Design and Operating Cost Analysis of a Solar Energy Propulsion System for an Electric Passenger Boat for the Paraguay River

Denis Cuevas, Renato Orué and Jean-Claude Pulfer
Laboratory of Mechanics and Energy, Faculty of Engineering
National University of Asuncion
Campus San Lorenzo, Paraguay
renatorue10@gmail.com denis.cuevas@outlook.com jcpulfer@ing.una.py

Abstract

This paper is the result of a final degree project, consisting in the design of a propulsion system for a transportation boat based on electric motors powered partially by solar energy comparing its costs with a conventional propulsion system by combustion engines. The boat is meant to be used to transport up to 30 passengers and 1 ton of goods on the Paraguay River in the northern part of the Paraguayan Chaco region. First was designed the most suitable hull, for which simulations were executed with computerized software with the main aim to optimize the hydrodynamic resistance of the vessel obtaining as outcome a 10 m long and 4.7m wide catamaran. Then was carried out the complete sizing of the electric propulsion system, including the photovoltaic array integrated into the roof of the boat, charge controllers, battery banks, electric motors, recharging stations and BOS. The dimensioning was made considering a route between various places located on an almost 250 km long section of the Paraguay River. The economic study showed that applying the Present Value of Costs for the solar propulsion system is 3 times lower than the one for the conventional system for a 10 years' period.

Keywords
Solar power, electric boat, catamaran, Delft Ship, Michelet, Present Value of Costs

1. Introduction
Today, humanity still depends on more than 80% of non-renewable energies, such as petrol, natural gas, coal and uranium. Their reserves are limited and will inevitably run out in a not-too-distant future. Fuels also generate significant environmental pollution during their exploitation and use and when burned emit greenhouse gases that can alter the climate. It is for these reasons that the world is in search of alternative energy sources such as solar energy, wind energy, geothermal energy, biomass, among others, being friendly to the environment. The increasing spreading of these alternative energy technologies during the last 20 years has generated an incredible reduction of their investment costs and made many of them competitive to conventional energy technologies.

The department of Alto Paraguay is one of the most isolated, less populated and poorest departments of Paraguay located in the northeastern part of the country along the upper part of the Paraguay river, which is until today an important transport way for the local population living alongside the river. Most roads are unpaved, what makes it difficult to circulate during rainy periods and therefore many communities are accessible only by water. Hence, since the beginning of its colonization by the Spanish and until today boats have been the most used transport medium in this part of the country. In our days they mainly use internal combustion engines (ICE) generating high operation costs, which lately are growing strongly due to increasing fuel prices on an international level.

So, the aim of this study, which is the result of a final degree project of Cuevas, D. and Orué, R. tutored by Pulfer, JC., was to demonstrate that solar energy can also be used as a sustainable energy source for water vehicles, moving from the internal combustion propulsion to an electrical system. The proposed boat would work using partially the energy coming from on-board photovoltaic solar panels and batteries. The remaining energy would be coming from off-board charging stations located in different places, where the boat would stop overnight during the almost 250 km long trip between Carmelo Peralta and Bahía Negra to recharge the batteries.

1.1 Objectives

The main objective of this study is the design of an electric propulsion system for a boat to be used to transport passengers and goods between different communities located on the upper Paraguay river. The specific objectives are the followings:

- Selection of an existing hull design with low water resistance
- Design of the photovoltaic generating and storage systems for the boat
- Selection of an electric propulsion and the emergency generation systems
- Calculation of energy consumption and solar generation
- Realization of an economic assessment comparing the studied propulsion system with a conventional one based on internal combustion engines

2. Methods

The first step of the iterative designing process consisted in the design of a suitable hull for the boat considering the specified payload, as well as the estimated weight of the boat including the solar energy equipment, the main part coming from the batteries. The hull also should have a water resistance as low as possible to obtain an optimum energy consumption for the displacement of the vessel in the water. For this reason and to get a high stability on the water, a catamaran type configuration was chosen. The design was made using the Delft Ship free version software having a database of different basic hull models, which can be modified and scaled according to the needs of the project. As a main numerical outcome, it calculates the different hydrostatic parameters of the designed model. As Delft Ship is not able to calculate these parameters for catamaran configurations, another complementary software called Michlet was used, which takes into account the additional resistance created by the interference of waves between both hulls depending beside the speed also on the separation between them. Both hulls are united by a platform used to receive the pay load and part of the equipment. The roof covering this platform receives the solar panels generating a considerable part of the energy consumed by the two electric out-board motors, one for each hull.

On the basis of the water resistance vs. speed curve of the catamaran, which is characterized by its wavy shape typical for catamarans, was then determined the optimum cruising speed electing one of the resistance valleys. The water resistance depending strongly on speed and the actual tie allowed then to calculate the energy consumption between the different ports the boat will deserve. The longest of these partial trips up stream was used to obtain the necessary battery capacity considering as the worst-case scenario that the solar panels will not generate any energy during the trip. To determine the distance on the strongly meandering river between the different ports the application Google Earth was used.

The whole electric power system of the boat is composed of the following parts: The 2 DC outboard motors receive the energy from the lithium-ion batteries located inside the hulls. The solar panels recharge the batteries during daytime controlled by solar charge regulators. Additionally, when necessary, the batteries are recharged with electricity from the grid at the ports, where the boat stays overnight connecting the onboard battery charger with a cable to an industrial socket located on the dock. The boat is also equipped with 2 gasoline engines driven gensets, what allows to move the boat even in case of completely discharged batteries. The whole power system is doubled, what means that each motor has its own totally independent system as described above.

The base information to size the solar system was the mean solar global radiation on a horizontal plane in the zone of Fuerte Olimpo, which is the port approximately in the middle of the deserved section of the Paraguay river. As the boat is moving and changing its orientation constantly, the highest yield is obtained throughout the year when the solar array is installed horizontally. To allow rainwater runoff from the solar panels a small tilt was given in form of a gabled roof, with half of the solar panels on each side of the boat. To obtain a reasonable power of the solar array was taken into account the maximum daily global radiation registered during clear days in summer, the way that the array will be able to generate a quantity of energy similar to what the boat will consume in a normal operating day. So, only during days with less solar radiation it will be necessary to recharge the batteries from the grid. The mean

values of daily power generation by the solar panels for each month of the year was calculated using the on-line application PVWatts.
For the economic comparative study were calculated for the solar electric boat on one hand and the conventionally driven boat on the other hand the annual costs of the propulsion system only, as the remaining costs, such as crew, operation and maintenance costs of the boat itself are the same for both options. The considered costs include those for energy (gasoline, electricity), maintenance of the propulsion system and depreciation of the investment considering useful life of the different components. Based on these costs was then calculated the Present Value of Costs for a 10 years' period for both options, what allows to compare them.

4. Data Collection

Global solar radiation in the area of the project is one of the highest in Paraguay. According to NASAs POWER database the mean annual value in a horizontal plane per day in Fuerte Olimpo is 5.08 kWh/m^2. The monthly mean values are represented in Table 1:

Table 1: Mean monthly global solar radiation on a horizontal surface in kWh/(m^2 day) for Fuerte Olimpo, Paraguay, source: NASA POWER

Month	Radiation	Month	Radiation
January	6.39	July	3.62
February	5.91	August	4.38
March	5.67	September	4.85
April	4.91	October	5.50
May	3.76	November	6.28
June	3.37	December	6.38

The boat was designed to transport 30 passengers, a 2 persons' crew and 1000 kg of goods. The principal dimensions of the boat are the followings Table 2 (see also Figures 2 and 3):

Table 2: Principal dimensions of the boat

Description	Dimension	Description	Dimension
Length of the hulls	10.00 m	Length of the roof	11.80 m
Maximum width of the hulls	1.00 m	Width of the roof	6.00 m
Depth of the hulls	1.25 m	Surface of the roof	70.8 m^2
Length of the platform	10.00 m	Empty weight of the boat	2750 kg
Width of the platform	4.70 m	Weight of electric propulsion system	2560 kg
Useful surface of the platform	47.0 m^2	Payload	3860 kg

The distances of the route between the main locations on the Paraguay river to be deserved by the boat are those listed in Table 3 (see also map in Figure 1). The homeport of the boat will be Carmelo Peralta. The main reason is that this small town is now easily accessible under any weather conditions thanks to a recently built paved road connecting Carmelo Peralta directly to the Transchaco-Route connecting the capital Asuncion to Bolivia in the northwest of Paraguay. This new road is part of the Biocenanic-Route passing through Paraguay connecting the Atlantic Ocean in Brazil with the Pacific Ocean in Chile. Bahía Negra is the northernmost Paraguayan town on the Paraguay river before reaching the border with Brazil and Bolivia.

Table 3: Distances between the main deserved localities (south to north)

Route	Distance
Carmelo Peralta – Puerto Guaraní	57.0 km
Puerto Guaraní – Fuerte Olimpo	31.2 km
Fuerte Olimpo – Puerto Leda	87.0 km
Puerto Leda – Bahía Negra	70.6 km
Total	**245.8 km**

To be able to determine the real speed of the boat it is necessary to know the flowing speed of the Paraguay river. According to the consulted sources it is in average about 0.3 m/s or 1 km/h. Therefore, when the boat is circulating upstream this speed has to be rested from the speed of the boat and when it's moving downstream it has to be added.

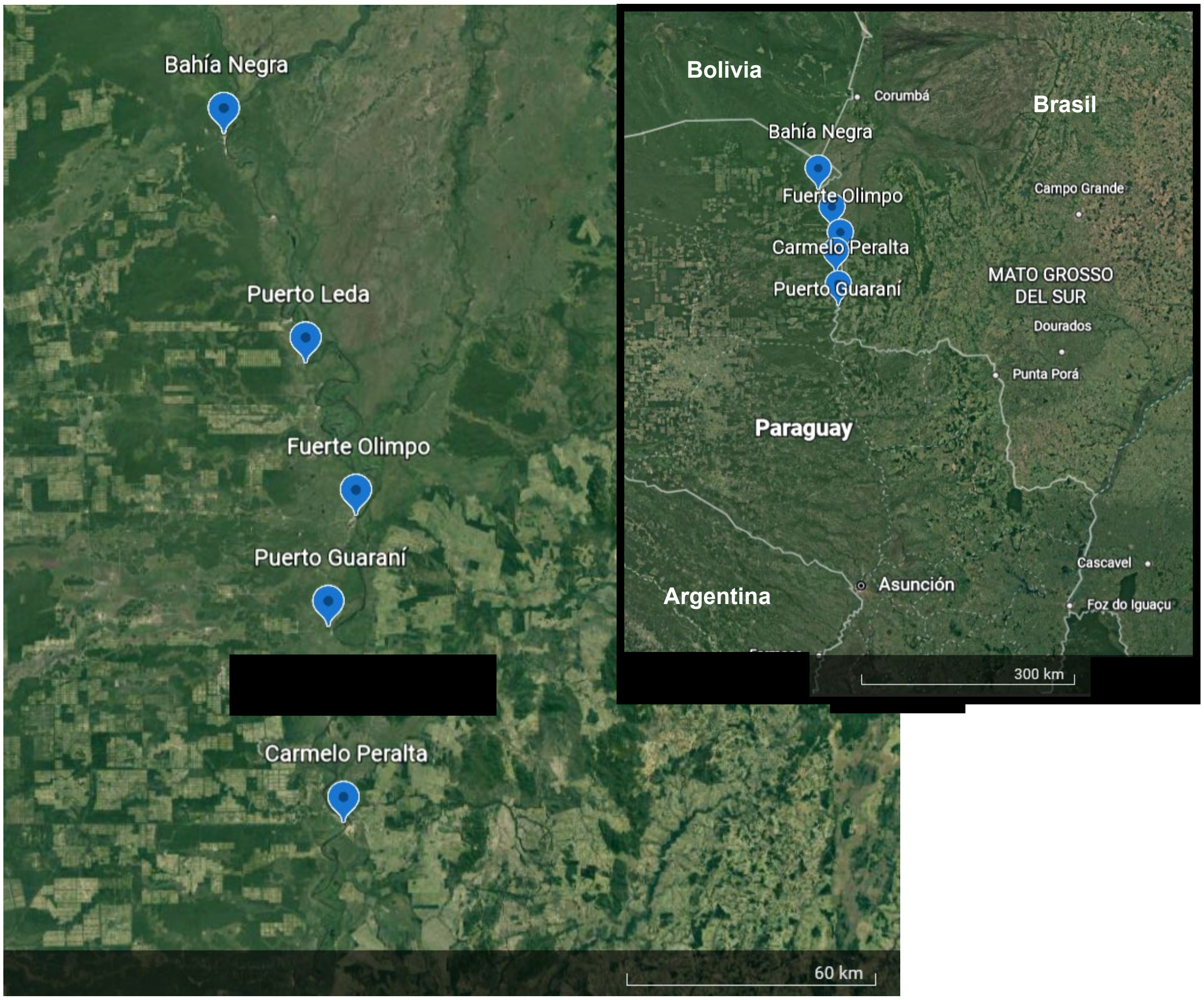

Figure 1: Satellite picture of the area of use of the solar boat with main deserved ports, source: Google Earth

5. Results and Discussion

5.1 Numerical Results

The dimensioning of the components of the electric power system of the boat gave the following results: (Table 4)

Table 4: Components of electric power system

Component	Characteristics	Quantity
Solar panel	320Wp, monocrystalline silicon, half-cell, 60 cells	42
Battery	LiFePO4 200Ah/48V with BMS	20
Motor	Outboard electric DC motor 10kW by Torqeedo	2
Charge regulator	100A/150V MPPT by Victron Energy	2
Inverter-charger	15 kVA/48V by Victron Energy (inverter not used)	2
Monitoring system	By Victron Energy	2
Emergency genset	7.5kW single phase gasoline by Caterpillar	2

Table 5: Proposed schedule and power consumption of the solar boat for each complete weekly trip

Start place	Arrival place	Distance	Day	Time start	Time arrival	Dura-tion	Power	Consum ption
Carmelo Peralta	Puerto Guaraní	57.0 km	Monday	6:00	11:12	5.18 h	20 kW	104 kWh
Puerto Guaraní	Fuerte Olimpo	31.2 km	Monday	13:00	15:51	2.84 h	20 kW	57 kWh
Fuerte Olimpo	Puerto Leda	87.0 km	Tuesday	6:00	13:55	7.91 h	20 kW	158 kWh
Puerta Leda	Bahía Negra	70.6 km	Wednesd.	6:00	12:26	6.42 h	20 kW	128 kWh
Bahía Negra	Puerta Leda	70.6 km	Thursday	6:00	11:27	5.43 h	20 kW	109 kWh
Puerta Leda	Fuerte Olimpo	87.0 km	Friday	6:00	12:42	6.69 h	20 kW	134 kWh
Fuerte Olimpo	Puerto Guaraní	31.2 km	Saturday	6:00	8:24	2.40 h	20 kW	48 kWh
Puerto Guaraní	Carmelo Peralta	57.0 km	Saturday	10:00	14:24	4.38 h	20 kW	88 kWh
		491.6 km				41.25 h		825 kWh

The motors made by Torqeedo, the world leader in electric boat motors from Germany, have a continuous electric power of 10 kW and a maximum power of 14 kW each. According to their data sheet their propulsion power is 5.6 kW each. So, both together have a propulsion power of 11.2 kW. This allows to move the boat with a cruising speed of 12 km/h, when it has a depth of 70 cm (see Figure 5). Therefore, the total electric power is 20 kW for both motors. To calculate energy consumption for each partial trip (see Table 5) this power was multiplied by the duration of each partial trip calculated by considering a real speed of 11 km/h upstream and 13 km/h downstream.

The mean daily electricity generation by the solar panels is estimated by the PVWatts software in 56.2 kWh during the first year. The maximum value is reached in January with 69.1 kWh and the minimum in June reaching 38.1 kWh. As showed in Table 5 the calculated energy consumption during the 6 days lasting trip is 825 kWh. So, in an annual average generation during a week including Sundays, when the boat will stay tied up in Carmelo Peralta, will be of 393 kWh or 47.7% of total consumption. The following years energy generation will decrease by 0.5% per year due to degradation of the solar panels. As already mentioned, the missing energy will be provided by grid electricity in all of the 5 ports showed in Figure 1.

As one complete trip has a duration of one week, theoretically 52 trips per year could be made. Nevertheless, once or twice a year major maintenance works has to be done. So, only 50 trips per year were considered for the economic study. The use of the emergency gensets was considered to be during 5% of the total annual operation time of 2050 h. The total investment costs for the whole propulsion system of the solar boat without considering the boat itself is about US$140,000. This amount includes the solar panels, the batteries, the electric motors, the gensets and all the components of BOS. It includes also the 5 charging stations in the main deserved ports. In the case of the conventional boat only about US$12,000 are necessary for the 2 ICEs and corresponding fuel tanks. Were considered 2 20 HP outboard 4 stroke gasoline engines by Tohatsu with a specific fuel consumption of 6.5 l/h each. For the solar boat the total cost of the propulsion system during the first year reaches US$15,396 (see Table 6). 80% of this amount is spent for depreciation of the investment. The remaining 20% are needed for O&M. In the case of the ICE boat the total cost of the propulsion system during the first year is US$39,572 (see Table 7), 2.6 times the cost for the solar boat. 81% of this amount are needed for fuel. Comparing these costs, it is obvious, that the solar boat is a much better solution, not only from the environmental point of view, but also from the economical one. The actual official fuel price is US$1.20

per liter for unleaded gasoline with 93 octanes and the grid electricity tariff is US$0.065 per kWh. Considering an annual inflation rate on fuel and maintenance costs of 5%, a constant tariff for grid electricity (the most likely scenario in Paraguay due to the source of grid electricity, which is 100% hydraulic coming mainly from the Itaipú plant shared with Brazil), the 0.5% annual degradation of the solar panels and an annual discount rate of 10%, the cumulated Present Value of Costs (PVC) for the solar boat during the first 10 years of operation is US$96,888 compared to the PVC for the conventional type boat of US$292,858, what represents a 3 times higher amount.

Table 6: Cash flow in US$ of the propulsion system for the solar boat during the first 10 years

Type of cost	1	2	3	4	5	6	7	8	9	10
Electricity	1474	1482	1489	1496	1504	1511	1519	1527	1534	1542
Fuel	1132	1188	1248	1310	1375	1444	1516	1592	1672	1755
Maintenance	500	525	551	579	608	638	670	704	739	776
Depreciation	12291	12291	12291	12291	12291	12291	12291	12291	12291	12291
Total	**15396**	**15485**	**15578**	**15676**	**15778**	**15884**	**15996**	**16113**	**16235**	**16364**

Table 7: Cash flow in US$ of the propulsion system for the conventional boat during the first 10 years

Type of cost	1	2	3	4	5	6	7	8	9	10
Fuel	31980	33779	35258	37021	38872	40815	42856	44999	47249	49611
Maintenance	6396	6716	7052	7404	7774	8163	8571	9000	9450	9922
Depreciation	1196	1196	1196	1196	1196	1196	1196	1196	1196	1196
Total	**39572**	**41491**	**43505**	**45621**	**47842**	**50174**	**52623**	**55195**	**57895**	**60730**

5.2 Graphical Results

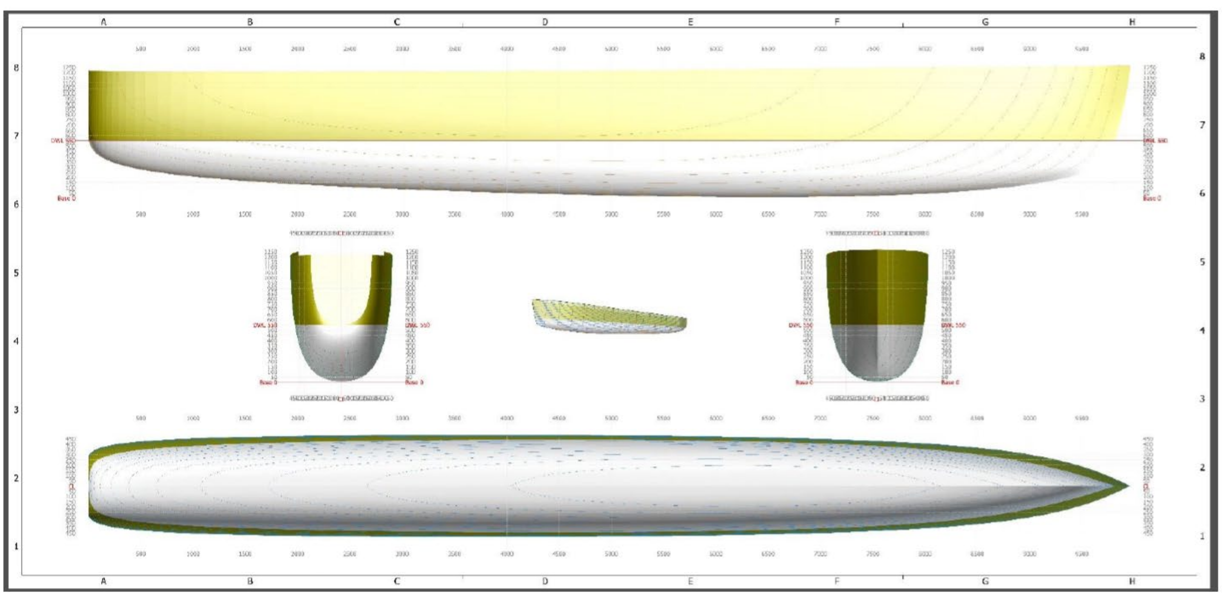

Figure 2: Plan of the hull designed with Delft Ship

In Figure 2 can be seen the result of the designing process of the hull with the Delft Ship software representing the principal views. Figure 3 represents a 3D sketch of the complete solar boat drawn with the help of the SketchUp designing software.

The simulation of the water resistance in function of the speed and the separation between the two hulls of the catamaran with the software Michelet generated the graph showed in Figure 4 with separations varying between 2 and 5 m. The wavy shape is due to the interference of the waves generated by the hulls in the space between both hulls. A bigger distance reduces this effect. For this project a 4 m separation was chosen. According to this graph the optimum cruising speed of the boat for this separation would be 12 km/h.

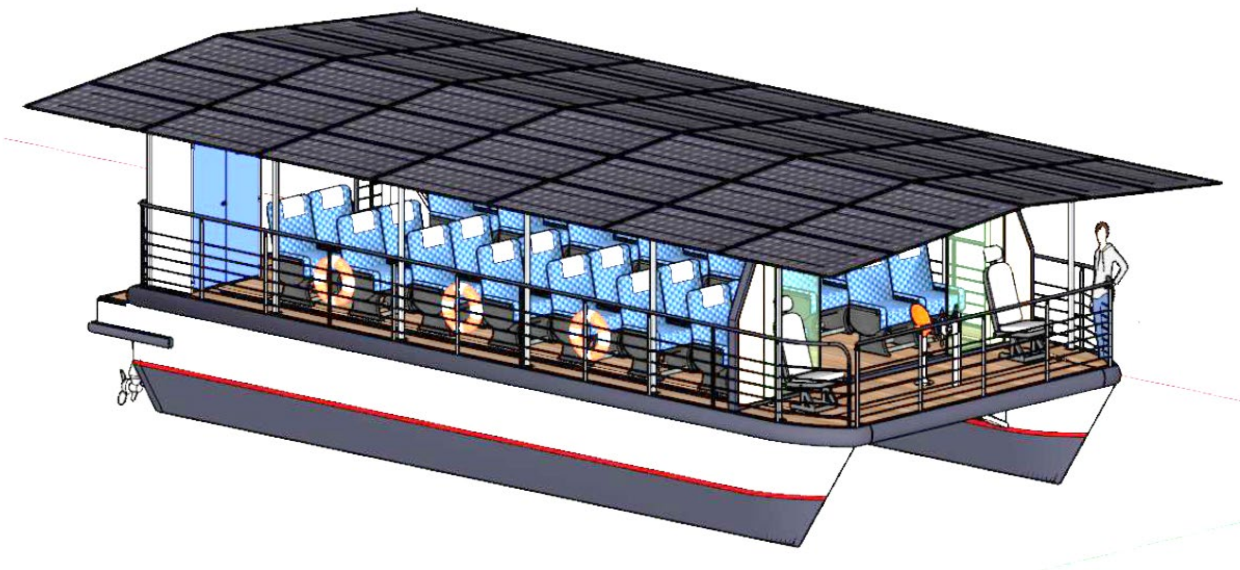

Figure 3: 3D sketch of the solar boat

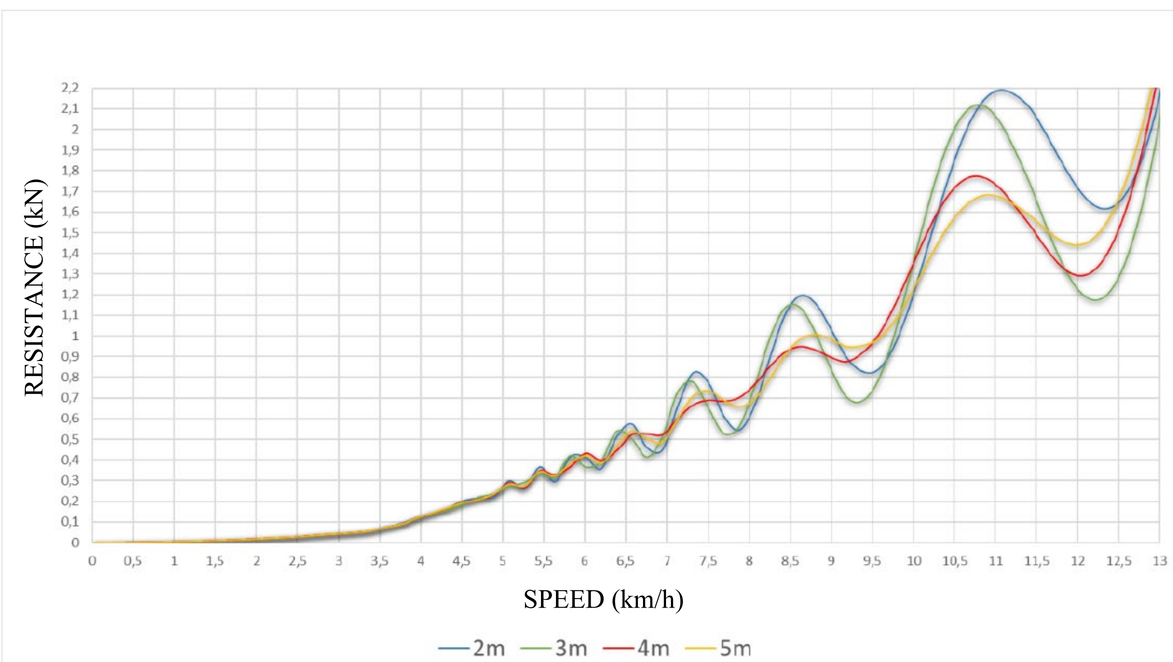

Figure 4: Graph of water resistance vs. speed and separation of the 2 hulls of the catamaran

Water resistance respectively the power needed to move the boat are depending also on the depth the hulls are immersed in the water. This dependence is shown in Figure 5 with the depth varying between 0.55 m and 0.85 m. The depth of 0.7 m is considered as the project value for the nominal payload.

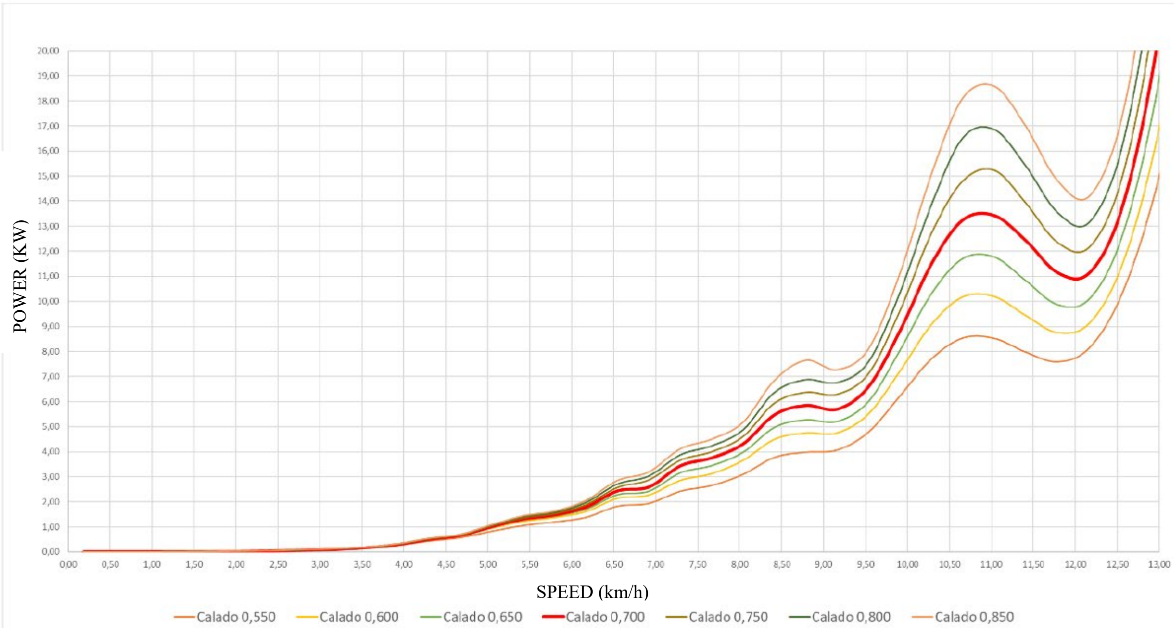

Figure 5: Graph of power vs. speed and depth

6. Conclusion

Using Delft Ship software, a hull for the catamaran boat with a low water resistance was designed. Then, using Michlet software was determined the optimum distance between both hulls and calculated the hydrostatic parameters of the boat. The main part of the study consisted in the design of electric propulsion system composed of the photovoltaic and energy storage systems and the electric motors. As on average the solar array covers less than a half of the energy consumption of the boat traveling in a weekly cycle between two towns distant of almost 250 km on the Paraguay river, the remaining electricity has to be provided from the grid through charging stations located in the deserved ports. The economic assessment was made using the method of Present Value of Costs (PVC) of the propulsion system for the solar boat comparing it with the same boat design using 2 ICEs. Despite of an investment more than 10 times higher for the solar system, it came out that its PVC for 10 years´ period is 3 times lower.

References

Brooks, W. and Dunlop, J., PV Installation Professional Source Guide, 2013
Cyberiad, Michlet 9.33 User’s Manual, 2015
Delft Ship, Manual de Delft Ship, 2016
Heroica Escuela Naval, Conocimientos Marineros, 1993
NREL, PVWatts calculator, 2020
Perpiñan, O., Energía solar fotovoltaica, 2013
Torqeedo: Electric mobility on the water, 2020
Victron Energy, Off-grid, backup and island systems, 2020
Yogi Goswami, D., Principles of Solar Engineering, 2015

Biographies

Denis Cuevas is an Electromechanical Engineer, graduated in 2020 at the School of Engineering of the National University of Asuncion, Paraguay. He actually is working as technical manager of a company specialized in maintenance of electromechanical installations.

Renato Orué is an Electromechanical Engineer, graduated in 2020 at the School of Engineering of the National University of Asuncion, Paraguay, previously graduated as Industrial Technician at the National Technical College of the Asuncion. He is currently performing engineering jobs for more than 4 years in a metallurgical company, especially in the field of metal structures leading a team of designers, developing innovation projects and planning production processes and quality controls.

Jean-Claude Pulfer is a researcher and lecturer at the School of Engineering of the National University of Asuncion, Paraguay, where he also is working as coordinator of a master's degree course on renewable energies and energy efficiency. He was graduated in 1983 as Rural Engineer at the Federal School of Engineering in Lausanne, Switzerland and then post graduated in 1985 in Urban Hydraulic Engineering at the Federal School of Engineering in Zurich, Switzerland. Since 1988 he is working in the area of solar energy applications, first in Switzerland and for 25 years in Paraguay. He is coauthor of several published papers on topics related to renewable energies. He is founding member and former president of the Paraguayan NGO Asociación Paraguaya de Energías Renovables APER.