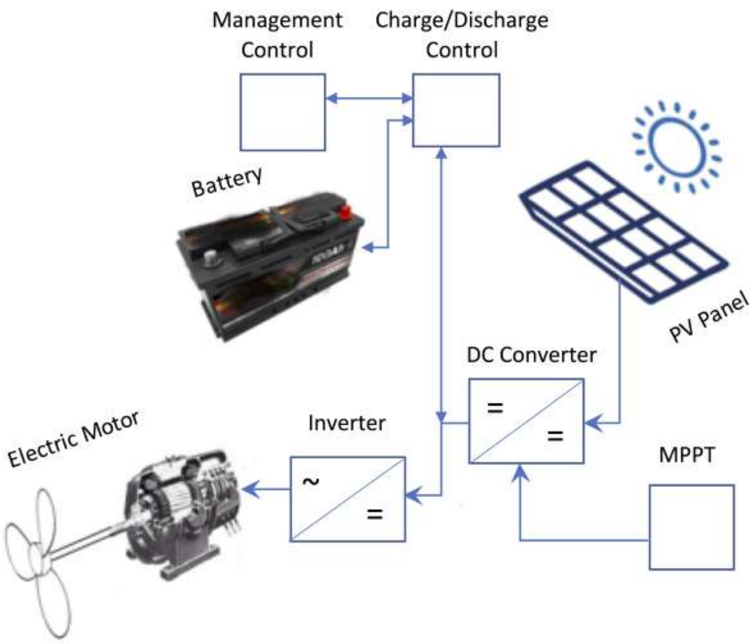

Figure 1. Scheme of the typical powertrain of a solar boat [17].

Figure 2 schematically depicts the various types of boats discussed in the subsequent sections. One can observe a displacement hull (SWATH), three potential displacement or planing hulls, namely the catamaran, monohull, and trimaran, and the flying monohull with hydrofoils, primarily reserved for sporting-type vessels.

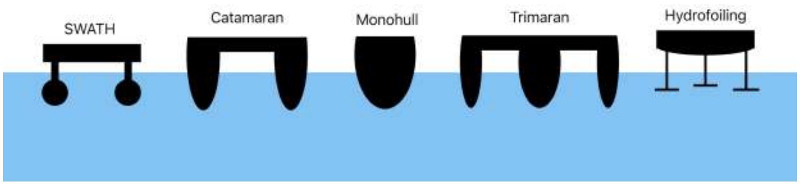

Figure 2. Different typologies of the boats mentioned in the paper.

The first paragraph examines maritime drones, the second focuses on sporting boats, and the third analyzes tourist boats. The paper concludes with a final section dedicated to other specific applications, followed by summarizing remarks and potential avenues for further development.

2. Maritime Drones

In recent years, autonomous vehicle studies have expanded across various domains, including aeronautics, automotive, and maritime applications [18,19]. Solar-powered autonomous surface vehicles (ASVs) offer the advantage of not requiring refueling or recharging at their base (port or mothership), thus potentially extending their mission's temporal and, in some cases, spatial range.

Maritime drones are primarily utilized for scientific monitoring purposes or military operations. In scientific monitoring, autonomous sailboats equipped with limited solar panels and small batteries are often employed to power control devices and auxiliary electric motors [20–23]. Notable early applications include low-cost, reusable, re-configurable ASVs developed to facilitate research on carbon dioxide air–sea flux and phytoplankton productivity [24,25].

An innovative system proposed in [26] combines autonomous vehicles and fixed buoys, achieving complete power and navigation autonomy through a fuzzy decision-making software architecture. This solution offers the maneuverability of a drone while enabling anchoring to the seabed, functioning as a buoy for measurements or battery recharging, ensuring the required energy autonomy for sustained operations.

Recent documentation by [27,28] showcases the use of commercial monohull ASVs for sea environmental monitoring. In [29], a commercial ASV is employed in the polar region, operating continuously during the long polar day months and at least two weeks during the polar night, emphasizing the need for reliability due to limited vehicle access. In this case, the ASV harnesses wave power and employs a solar-powered auxiliary motor.

Contrasting the earlier monohull boat approaches, ref. [30] presents a solar catamaran capable of autonomous navigation and continuous collection of water quality information in lakes. Another catamaran named Morvarid, described in [31], focuses on hydrography mapping and the characterization of shallow water environments like rivers, estuaries, lakes, and dams, emphasizing the optimization of energy harvested by PV panels.

Some drones may be small in size (less than 1 m) and operate at low speeds, such as those developed by [32] for seabed depth measurement in coastal regions or the recent drone described in detail by [33].

While there is a lack of scientific open literature on military drones, Figure 3, taken in January 2023 in the Persian Gulf, demonstrates their relatively high technological readiness level, likely based on a conceptual design similar to [23]. The picture shows two Saildrone Explorer unmanned surface vessels and the guided-missile destroyer USS Delbert D. Black. The appearance of the U.S. Department of Defense visual information does not imply or constitute DOD endorsement.

Figure 3. Photo by Mass Communication Specialist 2nd Class Jeremy R. Boan, from the U.S. Naval Forces Central Command website, for public release.

Solar-powered autonomous underwater vehicles (AUVs) also find applications but they necessitate solar panel exposure to sunlight. To address this requirement, ref. [34] proposes a solution wherein the AUV mission involves daily charging during sunlight hours and nighttime operation. This concept enables virtually unlimited endurance for ocean survey purposes. However, the growth of marine life on the solar panel surface poses a specific challenge in this application.

In order to overcome the aforementioned issue, ref. [35] develops an AUV that tows a surface boat equipped with solar panels and a fuel cell. This integrated system is designed for environmental monitoring and water quality assessment.

A distinct type of AUV is the solar glider as pioneered by [36]. While also geared towards underwater observation, this AUV lacks conventional propulsion mechanisms. Instead, its motion is controlled through buoyancy and the presence of hydrodynamic wings. This unique design allows the solar glider, a relatively small vehicle, to be powered by solar energy during surface intervals.

An ASV tows a sensor device in a different application discussed in [37]. This approach combines mechanical energy harvesting from sea waves and solar energy to power the control electronics and payload. Notably, this configuration offers advantages for acoustic sensors by mitigating interference from powertrain noise.

Table 1 summarizes the key characteristics of the aforementioned autonomous solar-powered vehicles. The dimensions range from model sized to those typical of small boats, with a focus on achieving autonomy at modest speeds. Consequently, the power output of photovoltaic panels varies from a few watts to 1 kW.

Table 1. Characteristics of the mentioned maritime drones.

Reference	Typology and Name of the ASV/AUV	Dimension and Weight	Solar Panel, Motor Power and Battery Capacity	Notes
[20]	Sailboat	4.2 m // //	25 W // 2.0 kWh	Equipped with a 5 m span rigid sail
[22]	Sailboat ASAROME	3.5 m // //	60 W // 7.7 kWh	Equipped with flexible sails, solar panel flat on the deck, and Savonius wind generator

Table 1. *Cont.*

Reference	Typology and Name of the ASV/AUV	Dimension and Weight	Solar Panel, Motor Power and Battery Capacity	Notes
[23]	Sailboat //	4.18 m 1.05 m 470 kg	50 W // 1.3 kWh	Equipped by rigid sail, and solar panel with sun tracking
[24,25]	Monohull //	5.5 m 1.5 m 1500 kg	1000 W // //	May form a fleet of long duration ASV platforms, but with a limited speed (3 km/h)
[26]	Monohull Buscamos-RobObs	5.0 m 1.97 m 1000 kg	1000 W 1800 W 10.8 kWh	Slow, but with 6 h autonomy. It can act like a buoy
[27,28]	Monohull SeaTrac	4.8 m 1.39 m 300 kg	750 W 500/1000 W 6.75 kWh	Highly hydrodynamic hull, effective control, very precise navigation
[29]	Monohull Autonaut	3.5 m 0.7 m 180 kg	315 W // 840 Wh	Very extended autonomy due to the combined use of wave energy
[30]	Catamaran //	4.9 m // //	300 W // //	Extended autonomy up to 24 h, safety docking capabilities
[31]	Catamaran Movarid	3.875 m 2.33 m 700/1700 kg	300 W // 8000 Wh	Equipped with a large solar panel. Sun tracking on one axis only
[32]	Paddle wheel boat //	0.86 m 0.63 m <39 kg	30 W // 84 Wh	Semi-autonomous, equipped with paddle wheels, extremely cheap
[33]	Monohull //	1.0 m // //	55 W // 84 Wh	Extremely small and cheap
[34]	AUV SAUV II	2.3 m 1.1 m 200 kg	120 W // 2 kWh	The PV panels suffer from marine life growth while submerged.
[35]	AUV/Boat Solar AEGIR	1.6 m 0.6 m 168 kg	80 W // 300 Wh	The PV panels are towed on a small surface vehicle
[36]	AUV Glider SORA	0.7 m 0.73 m 3.5 kg	1.5 W 5 W Capacitor	No motors, only buoyancy control, extremely efficient
[37]	AUV/Board The Wave Glider	2.0 m 0.6 m 75 kg	86 W // 665 Wh	Powered by sea waves

3. Sporting Boats

Solar boat competitions started in Japan in 1989 [38] and have been a prominent feature in various countries, serving as practical educational experiences for college and high school students. These events [39], such as Solar Splash and California Solar Regatta in the USA, Desafio Solar in Brazil, Frisian Solar Challenge and Young Solar Challenge in the Netherlands, and Monaco Energy Boat Challenge, allow students to develop interdisciplinary skills and teamwork abilities [40–42]. Technical subjects are also taught during these activities as exemplified by [43], which focuses on the naval and mechanical engineering aspects of hull construction in solar boats. Moreover, the competitions offer students opportunities to develop non-technical capabilities like leadership, effective communication, conflict resolution, and teamwork, thus fostering their lifelong learning skills [44].

In the present day, the World Cup Series in solar boats is organized by Solar Sport One. This series comprises a group of competitions that follow regulations periodically updated every five years. These regulations dictate the project specifications for building solar boats. Although limited archival papers exist on the design process, references to early projects can be found in papers such as those presented at the ASME Solar Energy conference, which were not digitally available until 2001. Nevertheless, the current regulations for each competition, along with numerous examples of specially developed boats, can be found online.

Early solar boats from Marquette University are mentioned in [38], which participated in competitions in Japan and the USA during the 1990s. The development of the first model of Korean sporting solar boats in 2006 is described in [45], while [46] provides details on the design of two successful Turkish solar boats, focusing on hull shape and powertrain optimization in compliance with competition regulations.

In [47], the key characteristics of boats competing in the Frisian Solar Challenge 2010 are listed, including the typology, dimensions, and solar–electric powertrain. The presence of monohulls, catamarans, and trimarans is highlighted across different classes, with optimal boat shapes determined by specific regulations that evolve over time to encourage the development of innovative multidisciplinary engineering solutions. The authors of [48] concentrate on the photovoltaic system of the boat they developed for the race, while [49] investigates the relationship between powertrain design parameters and propeller optimization. Additionally, ref. [50] summarizes insights from a hundred competitive solar boats, providing valuable suggestions for encapsulating PV cells for broader applications.

In South America, the impact of the annual Brazilian university solar boat competition, Desafio Solar, on education and public engagement, is described in [51].

The development of solar-powered hydrofoils for competitions began in 1994 at the Kanazawa Institute of Technology, as mentioned in [41]. However, detailed sources focusing on this popular architecture are scarce (for example, ref. [52] refers to a competition reserved for ASV in Japan). An example of solar boats derived from Frisian Solar Challenge competition boats is presented in [53], while the Netherlands stands out as a country with a significant number of sporting solar boats. The unique configuration of a partial trimaran is depicted in [54,55].

Table 2 provides a summary of the main characteristics of solar boats described in the literature.

Table 2. Characteristics of the referenced sporting boats.

Reference	Name	Typology	Length and Weight	Solar Panel Power and Battery Capacity	Notes
[38]	Sun Warrior	Monohull	6 m //	200–480 W 1.0 kWh	Originally it had no battery, hull from a sailing catamaran
[38]	Sun Warrior II	Monohull	6 m //	40–480 W 1.0 kWh	Fiberglass/foam hull, flexible setup for different races
[38]	War Eagle II	Monohull	6 m //	480 W 1.0–1.5 kWh	Carbon fibre reinforced plastics (CFRP) hull
[45]	Episode	Trimaran	5 m 180 kg	168 W 86 Wh	Desing of the hull made by CFD
[46]	Nusrat	Monohull	5.5 m 81 kg (hull)	480 W 1.0–1.5 kWh	Multiple configurations for different races, outboard motor
[46]	Muavenet	Monohull	5.2 m 41.5 kg (hull)	480 W 1.0–1.5 kWh	Multiple configurations for different races, onboard motor
[47–49]	Scylla	Monohull	6.04 m 162 kg	875 W 1.0 kWh	Standard dislocating boat
[54,55]		Semi-Trimaran	5.8 m 300 kg	1200 W 3 kWh	Hull made by optimized CFRP sandwich

In recent years, there has been an increase in the complexity and performance of competition-related projects; however, these developments have been inadequately documented in the scientific literature. As a result, valuable data, models, design criteria, and procedures are primarily available on temporary web pages, often belonging to teams or competition organizers. Unfortunately, this material is typically unreviewed, lacks uniformity, and is frequently presented in the teams' native language.

One notable exception is the work by [56], which provides a description of the AGH Polish boat from Krakow and offers insights into its behavior during a race.

In the subsequent subsection, a summary of the key characteristics of the most advanced sporting solar boats is presented. This information is derived from the tech talks conducted by the teams in compliance with the regulations of the recent editions of the Monaco Energy Boat Challenge. The purpose of this summary is to provide an overview of the current state of the art in this field.

Monaco Energy Boat Challenge

In [57], a compilation of technical presentations from the competing teams in 2019, 2021, and 2022 is presented, featuring videos and slides. This article provides a summary of the most significant design data available for the solar class boats that were made accessible during the competition.

In the solar class, the dimensions of the solar panel and battery are consistent among all participants, unless otherwise indicated, at 6 m^2 and 1500 Wh, respectively. Table 3 illustrates that a significant number of teams opted for hydrofoil boats due to race regulations.

Table 3. Solar boats in the Monaco Energy Challenge 2019–2021–2022.

Team, Name and Nation	Typology	Length and Weight	Motor Power, Maximum Speed in Dislocation and Foiling	Notes
Sunflare Solar Team The Netherlands	Hydrofoil	6 m 91 kg	6 kW 35 km/h 53 km/h	Mechanically oriented foils
University of Antwerp Shark Belgium	Monohull	6.2 m 100 kg	6.5 kW 27 km/h //	//
BME Solar Boat Team Hungary	Monohull	6.4 m //	15 kW 18 km/h //	//
Han Solar Boat The Netherlands	Hydrofoil	5.8 m 100 kg	// // //	Mechanically oriented foils
Solar Boat Twente Rising Trident The Netherlands	Hydrofoil	6 m 120 kg	6 kW 30 km/h 50 km/h	Electronically oriented foils
Tecnico Solar Portugal	Hydrofoil	// //	2 × 5 kW // //	Hydraulically oriented real foil, counter-rotating propellers
Durban University Siyamba South Africa	Trimaran	5.1 m 180 kg	4 kW 18 km/h //	//
Adria Rijeka Toredo Navalis Croatia	Trimaran	6.8 m 79 kg	8 kW 35 km/h //	//
Swiss Solar Boat Dahu Switzerland	Non-symmetric Catamaran Dahu	7 m 200 kg	// 24 km/h 45 km/h	Counter-rotating propellers
AGH University of Science and Technology Poland	Hydrofoil	6 m 110 kg	2 × 4 kW // //	//
DB20 The Netherlands	Hydrofoil	// 200 kg	10 kW // 35 km/h	V-20 class, passive Hydrofoils, 1800 W PV panel, 1700 Wh battery

The hydrofoils employed are typically mechanically, hydraulically, or electrically activated. Despite the limited power output of the motors, typically around 6 kW, the top boats achieve impressive maximum speeds of approximately 50 km/h or 28 knots.

Regarding the hull structure, the customary trade-off between lightweight construction and the cost is altered by a design and methodology that prioritize sustainability. Consequently, most boat designs incorporate a life cycle assessment phase and consider the calculation of the CO_2 footprint. This approach leads to the utilization of structural natural fibers [58], recycled carbon fiber [59], and a preference for out-of-autoclave processes, such as vacuum-assisted resin transfer molding [60].

Figure 4 depicts two boats from different classes competing in the Monaco Energy Challenge. The boat on the left represents the Swiss solar class boat sailing on hydrofoils, while the boat on the right represents the University of Bologna energy class boat, which emerged as the winner in the 2021 and 2022 editions. In the energy class, solar panels are not obligatory but contribute a few hundred watts to the system.

Figure 4. Solar and energy classes at Monaco Energy Challenge 2022. Photo courtesy of the UniboAT.

4. Touristic Boats

Within the scope of this section, the relevant literature predominantly covers the past decade, reflecting the recent surge of interest in solar-powered commercial boats, particularly for touristic purposes.

One notable instance of a recreational boat suitable for lake environments was presented by [61] in 1990. The authors assert that a photovoltaic (PV) boat propulsion system with satisfactory performance can be designed within the low power range, primarily constrained by battery technology at that time. Hence, solar power is suitable for recreational and for-hire boats, commonly operational on weekends during summer. Such boats are utilized for activities like sport fishing or by authority personnel for short-distance, low-speed operations. Additionally, passenger boats and ferries in lakes can benefit from solar power, with supplementary charging while docked or through enhanced battery systems.

In a comprehensive overview of the solar boat market in France conducted in 2013 by [62], the presence of similar applications in Swiss lakes is mentioned, dating back to 1994 with the boat Solifleur (see Figure 5). Unfortunately, there are no technical data available for this boat. However, it is known that it was still operational in 2013. An interesting detail is that the boat generated more energy than it consumed annually, feeding excess energy into the grid.

Figure 5. Solifleur, first passenger solar boat, built by Mark Wüst, MW-Line. Photo by Theo Schmidt CC BY 3.0.

In 2012, ref. [63] detailed the design of a solar–electric powertrain for a 14-meter touristic catamaran, specifically engineered for continuous operation of 5 h per day. The authors contended that it takes ten years to recoup the project's economic costs and six years to offset the energy consumption (and associated CO_2 emissions) involved in manufacturing the PV panels. These findings establish the economic and environmental sustainability of the project.

In the work of [64], an overview is provided on notable commercial solar boats that have been constructed thus far. Additionally, an innovative concept involving the utilization of rigid sails to support solar panels in a 32 m boat is presented.

A significantly different approach is proposed by [65] specifically tailored to the waters of Indonesia. In this case, the motor power and resulting speed are notably lower than in other instances.

Detailed designs for a small and relatively affordable personal pleasure boat are described in [66] and more recently in [67].

The development of a high-performance solar passenger catamaran intended for use in protected marine areas in Italy is outlined by [68]. The boat's architecture is based on small waterplane area twin hulls (SWATH).

Optimization of the PV powertrain for a leisure catamaran boat accommodating 42 passengers and operating in Taiwan is addressed in [69]. Mathematical algorithms are employed to enhance the performance of the system. The boat typically maintains a service speed of 9 km/h for approximately 5 h, which are customary values for such touristic applications.

The design and construction of a touristic boat for use in the Indonesian sea, encompassing the hull, powertrain, mechanical systems, and propeller design, is detailed in [70–73]. The boat's intended operation is to sail for four hours daily, traveling at approximately 10 km/h.

A preliminary investigation into a solar catamaran hull measuring 5 m in length, intended for use in sport fishing or tourism in lakes, is conducted in [74,75]. The study concludes that a 2 kW motor is required to sustain an 8 km/h speed.

In [76], the same idea is applied to a project in China, with the author considering the addition of an onshore solar power station and performing an economic analysis that demonstrates the economic viability of using photovoltaic energy over internal combustion engines.

The utilization of mixed wind and solar energy for touristic purposes is explored in [77,78] through the implementation of rigid sails, with a primary focus on economic considerations.

In [79], a small leisure boat is examined for use in Latvian rivers, with a prototype designed and tested to assess its capabilities.

The energy management of a solar-powered touristic boat, designed in [80,81] and operating in the Galapagos Islands, is investigated in [82]. The authors analyze the boat's energy sources, including its photovoltaic self-production and fossil fuel consumption from the grid.

Recently, a traditional long-tail boat was repurposed as a solar-powered taxi boat as reported by [83,84].

The economic evaluation of replacing diesel engines with hybrid or fully solar-powered solutions, both off grid and on grid, is conducted in [85]. The analysis focuses on a tourist boat operating in an artificial lake in Turkey. The authors present a comprehensive case study and determine that, even without accounting for the environmental benefits, the economic breakeven point is achieved in approximately ten years, compared to internal combustion engines.

The paper also provides additional information on the characteristics of touristic boats for comparison purposes as summarized in Table 4. These solar-powered touristic boats exhibit various design features, with dimensions typically ranging from 4.5 m to 7 m for monohulls used privately and from 14 m to 32 m for public transport catamarans. Emphasis is placed on achieving autonomy at speeds between 6–15 km/h. Consequently, the power of photovoltaic panels employed varies from 3 W to 20 kW.

Table 4. Characteristics of the referenced touristic boats.

Reference	Name	Typology and Length	Motor Power and Speed	Solar Panel Power and Battery Capacity	Notes
[61]	Korona	Monohull 7.2 m	2.2 kW 12 km/h	900 W 12.6 kWh	Experimental prototype based on a hull not specifically designed for the scope
[63]	//	Catamaran 14 m	8–15 km/h	10 kW 90 kWh	Solution for tourist navigation in areas where combustion engines are prohibited
[64]	Solar Shuttle Boats	Catamaran 14–27 m	2 × 8–2 × 18 kW 12–15 km/h	// 2 × 13.5–2 × 72 kWh	Among the first public transportation commercial boats that depended completely on solar power
[64]	Volitan	Monohull/sail 32 m	150 kW 22–33 km/h	10 kW //	Concept of hybrid, rigid sail–solar boat. It has never been built
[65]	//	Monohull 4.5 m	2 × 0.3 kW 2–6 km/h	100 W 1.2 kWh	Made to encourage the local community to change perspective about solar energy
[66]	//	Monohull 4.5 m	2.7 kW 7 km/h	1.4 kW 1.95 kWh	Small pleasure boat basically designed for day and weekend trips
[67]	//	Monohull 4.2 m	500 W 5 km/h	440 W 4.8 kWh	Low-cost design for coastal navigation without wave and tidal issues
[68]	//	SWATH 15 m	2 × 20 kW 14.5 km/h	12.6 kW 96 kWh	Zero-emission craft for Mediterranean coastal Marine Protected Areas
[69]	//	Catamaran 14.5 m	9 kW 9 km/h	8 kW 34.5 kWh	A leisure passenger catamaran operated in Taiwan with 42 person capacity
[70–73]	//	Catamaran 12.6 m	10 kW 8–11 km/h	8 kW 38 kWh	Concept of a medium size solar-powered recreational boat for tourism in Indonesia
[76]	//	Catamaran 14 m	2 × 7.5 kW 9–12 km/h	3.6 kW 34 kWh	Concept of a medium recreational boat for tourism in inland lakes in China
[79]	//	Monohull 5.5 m	500 W 6 km/h	300 W 600 Wh	Prototype of small personal leisure boat intended for Latvian rivers
[80–82]	Gènesis Solar	Catamaran 15.4 m	2 × 10 kW //	4.2 kW 26 kWh	Public transport trajects for tourist in the protected environment of the Galapagos Islands
[83]	E-tail	Monohull 13 m	7.8 kW 8–10 km/h	1 kW 4 kWh	Prototype of a traditional long-tail boat, used to transport tourists in Thailand
[85]	//	Catamaran 14 m	2 × 10 kW 6–10 km/h	4 kW 60–120 kWh	This boat operates on a dam lake for tourist activities in Turkey
[85]	Aquawatt 550	Monohull 5.5 m	0.8–1.6 kW 6–10 km/h	0.4–1.6 kW 5 kWh	Commercial personal leisure boat for central European lakes
[85]	Aquawatt 715	Monohull 7.15 m	4 kW 13.5 km/h	4.4 kW 17.5 kWh	Solar-powered version of a long-time popular electric boat
[85]	SolarWaterWorld SunCat 46	Catamaran 14 m	6 kW 8–10 km/h	4 kW 46 kWh	Commercial traject boat for tourist, operating in Germany
[85]	Navalt Aditya	Catamaran 20 m	2 × 20kW 13.5 km/h	20 kW 50 kWh	Commercial large-size touristic ferry operating in India

Figure 6 showcases a representative example of a solar energy-powered touristic boat.

Figure 6. A typical solar tourist boat: the SunRider. Photo Sandith Thandasherry CC BY 4.0.

5. Other Applications

Alternative concepts for utilizing solar energy as the primary propulsion source are explored in filed patents. However, many of these concepts have not materialized into actual products, while others exhibit minimal innovation compared to existing technologies. This section discusses notable patented ideas and describes two iconic solar boats.

The first mention of solar-powered boats as a possibility can be traced back to the patent by [86] in 1976. Subsequently, the French patent by [87] in 1980 explicitly claims the use of electric motors, solar panels, and accumulators for boats. Over the following years, various concepts emerged worldwide.

For instance, in Japan in 1995, Ref. [88] proposed a small jet propulsion solar speedboat designed for a single passenger. More recently, China has seen a surge in patent applications. Some of these patents reflect applications discussed in previous sections, while others propose novel ideas. Ref. [89] asserts the benefits of a solar fishing boat, emphasizing its silent operations, which are also advantageous for tourist vessels [89,90]. Another patent [91] illustrates a civilian drone application closely resembling the military counterpart shown in Figure 3.

The second group of patents encompasses scientific and conservationist applications [92] as well as two unmanned vehicles—one for advanced military purposes [93] and the other for aquaculture [94]. The Ocean University of Guandong [95] proposes a variable geometry speed boat, likely an autonomous surface vehicle (ASV). In Korea, ref. [96] advocates for the use of solar-powered boats to collect sea garbage, motivated by environmental concerns.

India has also made recent contributions, ranging from a small boat [97] to a relatively large futuristic solar bus on hydrofoils [98]. A notable idea from Canada, presented by [99], demonstrates a portable solar electric watercraft that reaches a higher technology readiness level, indicating its proximity to the market.

In the relatively recent past, several solar-powered vessels embarked on demonstrative cruises to showcase their capabilities. In 2007, the "Transatlantic 21", a 14-meter catamaran designed by Loic Blanken and built by the German company Sun21, completed its journey across the Atlantic Ocean from Seville, Spain, to New York City in just over five weeks, covering a distance of approximately 7000 km [64,68,100].

Three years later, the Tûranor, depicted in Figure 7, was launched on 31 March 2010 [101]. Named after the phrase "Power of the Sun" in J.R.R. Tolkien's fictional Elvish language, this catamaran became the first solar-powered boat to circumnavigate the globe in 2012 [102]. It holds the distinction of being the world's largest solar-powered boat, with a length of 31 m, width of 15 m, maximum speed of 26 km/h, cruise speed of 15 km/h, and a daily travel range of up to 350 km. The boat is equipped with 537 square meters of solar panels, generating a maximum power output of 93 kW, while each of its two motors has a power of 60 kW.

Figure 7. The Turanor solar boat. Photo Maxim Massalitin, CC BY 3.0.

With a crew capacity of four and the ability to accommodate up to 50 passengers, the Tûranor has been utilized for scientific expeditions, educational purposes, and the promotion of solar power [64,68,100].

6. Conclusions and Future Directions

In the preceding sections, various solar-powered vehicles are discussed, some of which were also mentioned by Voerman (2010) in a brief analysis conducted in 2010.

Figure 8 provides a comparison of different boat types based on the ratios between battery capacity, maximum motor power, and peak solar panel power. It is important to note that this representation is qualitative in nature, as boats do not typically operate at maximum power, and solar irradiation varies throughout the day.

Nevertheless, the graph allows for the categorization of commercial boats into three main groups:

- Short-range solar boats: These boats primarily rely on solar energy for their regular operations, with motor power levels comparable to the solar energy input.
- Long-range solar boats: Similarly, the motors in these boats have power levels of the same order as the solar panels. However, the larger battery capacity enables continuous operations during nighttime or adverse weather conditions.
- Solar energy-assisted electric boats: This type of boat is characterized by significant battery and motor sizes, rendering the contribution of solar panels negligible.

The figure also includes a typical sporting boat, which exhibits minimal autonomy due to its distinct objectives.

In the case of the first two boat types, solar energy utilization is a crucial factor. Consequently, when designing these boats, considerations such as the size and shape of the vessel revolve around various factors, including the required surface area of the solar panel for the intended mission. Conversely, for the third boat type, the photovoltaic (PV) system's size is optimized while considering other functional requirements. However, it typically does not significantly impact the overall naval architecture.

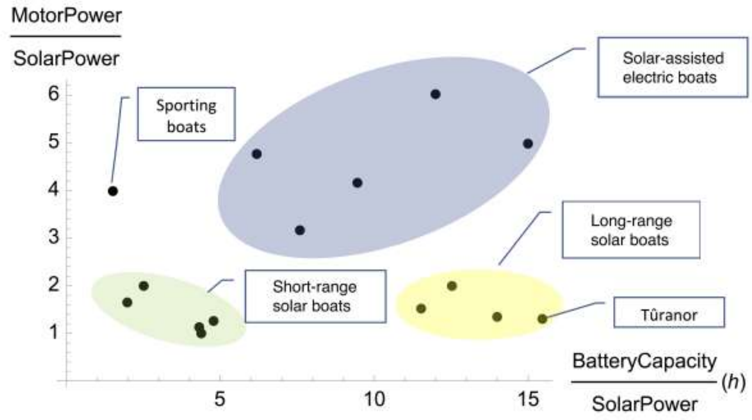

Figure 8. Summary of the boats' nominal characteristics.

The rationale behind the adoption of solar energy as a propulsion source for boats is summarized as follows:

- The need for long-lasting autonomy, spanning several hours, days, or even months.
- Low power density requirements to encourage students to find optimal hydrodynamic, structural, and electronic solutions for competition boats.
- Absence of local pollutant emissions to ensure compatibility with protected or naturalistic areas.
- Silent operations to minimize noise pollution.
- Independence from charging stations. However, the aforementioned low power density limits the suitability of PV energy for discontinuous, low-power-demanding applications.

Solar-powered boats are typically employed in scenarios where the energy demand for the mission is relatively low. In the case of maritime drones, the itinerary is short, and speed is typically low, allowing for small electric motors with sufficient power to last the entire mission. Sporting boats, particularly hydrofoils, have limited mission durations of a few hours, enabling the use of relatively low-powered motors. Solar-powered commercial boats primarily operate in coastal trade, especially in tourism applications. These boats generally operate at low speeds and can be equipped with large-capacity batteries to support the mission, even with relatively powerful motors. The Tûranor, although unique, provides insights for special operation vessels.

The possible development of solar-powered boats is predominantly influenced by environmental and social needs, emphasizing the pursuit of sustainability in marine transportation rather than rapid technological advancements because progress in this field is slow due to the maturity of most involved technologies.

In the future, the energetic autonomy of solar-powered boats may be combined with autonomous navigation, leading to crewless vehicles in sectors beyond small drones driven by environmental and social imperatives. However, developing solar-powered boats is an area of ongoing innovation and research.

Here are some possible challenges and advancements we may see in the near future:

1. Improved solar panel efficiency: One area of focus is enhancing the efficiency of solar panels used on boats. Researchers and engineers are continually developing more efficient photovoltaic cells, which can generate greater amounts of electricity from sunlight. Higher efficiency solar panels would enable boats to generate more power, increasing their speed and range. A specific issue to be investigated is the durability of PV modules, particularly when exposed to marine environments.
2. Energy storage technology: Advancements in energy storage technology, such as batteries, will play a crucial role in the future development of solar-powered boats. More efficient and lightweight batteries with higher energy density will allow boats to

store larger amounts of solar-generated energy, extending their operational range and enabling them to operate during low-light conditions.

3. Wind energy or hydrogen fuel cells: Besides solar energy, there is growing interest in combining solar power with other zero-emission technologies, such as wind energy or hydrogen fuel cell technology, for marine applications. Integrating solar panels with these systems could enhance the efficiency and range of solar-powered boats.
4. Lightweight materials and design: Future advancements may focus on using lightweight materials and innovative boat designs to maximize energy efficiency. Lighter boat structures reduce energy requirements and allow for the better utilization of solar power. Advanced composite materials and hydrodynamic designs can decrease drag and increase overall performance.
5. Smart energy management systems: Developing intelligent energy management systems will be crucial for optimizing the use of solar power on boats. These systems would dynamically allocate energy based on real-time conditions, such as solar irradiation, battery charge levels, and boat speed. Smart energy management can enhance overall efficiency and ensure optimal utilization of available solar energy.
6. Integration of electric propulsion systems: Solar-powered boats can benefit from advancements in electric propulsion technology. More efficient electric motors and propulsion systems will increase speed and better maneuverability. Additionally, advancements in electric motor design can lead to quieter and smoother operation, enhancing the boating experience.

These are just a few potential areas of development for solar-powered boats in the near future. As renewable energy technologies advance, we can expect continuous improvements in efficiency, range, and overall performance, making solar-powered boats even more viable and appealing as a sustainable mode of water transportation.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
PV	Photo Voltaic

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