PV-boats: design issues in the realization of PV powered boats

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Abstract

PV integration in boats is rarely seen, but offers clean and silent transportation while on the water. In order to research the PV realization into boat design challenges, the University of Twente and the NHL hogeschool, both in the Netherlands, started a joined research into PV integration in boats. By studying 3 cases, PV boat specifications and the key design challenges are researched. The first case, the Frisian Solar Challenge 2010, offered the possibility to gather information about 44 innovative PV powered racing boats. The Frisian Solar Challenge is a 5 day 220km race for PV powered boats. Boats need to be fast, efficient and reliable to finish the race at high positions. The second case shows the NHL hogeschool's PV powered racing boat design and building process which attended the Frisian Solar Challenge 2010. The third case is a study in PV powered boats found worldwide. From 105 boats, specifications are collected to learn recent developments in PV powered boats. From these 3 cases follows that light weight is one of the key parameters to build a successful PV powered boat. Especially PV modules with lower weight can bring successful PV powered boat designs. Furthermore, boats equipped with monohull designs offer high efficiency with low drag. However, catamaran designs prove to be successful as well, bringing higher stability in boat designs. Mature technology is needed to sail with reliable hardware.

Keywords: PV boats, PV design, Green transportation

1 Introduction

There is a need for cleaner and greener transportation on the water. Using PV in boats is a means to generate electrical energy while on the water, without using polluting combustion engines. Integrating PV into boats is rarely seen. Research needs to be done how to integrate PV into boats which fulfills user's needs (Reinders, 2008). The process of creating PV integrated boats is very new and not matured yet. Up until now, building a PV boat accompanies high costs, on-board-systems failure and short product lifetimes. Therefore, PV boats own a very small niche in the water sports market (Joore, 2009).

Fryslân is a province in the northern parts of The Netherlands with many open waters (2.500km^2, approximately 40% of total Frisian area) and houses almost 40.000 motorized boats. However, for environmental reasons, on many waters it is prohibited to sail with a combustion engine.

Fryslân is planning to become a CO_2 neutral province in 2020. This stimulates research into 'green' technology and events like the Frisian Solar Challenge.

In order to meet the whishes (and demands) of the Frisian government and especially consumers, research into commercializing environmental friendly PV powered boats needs to be conducted. However, less is known about the building and design processes of PV powered boats (Reinders, 2005).

During summer, Fryslân shows high irradiation, up to 5,7kWh/m^2/day (averaged over 22 years), with maximum variations between April and August of 25% (NASA, 2010). This amount of irradiation could provide for approximately 6.5 kWh/day of electrical energy during the summer period, when 8m^2 is equipped with 15% efficient c-Si PV cells.

To improve PV integration in boats, 3 cases are evaluated to find trends in PV powered boats. The following 3 cases were researched: 1) the Frisian Solar Challenge (FSC) with 44 participating solar racing boats, 2) the building of an A Class solar racing boat attending the FSC and 3) research into 105 PV powered boats worldwide (still going on). From these cases, the following data was collected:

- PV boat specifications
- Key boat design challenges
- User expectations

To build a commercial successful PV boat, not only the boat's proper technical functioning is of importance, also user's needs and wishes are of consideration. Trends into the development of PV boats can give an overview of user's needs and wishes and market segments which are interested in PV boats.

In this paper, a PV powered boat is considered *PV powered* if it is able to sail with electric propulsion, powered by PV or battery packs, charged by PV. This also includes boats which are equipped with range-extenders or combustion-electric hybrid engines. In the last case, PV modules must be a retrofitted or original element into the boat's structure to qualify as PV powered boat and the boat must be able to sail only on electric propulsion.

2 METHODOLOGY + CASES

2.1 Frisian Solar Challenge

The FSC is a race for PV-powered boats, held in June every two years since 2006 in Fryslân, The Netherlands. This race intends to encourage technical innovations in electrical transportation on the water and economical spin-offs in the northern parts of The Netherlands. Participants in the race have to sail a 220km trajectory, divided over 5 days, in which speed and power management are the key challenges. Leg distances vary between 5km and 56km, showing the need for a fast boat, as well as an efficient one, to win the race. To attend the FSC, it is possible to classify for 3 classes: A, B and TOP. The most important specifications for each class are shown in Table 1.

Table 1: FSC classes A, B and TOP

	A	B	TOP
Maximal boat length (m)	6	8	8
Maximal Width (m)	2.4	2.6	2.6
Maximal PV power (Wp)	875	1050	1750
Crew member(s)	1	2	1
PV technology	c-Si	c-Si	any
Battery capacity (kWh)	1	1	1

A and B classes are equipped with provided c-Si PV-modules, whereas the TOP class may use whatever PV technology they prefer. Figure 1 to 3 show typical configurations for A, B and TOP class boats.

Figure 1: Typical A class boats

Figure 2: Typical B class boat

Figure 3: Typical TOP class boats

In total, 45 teams participated in the race, of which 27 in the A class, 8 in the B class and 10 in the TOP class. To qualify for the race, attendants have to prove their boat can sail with a minimum speed of 12km/h.

During the FSC, a questionnaire was handed out, in which the teams were asked to give their boat specifications. Up until the end of August 2010, 9 questionnaires have been returned. A summary of the most important questions is given in Table 2.

Table 2: questionnaire FSC classes A, B and TOP

	range
Length (m)	5 - 8
Width (m)	1.6 - 2.4
Weight (kg)	145 - 335
Maximum speed (km/h)	11.6 - 31
PV power (Wp)	875 - 1750
PV module weight (kg)	10 - 85
PV technology	
Hulltype	
Hull material	
Electrical systems	
Length (m)	

2.2 NHL solar racing boat

The NHL hogeschool's university of applied sciences and engineering department in Leeuwarden participated in the FSC 2010 with a custom made PV powered racing boat.

In preparation for the FSC, the design and building of the NHL solar racing boat was researched to identify bottlenecks which are encountered during the design and building phases. This boat is shown in Figure 4.

Figure 4: A class NHL solar boat 'Scylla'

The boat hull was made of foam, sandwiched by carbon fiber reinforced epoxy (FR epoxy). As any normal A class boat in the FSC, 5 PV modules were provided to power the boat.

Each PV module was equipped with a maximum powerpoint tracker (MPPT). Energy was stored in a 1kWh lithium-polymer (LiPo) battery pack, monitored with a battery management system (BMS). An electrical engine was used to propel the boat with a custom made propeller, controlled by a motor controller using pulse modulation. Total empty weight of the boat was 162kg. According to FSC regulations, maximum voltage onboard did not exceed 52V. However, the boat was able to reach speeds up to 28km/h, driving the motor with 4.5kW electrical power. Table 3 shows the specifications of the NHL solar racing boat. According to FSC regulations, no shore power was used to charge the battery pack during the race.

Table 3: NHL solar racing boat specifications

Class	A
Length (m)	6.04
Width (m)	1.68
Weight (kg)	162
Maximum speed (km/h)	28
PV power (Wp)	875
PV module weight (kg)	85
Crew member(s)	1
PV technology	c-Si
Hulltype	single
Hull material	epoxy/carbon, foam

The team which build the NHL solar racing boat consisted of 8 members with 4 disciplines, namely mechanical engineers, electrical engineers, shipbuilders and business administrators (Figure 5).

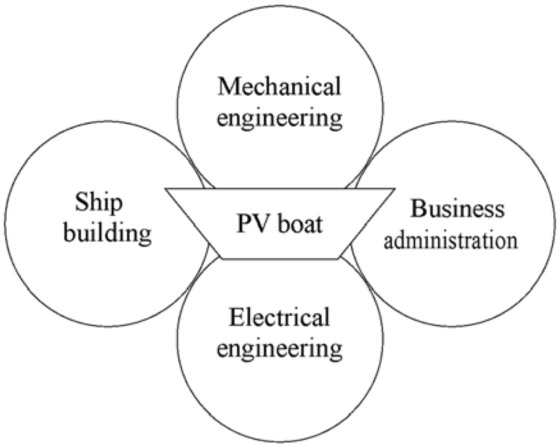

Figure 5: Disciplines represented during the build of the NHL solar racing boat.

During the race, relevant NHL solar racing boat data was logged. Which data was monitored is showed in Table 4. Data was logged every day, except for the sprint and prologue, at the first day.

Table 4: overview of logged NHL solar racing boat data during the FSC 2010

	P (W)	V (V)	I (A)
Battery	×	×	×
PV	-	×	-
Motor	×	×	-

Also, State-Of-Charge (SOC) and battery temperature were logged. The log-interval for all data series is 60 seconds. While writing this paper, data with a 5 second interval, logged by a third party, wasn't available yet.

The key unknown factor in the race is the behavior of incoming irradiation. In preparation and during the race, irradiation data needs to be monitored continuously and forecasts about available energy in relation to the remaining distance should lead to efficient sailing and power management. Figure 6 shows actual measurements from the NHL solar racing boat (simplified to increase readability). Similar data can be found for lower power ranges in Ageev et al (1999).

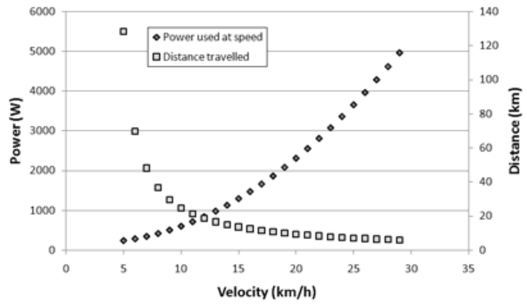

Figure 6: Typical speed/travelled distance relation of an electric boat.

2.3 PV powered boats worldwide

Preceding the FSC, a PV powered boats overview was made, yet consisting 105 boats. (however, not complete up to this date). In this overview, boats from races similar to the FSC were not included. Only commercial available and historical notable boats are added to the overview. Data collected in the overview is shown in table 5.

Table 5: PV powered boats research parameters

	range
Year of production	1984 - 2010
Length (m)	2,13 - 33
Width (m)	0,91 - 22,8
Maximum draft (m)	0,1 - 1,2
Empty weight (t)	0,2 - 85
Full weight (t)	0,5 - 35
PV surface (m^2)	1,5 - 536
PV power (kWp)	0,15 - 93,5
PV technology	
Engine power (kW)	0,14 - 150
Number of engines	1 - 2
Engine technology	
Battery technology	
Battery Capacity (Wh)	720 - 230 400
Cruise speed (km/h)	3 - 15
Max speed (km/h)	4 - 55
Person capacity	1 - 150
Price (€)	9 500 - 24 000 000

From these 105 boats, 83 were identified as unique (minor variations in a line of boats counts as 1 boat).

3 RESULTS

3.1 Frisian Solar Challenge

During the FSC, 3 classes (A, B, TOP) competed within their pools for first, second and third place. Generally it can be said that TOP class boats sail the 220km route in the shortest time, followed by A class boats and finally B class boats. Table 6 shows average velocities (km/h) for all classes over the 220 km trajectory. Generally TOP class boats have the largest amount of available electrical energy, due to 1750Wp installed PV power, and the lowest weight. A class boats have less power than B class boats, but weight is lower (1 crew member, approximately 70kg), therefore performing better. Table 7 – 9 show basic configuration of the winning boats in all classes.

Table 6: average velocities (km/h) for A, B and TOP class boats during the FSC 2010

	A	B	TOP
1st place	13.70	11.43	19.54
2nd place	13.50	10.86	19.05
3rd place	13.37	10.47	17.86

The following configuration was used in the winning boats:

Table 7: Boat configuration A class (875Wp)

	hull	material	weight
1st place	trimaran	FR epoxy	145
2nd place	mono	FR epoxy	168
3rd place	mono	FR epoxy	162

Table 8: Boat configuration B class (1050Wp)

	hull	material	weight
1st place	trimaran	FR epoxy	-
2nd place	mono	FR epoxy	-
3rd place	catamaran	FR epoxy	-

Table 9: Boat configuration TOP class (1750Wp)

	hull	material	weight
1st place	mono	FR epoxy	120
2nd place	mono	FR epoxy	-
3rd place	mono*	FR epoxy	-

*monohull with hydrofoils

3.2 NHL solar racing boat

The NHL solar racing boat participated and sailed the complete FSC trajectory, finishing at 3rd place. Designing and building a PV powered racing boat provided many insights in the challenges which are encountered during preparations for the race.

Although the NHL solar racing boat finished 3rd place, during the qualification day, the boat proved to be the 3rd fastest boat seen over all classes (A, B and TOP), and has received an award for this achievement.

Hardware specifications of the NHL solar racing boat are shown in Table 3 and a speed / power relation in Figure 6. Evaluation of the race was easily conducted, since data during the race has been logged and visualized.

Weaknesses which turned out during the race were mostly due to human error and design flaws. Some time loss was caused by running on the ground. This resulted in misalignment of the rudder and a time loss of 14 minutes. Another serious problem was overheating of the batterypack, which occurred several times during sprint conditions at the end of a leg. Fortunately, the BMS stepped in before serious damage was caused and shut the battery pack off. However, this resulted also in time loss (the boat was not propelled anymore and forced to wait to cool down the battery pack). This overheating was caused by bad battery pack compartment ventilation conditions in combination with high currents drawn from the batteries (up to 80A for long periods with low battery voltage).

During sailing in tumultuous waters, some water entered the boat and set 4 out of 5 MPPT's under water, resulting in a major drop back of incoming PV power for 56 minutes. Fortunately, relieving of the water showed no MPPT failure.

Strengths of the boat were the PV module integration as part of the hull, giving strength with minimal added weight, without having the need for an extra support for the PV modules on top of the boat. This also lowered the boat's gravity centre.

Using composite materials resulted in a low weight design, making the boat capable of reaching speeds up to 28km/h.
Hardware used in the boat was commercially available, showing no problems at all with causes other than mentioned above.
Hardware monitoring which was read-out in the boat and at shore proved to be an advantage to strategically plan and sail the race and to identify problems in an early stage. Table 9 shows the strengths and weaknesses of the NHL solar racing boat design.

Table 9: NHL solar racing boat Strength and weaknesses

Strengths	Weaknesses
PV integration	Bad ventilation conditions
Lightweight design	Not watertight
Mature technology	Team dedication
Data monitoring	

The key question during the design process was to, or not to, apply techniques to increase PV power output, with the cost of adding extra weight to the boat. Therefore, trade-offs needed to be made considering the extra weight versus the (expected) increase of PV power output. This is illustrated in Figure 7.

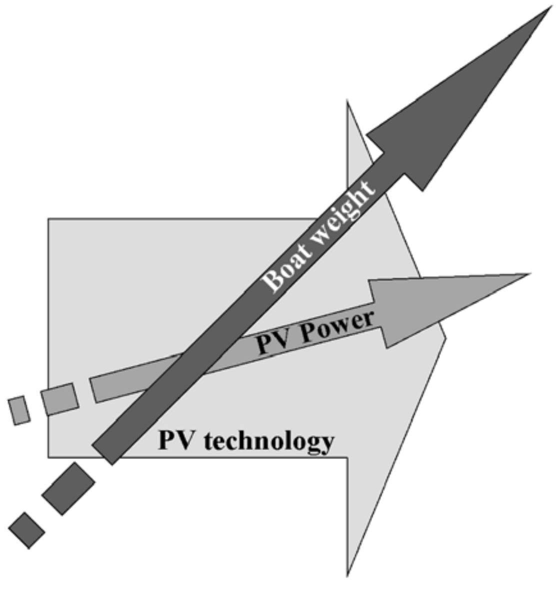

Figure 7: trade-off between increased boat weight and increased PV power during build of NHL solar racing boat.

Building the NHL solar racing boat comes with many parameters, which influence one and another. To understand the decisions made, the various parameters have been put in a overview to understand the relations between the parameters. A simplified version of this overview is shown in Figure 8.

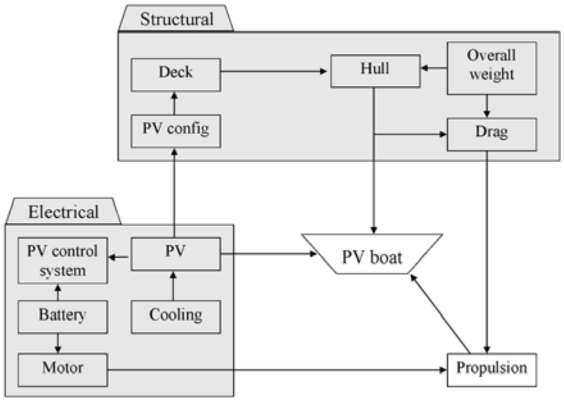

Figure 8**:** Simplified version of parameters while building the NHL solar racing boat.

The design of the boat is influenced by 3 key parameters, namely propulsion, hull and PV (illustrated in Figure 8).

3.3 PV powered boats worldwide

An overview was made with 105 PV powered boats, found worldwide. From these 105 boats, 83 were identified as unique models. Since not all data for all boats was available, analysis was done on the boats which had sufficient data. These 83 boats were subdivided into 3 key categories, namely 'people's transportation', 'recreation' and 'private/research' (Figure 9). Figure 10 - 12 show typical boats from these categories.

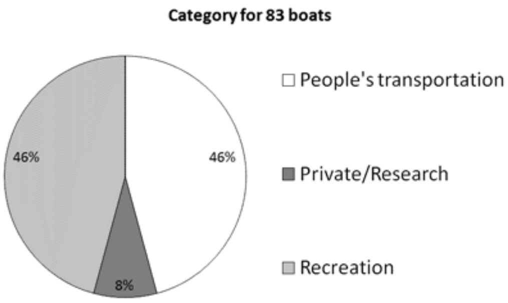

Figure 9: PV powered boat categories

Figure 10: Sonnenschein; typical PV powered people’s transportation boat build by SUEK GmbH, Austria.

Figure 11: SOL10; typical PV powered recreation boat build by KOPF AG, Germany.

Figure 12: Sun21; Typical PV powered boat for private/research purposes. Used to cross the Atlantic Ocean, build by Swiss transatlantic21 Association (2007).

From the 83 distinguishable boats, specifications are collected to find trends in PV powered boats developments.

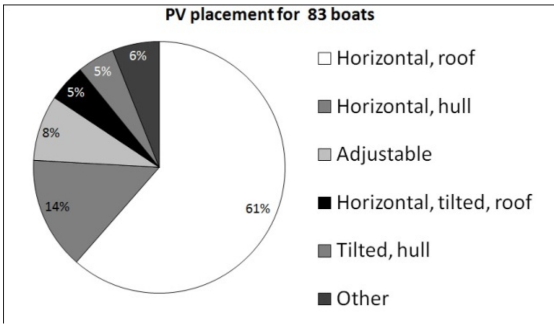

Figure 13: PV placement on 83 PV boats.

Figure 13 shows various kinds of PV placement on PV powered boats. From the figure follows that the most used PV placement is in a horizontal plane (61%), on the roof on the boat (see Figure 10 and 12), followed by horizontal placement on the hull (14%, Figure 14). One or more adjustable PV modules is seen on 8% of the PV powered boats (see Figure 15).

Figure 14: PV powered boat ‘Czeers MK1’ with horizontal PV placement in the hull (2007).

Figure 15: PV powered boat ‘Solar Glisseur’ with adjustable PV; One of the first solar powered boats (1984).

For 28 boats, the boat length/weight ratio was calculated (Figure 16). This shows that with increasing boat length, the weight/length ratio is also increasing. Together with length, maximum boat velocity is plotted against the boat length. This shows an average boat velocity between 10 and 15 km/h. There seems to be no significant relation between length/weight ratio and boat velocity.

Figure 17 shows a relation between installed PV power and year of production for 35 boats. Per year, more PV power is installed. However, smaller amounts of installed PV power are also maintained. There doesn’t seem to be an installed PV power growth. One boat was left out of the graph, since its installed PV power was of the scale (93,5kW in 2010).

Figure 18 shows installed PV power versus boat weight. Just like installed PV power and year of production, there seems to be no relation between the boat weight and installed PV power. Again, one boat was left out of the graph (93,5kW with 85t).

From 84 out of 105 boats, boat length was available, which is shown in Fig. 19. Boats with a length between 6 – 8m seems most favorable.

From 83 boats, the hull type was available, which is shown in Fig. 20. Mono and catamaran hulls are chosen the most for PV powered boats.

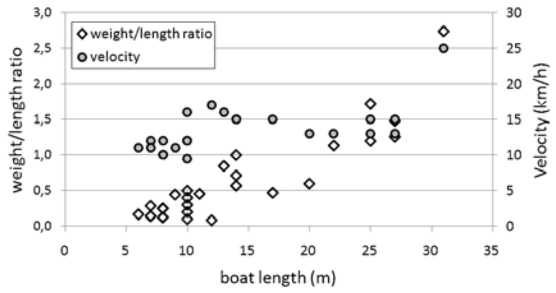

Figure 16: Weight / length ratio of 28 boats and their speed.

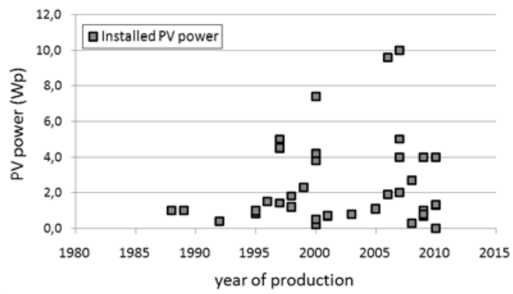

Figure 17: Installed PV power with production year for 35 PV boats worldwide.

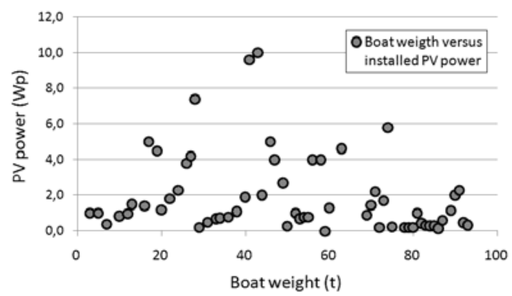

Figure 18: Installed PV power with boat weight for 61 boats worldwide.

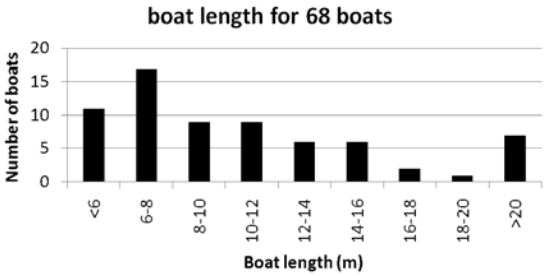

Figure 19: amount of boats with certain boat length.

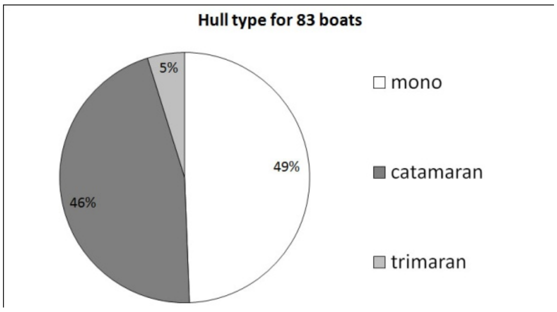

Figure 20: Hull types for PV powered boats

A typical monohull configuration can be seen in Figure 14. A catamaran hull is shown in Figure 15 and a trimaran is shown in Figure 1 (boat A11).

4 CONCLUSIONS

When looking at the 3 research question which were stated in the introduction (PV boat specifications, key boat design challenges, user expectations), most of the information was provided by the research into PV powered boats worldwide. The FSC showed the most key design challenges for both the race and the individual boat.

4.1 Frisian Solar Challenge

The FSC has shown that not the fastest boat, but the most reliable boat will win. Therefore, creating a ‘dragster’ is not the best strategy to win the race. Efficiency and reliability play the most important role. Also, strategy plays an important role. Many designs were introduced (monohulls, catamarans, trimarans, monohulls with hydrofoils), but within the TOP class the 3 winning boats all used monohulls. Third place was for a boat with a monohull and hydrofoils. However, this technology did not work well and showed many problems, resulting in a 3rd place. This boat was able to reach speeds up to 35km/h, 3km/h faster than finished number one. Same goes for A and B class boats. Reliable designs tend to win over faster, more efficient types.

Boats participating the FSC are mostly made from fibre reinforced epoxy. Al boats with 1st, 2nd or 3rd place used a FR epoxy hull. This material, when well used, ensures a light boat design with sufficient stiffness. In combination with high electrical efficiencies, reliable hardware and good sailing strategy, this results in a winning position.

4.2 NHL solar racing boat

Design challenges were best illustrated during the design and building of the NHL PV powered racing boat. Key problems were caused by design flaws. Hardware compartments were not ventilated well, resulting in high ambient temperatures. A ventilation technique or other cooling method needs to be applied to ensure the possibility to sail with high currents, without problems. When sailing in tumultuous waters, resulting in higher waves, water can enter the boat, damaging or disabling electronic equipment. This was also caused by not sealing electronic equipment compartments up to watertight levels. Electronic compartments need to be watertight, or measures need to be made to prevent water from entering the boat.

A proper team needs to be assigned to design, build and maintain the NHL solar racing boat. Although the disciplines within the team were chosen well (Fig. 5), during the building, designing and race, business administration and mechanical engineering were represented well, whereas ship building and electronic engineering were represented poorly. Electronic problems were therefore not identified well, leading to failure and time loss. Trade-off assessments need to be done on increasing PV power technologies versus added weight.

4.3 PV powered boats worldwide

User expectations are best answered in an overview made for 105 PV powered boats worldwide. This showed which configurations are most preferred among PV powered boat builders.

The weight / length ratio for PV powered boats shows a trend which goes up: the longer the boat, the higher the weight / length ratio will be. Velocities however remain the same.

This is probably because there is no need for higher speeds than 15 km/h (with some exceptions). Within some Frisian water, speeds above 6km/h aren't even allowed. Therefore, users don't expect higher velocities for PV powered boats. Most boats have lengths under 20m, with a top around 6-8m. This is probably caused by a favorable weight/length ratio at 6-

8m, resulting in a weight which can be propelled well with PV power at the right velocities. Most boat types are equipped with a mono hull, followed by a catamaran hull. Monohulls are efficient hulls, resulting in low drag conditions. Catamarans however are more stable. Since this configuration is seen in many PV powered boats, is shows that stability is an important factor for PV boat owners / builders.

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