Solar-Powered Sailing Yachts in the Tropics

Martin Henz[1], Joerg D. Weigl[1], Anand Sundaram[1], Evan Lowell[2], Eric K.-M.Yee[3]
[1]National University of Singapore, 21 Lower Kent Ridge Road, Singapore 119077, {uspmjh,engwjd}@nus.edu.sg
[2]Boston University, elowell@bu.edu
[3]SUniversity of California, Irvine, ekyee@uci.edu

Abstract

Sailing yachts require an additional propulsion source beside the sails for emergencies to be manoeuvrable in absence of wind or in tight conditions such as ports. Typically, small inboard or outboard combustion engines serve this purpose. In the tropics, solar energy is abundantly available throughout the year, and therefore solar-powered electric motors are attractive alternatives to combustion engines. We explore the dimensioning of solar panels for such a boat and conclude that for a fixed desired range under electric power and a fixed available charging time, the required solar panel surface grows roughly proportional to the cube of the length of the boat, whereas the available surface for solar panels grows proportional to its square. Even in the tropics, solar power therefore ceases to be feasible as exclusive auxiliary power from a certain length of the boat upwards.

To verify these conclusions, our team has converted one of the smallest available sailing yachts, a 7.7m long motorised sailing yacht to a carbon-neutral vessel by retrofitting it with a 2.0kW electric outboard motor and two 24V 200Ah marinised lithium-ion phosphate battery sets. Three 275 W mono-crystalline solar panels serve as cockpit roof and are mounted on a custom-built stainless steel truss. The battery lasts for 5 hours of continuous full throttle operations and can be fully charged by the solar panels in less than four days under typical light conditions in Singapore. The solar charging data can be monitored remotely by a newly developed web interface. The boat was converted in October 2014 and is currently the only carbon-neutral motorized sailing yacht in Singapore.

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 enable electric propulsion, even when no shore power is available.

Equipping sailing yachts with electric motors instead of combustion engines removes a source of noise and close-area pollution. Solar power as exclusive energy source leads to carbon-neutral operations. Carbon-neutral motorised sailing yachts pose 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 fund additional costs that arise from solar powered propulsion. At the same time, keeping the sails as the main method of propulsion means that the demands on the electric drive are relatively modest.

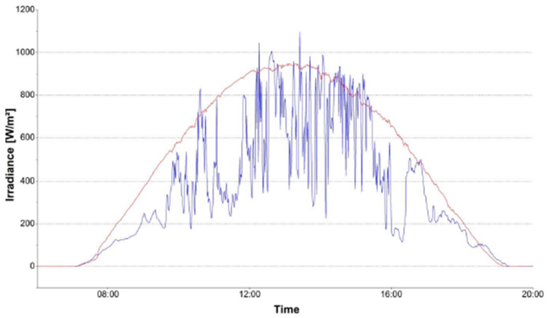

Figure 1: Irradiance profile of a single radiometer during a typical day with high variability in tropical Singapore (blue curve) and of a rare day with clear-sky conditions (red curve); Source: SERIS meteorological station, 1-min data

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.

2 Location

The tropics provide more abundant and consistent solar power than other climate zones. Figure 1 shows the irradiance profile of two days in Singapore with significantly different sunshine characteristics.

Generally, the solar irradiance profile has a bell shape. Starting from sunrise around 7am in Singapore, the solar radiation increases and reaches its peak at solar noon around, after which the solar radiation deceases, reaching zero when sun set at around 7pm. The red curve on the graph shows the solar irradiance on a clear-sky day, while the blue curve shows a typical day in Singapore. 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.

From the data of Meteonorm version 7 [6], the annual irradiation in Singapore is $1632 kWh/m^2$. The average solar radiation per day is thus:

$$Radiation_{singapore} = \frac{1632kWh}{m^2 \cdot 365days} = 4.471kWh/m^2day$$

Compared to a daily theoretical power output of the sun of about $24 kWh/m^2$ adjusted for sea level conditions, we have effectively about 4.5 hours of full sunlight per day in Singapore.

3 Dimensioning of Components

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 is thus a crucial factor for the feasibility of solar-electric propulsion of sailing yachts. To illustrate this conclusion, we compare a small pocket cruiser with a medium-sized yacht.

As pocket cruiser, we consider a Maxi 77 with a length overall (LOA) of 7.7m and a gross displacement of 2 tons. The mentioned rule of thumb for dimensioning the auxiliary power requirement leads to a motor power of 2kW. In order to operate the boat exclusively under electric power for 3 hours continuously under 24V, we require 250Ah, which could be provided by 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. Assuming three solar panels with 275W each, and an efficiency of solar charger and batteries of 95% and 90%, respectively, we can collect $3 \cdot 275W \cdot 0.95 \cdot 0.9 = 705.4W$ in full sunlight, which amounts to 3.1kWh per day. Thus, we can charge the 6kWh batteries in less than two days. Three mono-crystalline panels of 1x1.65m have a combined surface area of 4.95m2, which can placed above the cockpit of such a boat.

For comparison, let us now consider a solar-powered medium-sized yacht of Bavaria 38 design. This boat has a displacement of 8 tons and a LOA of 11.7m. Considering the mentioned rule of thumb, operating this boat continuously for 3 hours under electric power would require lead-acid batteries of a combined energy storage of 24kWh and a mass of around 560kg to achieve the same range. The battery weight and required storage space might be considered problematic for a boat of this size. In order to fully charge these batteries within two days in a tropical environment, we calculate a surface area of 19.8m2, which is clearly prohibitively large for a sailing boat with less than 12m LOA.

4 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 truss 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. Figure 2 shows the relative positions of truss and boom and the arrangement of the panels.

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 up the mast on a masthead sloop.

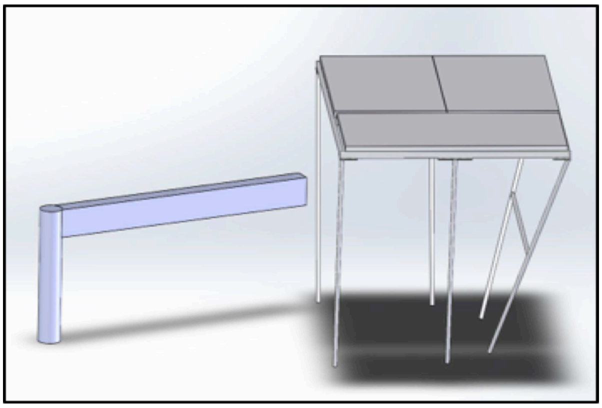

Figure 2: CAD model of the solar panel truss and the boom of the boat, verifying the unimpeded movement of the boom after installation of the truss.

5 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 3, 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.

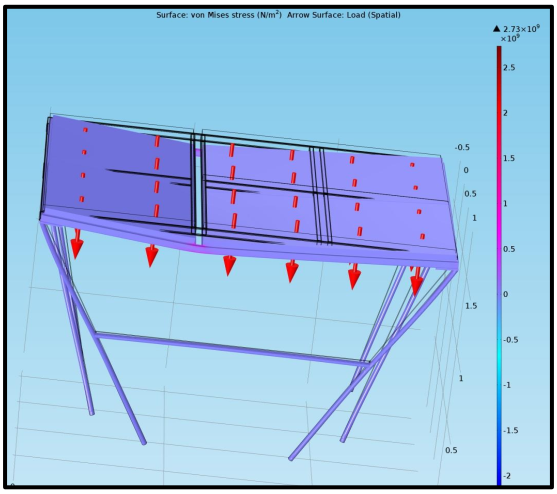

Figure 3: Perpendicular force with scaled deflection

Figure 4 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.

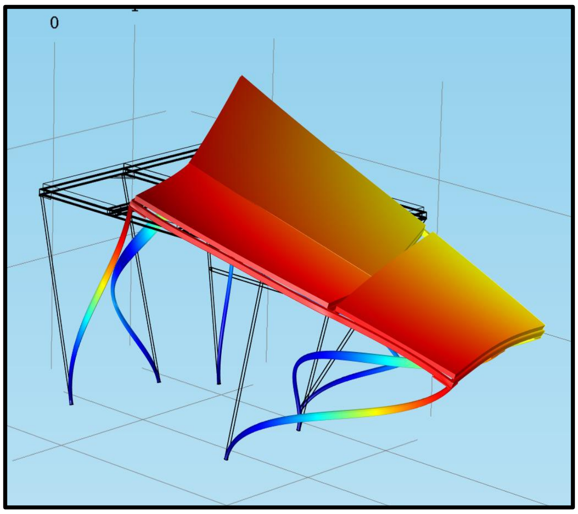

Figure 4: Buckling simulation (isometric view)

Figure 5: deck and interior of chosen boat type Maxi 77

6 Testing, Assessment and Future Work

Following the dimensioning consideration in Section 3, the size of the boat was the primary criterion for the selection of our target vessel. 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 available, see Figure 5.

Three 275W mono-crystalline solar panels serve as cockpit roof and are mounted on a custom-built stainless steel truss. Two panels are mounted transversally and one longitudinally. Fortunately, the backstay of Bo Bo Cha Cha is around 30cm to the port side of the centred rudder and tiller, which allows it to run between the two transversally mounted panels on the starboard side and the longitudinally mounted panel on the port side. Circular plates are located between the poles and the frame to serve as welding surfaces. A steel tube between the aft poles provides additional stability.

To reduce weight and increase the range, we installed two 24V marinised lithium-ion phosphate battery sets with 200Ah each, instead of lead-acid batteries. The battery set lasts for 5 hours of continuous operation. The solar panels can fully charge this battery set in less than four 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, see Figure 6. The theoretical range of 5 hours under full-throttle electric-only operation with a battery capacity of 400Ah at 24V and a 2kW motor is experimentally confirmed. We also verified a full recharge time of the batteries of three and a half days.

While this runtime of 5 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 140kg (i.e. the mass of the batteries), the electric option provides more convenience, less noise and no carbon emissions during operations. A re-charge time of 3 and a half days limits the daily cruising range in wind-deprived conditions, but the three 275W panels proved sufficient for hybrid wind/solar operation in practice during the test runs.

The boat is equipped with an on-board Odroid-based computer as a data acquisition system, monitoring the flow of energy between solar panels, batteries and motor, and serving as a fuel gauge for safe operations on board. For continuous off-board monitoring in coastal waters, the system is currently connected to a data storage server via the Internet, using a GPRS data modem. The solar charging data can be monitored remotely using a newly developed web interface.

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.

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.

Figure 6: Pocket cruiser Bo Bo Cha Cha (Maxi 77) with a crew of six, operating in Singapore waters in light winds in wind/electric hybrid mode

Acknowledgments

We acknowledge the generous support by Rezeca Renewables.

References

[1] M. Henz, *Is a Combustion Engine Needed on a Motorised Sailing Yacht?* Changi Log, No. 25, pp. 38–40, Changi Sailing Club, Singapore, January 2015.

[2] D.W. Taylor, *The Speed and Power of Ships*, Europäischer Hochschulverlag GmbH & Co. KG, 2014.

[3] P.R. Van Mater Jr., R.B. Zubaly and P.M. Beys, *Hydrodynamics of High-Speed Ships*, Davidson Laboratory, Stevens Institute of Technology Report No. 876, October 1961.

[4] Erje Products AB, *Maxi 77 Teknisk Handledning*, 1980 (owner's manual in Swedish).

[5] Cruise 2.0 R/T Operating Manual, Version 5.0, Torqeedo GmbH, Starnberg, Germany.

[6] Meteonorm, computer software, Version 7, Bern, Switzerland, Genossenschaft Meteotest.

[7] Captain's Log of Bo Bo Cha Cha, `https://www.facebook.com/BoBoChaCha.Maxi77`