Abstract

Electric motors powered with batteries that are charged by solar panels provide an attractive alternative to internal combustion engines as an auxiliary propulsion method for cruising sailing yachts, especially when shore electric power is not available. This project explores the conversion of existing yachts to the solar-electric alternative, making them quiet, clean and carbon neutral during operations. More specifically, we address the question under what circumstances currently available solar panels, controllers, batteries and motors present a viable option for converting conventionally powered cruising yachts to solar-electric auxiliary propulsion. We argue that small sailing yachts provide a more promising target for conversion than larger ones and that tropical conditions favour solar-electric propulsion. Thus, a small cruising sailing yacht operating in the tropics serves as a case study for conversion. The dimensions of the chosen boat, along with requirements on the desired range and charge time inform the choice of motor, battery and solar panels. We describe the design of a custom-made truss for solar panels, considering the required solar panel size, as well as ergonomic, aesthetic and mechanical design constraints. A finite element analysis of the truss simulates the wind load in severe weather conditions. We conclude with a preliminary evaluation based on test voyages in Singapore and Indonesia.

Keywords: solar charging, electric boats, carbon-neutral transport, hybrid wind-solar drive

1 Introduction

Cruising sailing yachts are leisure craft, designed for passengers and crew to enjoy the maritime environment, experience the forces of the wind and make use of them for propulsion at speeds that provide a welcome contrast to fast-paced lifestyles. For the purpose of convenient manoeuvring in harbours and anchorage, extended periods of unfavourable winds and for emergencies, cruising sailing yachts are typically fitted with inboard or outboard combustion engines connected to a propeller via a transmission as secondary means of propulsion. The alternative of electric motors enjoys increasing popularity, due to their clean operation, low noise and easy handling. Their power sources are typically batteries charged with shore power. In climates with ample sunshine, on-board solar panels may present an alternative for charging the batteries, and may even enable electric propulsion, when no shore power is available.

Sailing yachts have a lifespan of several decades and their owners often customise them for their
specific cruising needs. Instead of offering the solar alternative for new yachts, this project therefore explores the conversion of existing sailing yachts fitted with external or internal combustion engines to make use of solar-electric propulsion.

The conversion of motorised sailing yachts to carbon-neutral electric vehicles poses unique opportunities as well as challenges from business, design and engineering viewpoints. The reduced noise and smell that comes with electric propulsion attracts environmentally conscious sailors, who usually also have sufficient resources to finance such a conversion. Keeping the sails as the main method of propulsion means that the demands on the electric drive are relatively modest.

Sufficiently dimensioned solar panels can solve the requirement of carbon-neutral propulsion, but their installation within the functional and aesthetic constraints of a sailing yacht poses considerable challenges. The harsh environment of the open sea requires ruggedized designs that can withstand the movement of the boat, high wind speeds and prolonged exposure to salt water. Another challenge is to provide reliable electricity supply for on-board navigational instruments and household appliances, which typically require either 12V DC or 240V AC.

Our team has converted a Swedish-designed Maxi 77, a small conventional motorised sailing yacht with LOA (length overall) of 7.7m, to a carbon-neutral vessel by retrofitting it with a 2.5kW electric outboard motor and a 24V 250Ah lead-acid battery set. Three 275W mono-crystalline solar panels serve as cockpit roof and are mounted on a custom-built stainless steel truss. The battery set lasts for 3 hours of continuous operation. At daytime, the solar panels allow for docking manoeuvres even without any batteries. They can fully charge the battery set in two days under typical light conditions in the tropics. A DC-DC converter, in combination with an auxiliary battery, supplies 12V DC for navigational equipment and an inverter supplies 240V AC for household appliances. The auxiliary battery can also serve as an emergency power source for the motor.

The boat was converted in October 2014 and is currently the only carbon-neutral motorised sailing yacht in Singapore [1]. The boat underwent extensive testing in December 2014 and January 2015, cruising the waters surrounding Singapore and circumnavigating or visiting ten islands, including Singapore’s Pedra Branca in the South China Sea and the islands of Batam and Bintan in Indonesia.

2 Design Considerations

2.1 Boat Size

The power requirements for watercraft are a function of speed, displacement and hull shape [2]. Its components include drag forces on hull and deck structures, and depend on propeller and fuel efficiency. For small boats that operate well below their hull speed [3], a rule of thumb stipulates a power requirement of about 1kW for each ton of displacement. Since displacement grows with the cube of the length, and deck area only grows with the square of the length, a smaller boat can be powered more easily with solar panels that cover a certain portion of its deck than a larger one, everything else being equal.

The size of the boat was the primary criterion for the selection of our target vessel for conversion. The chosen boat—Singapore-registered Bo Bo Cha Cha—is a Maxi 77, a masthead sloop designed by Pelle Petterson for Erje Products AB and built from 1972 to 1982 [4]. As a pocket cruiser with a length overall (LOA) of 7.7m and a gross displacement of 2 tons, it is among the smallest cruising sailing yachts, see Figure 1.

The mentioned rule of thumb for dimensioning the auxiliary power requirement leads to a motor power of 2kW for the Maxi 77 design. We fitted the boat with a Torqeedo Cruise 2.0 R, an electric outboard motor with an input power of 2000W [5]. In order to operate the boat exclusively under electric power for 3 hours continuously under 24V, we require 250Ah. We chose to connect two 12V lead-acid batteries in series, each with a mass of 70kg and a capacity of 250Ah, which amounts to a total energy capacity of 6kWh and a combined mass of 140kg.

For comparison, a solar-powered yacht of a Bavaria 38 with 8 tons displacement and a LOA of 11.7m would require lead-acid batteries of a combined energy storage of 24kWh.
95% and 90%, respectively, we can collect and assume full sunlight conditions, the sun of about 1632 kWh/m².

From the graph, we notice that for a typical day, due to changing cloud cover, the average solar irradiation is much lower than for a clear-sky day. The total solar irradiation per day can be calculated as the area under the graph. From the graph, we notice that for a typical day, due to changing cloud cover, the average solar irradiation is much lower than for a clear-sky day. The total solar irradiation per day is thus:

\[
\text{Radiation}_{\text{Singapore}} = \frac{1632 \text{kWh}}{\text{m}^2 \cdot 365 \text{days}} = 4.47 \text{kWh/m}^2 \text{day}
\]  

Compared to a daily theoretical power output of the sun of about 24 kWh/m² adjusted for sea level conditions, we have effectively about 4.5 hours of full sunlight per day in Singapore.

Assuming three solar panels with 275 W each, and an efficiency of solar charger and batteries of 95% and 90%, respectively, we can collect 3 \times 275 W \times 0.95 \times 0.9 = 705.4 W in full sunlight, which amounts to 3.1 kWh per day. Thus, we can charge our 6 kWh batteries in less than two days.

We choose mono-crystalline panels of 1x1.65 m, and thus have a combined surface area of 4.95 m². By comparison, in order to charge batteries of 24 kWh in 2 days with solar panels of today’s available efficiency would require an area of about 19.8 m² in Singapore, most likely prohibitively large for a sailing boat with less than 12 m LOA.

## 3 Mounting of Solar Panels

Three key design constraints govern the design process. The first is to ensure that passengers and crew can continue to move on the boat, unimpeded by the structure or the panels. With this in mind, all of our designs are set two meters above the cockpit seats so that most people can walk around the boat without fear of hitting their heads. Secondly, we are concerned about the boom swinging into the mounting system. To meet this constraint, we allow the panels to hang out behind the boat. The geometry of the cockpit then leads to an arrangement of two transversally mounted panels besides one longitudinally mounted panel.

Our final constraint is to avoid any disruption of the backstay, a metal cord that runs from the mast to the rear of the boat to hold the mast on a masthead sloop. Fortunately, the backstay of Bo Cha Cha is around 30 cm to the port side of the centred rudder and tiller, which allows it to run between the two transversally mounted panels and the longitudinally mounted panel. Triangular plates are located between the poles and the frame to serve as welding surfaces. A steel tube between the aft poles provides additional stability.

Figure 2: Irradiance profile of a single radiometer during a typical day with high variability in tropical Singapore (blue curve) and of a rare day with clear-sky conditions (red curve); Source: SERIS meteorological station, 1-min data

Figure 3: CAD model of the solar panel truss and the boom of the boat, verifying the unimpeded movement of the boom after installation of the truss. Two panels are mounted transversally and one longitudinally.
4 Wind Load Analysis

To ensure the structure does not fail, several finite element analysis simulations are conducted. To examine a worst-case scenario for wind forces acting on the truss, Force 9 winds on the Beaufort Scale (also known as strong gale winds) are simulated, which reach velocities of 41–47 knots (21–24 m/s). We anticipate that the truss experiences the most stress when the wind acts perpendicular to it.

In Figure 5, the force is loaded on top of the panels and the response is scaled to highlight the areas of deformation. Under the simulated conditions, the structure deforms no more than two millimetres in the point with the most stress.

Figure 6 shows the results of a buckling load simulation, which calculates the load when the poles of the truss fail and illustrates how they deform. The structure rotates towards one corner as it collapses due to the asymmetrical arrangement of the solar panels. Fortunately, the buckling load of the poles is approximately 19 times higher than the load occurring in Force 9 winds. This indicates that it is unlikely for the truss itself to fail if the boat experiences severe wind and weather conditions.

5 Testing, Assessment and Future Work

The target vessel underwent extensive testing in January 2015, including voyages to six islands within Singapore (including Pedra Branca in the South China Sea), and to the islands of Batam and Bintan in Indonesia [7].

The theoretical range of 3 hours under full-throttle electric-only operation with a battery capacity of 250 Ah at 24 V and a 2 kW motor calculated in Section 2.1 is experimentally confirmed. We also verified a full recharge time of the batteries of two days.

While this runtime of 3 hours is shorter by about one order of magnitude than the runtime of an equivalent 2-stroke or 4-stroke outboard engine with a fuel supply of 140 kg (i.e. the mass of our batteries), the electric option provides more convenience, less noise and no carbon emissions during operations. A re-charge time of 2 days limits the daily cruising range in wind-deprived conditions, but the three 275 W panels proved sufficient for hybrid wind/solar operation in practice during the test runs.
We conclude that cockpit-mounted solar panels can provide reliable auxiliary propulsion to small sailing cruising yachts that operate in a tropical environment. Less consistent irradiation throughout the year in other climate zones may hamper the reliability of the solar energy source. The conversion of larger sailing yachts to solar power is limited by the weight of the required batteries and the size of the required solar panels to charge them.

The test vessel is currently undergoing instrumentation for remote data acquisition and replacement of the current battery system based on lead-acid batteries by a lighter yet more powerful system based on lithium iron phosphate batteries.

Future work includes a more detailed study of the interaction between the solar panels and the wind in various meteorological conditions and points of sail, using flow dynamics simulation.

Acknowledgments
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References
[7] Captain’s Log of Bo Bo Cha Cha, https://www.facebook.com/BoBoChaCha.Maxi77

Authors
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