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DESIGN, PRODUCTION, TESTING AND EXPLOITATION OF SOLAR COASTAL PASSENGER FERRY

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Professional paper

Abstract

This professional paper firstly considers the practical needs, technical experience, market situations, preliminary and feasible solutions of coastal passenger ferries. Secondly, it describes the process of development of a product from conception, design, organization, production, testing, exploitation and maintenance of a new model of solar coastal passenger ferries. The solarCat catamaran project presented in this professional paper has been conceived as self-sustainable zero emission passenger ferry, applying advanced technologies in hull construction, photovoltaics panels, lithium-based batteries and electric propulsion modifiable for different services for urban sites as public transportation vessel. Design and service profile represent an alternative approach to passenger transportation and operations at east Adriatic coastal areas and islands, enabling solar power on vessels for commercial services.

Key words: passenger ferry; electric propulsion; solar cells; lithium batteries; solarCat

1. Introduction

The development of a platform for multi-purpose solar coastal passenger ferries presented in this paper has been motivated by the importance of coastal and inter-island passenger transportation by employing former experiences and modern technologies.

The plan was further encouraged by the fact that the electric propulsion of ships has reached a high practical level. Permanent magnet electric engines have become very efficient and photovoltaic panels commercially viable although, much progress in future is still expected in marine electric propulsion. However, not all system components are at the same development level, with the further development of batteries showing the most promises in this context. Increased mass usage of electric propulsion in all types of vehicles will significantly reduce the cost of batteries and contribute to the improvement of their performances and safety in the future. Advances in materials and building technologies allow lighter structures. Besides, the current level of technological development favors lithium-based batteries technology that offers a better ratio of reliability and parameters like capacity, mass and safety.

The design and operational requirements are primarily planned for protected waters and urban sites as public coastal services and inter-island transportation. Moreover, the vessel could be used for other purposes such as for daily trips, educational activities or as a research ship. The concept has been recognized on the national level and has been awarded as vessels of the future of particular importance for Croatian coastal and inter-island communications.

By changing the way of thinking where ship services are no longer designed only for the coastal and island residents, but where ship services are setting integrated transportation network with more frequent and reliable sailing schedule, they are becoming financially sustainable by multiplying the number of passengers. Such quality of transportation for the coastal and island residents will improve in service quality and frequency. The more frequent sailing regime will result in more sailing miles and more pollution from conventional vessels. In the 21st century where pollution is the existential issue on a global scale, and where electric energy has taken a significant role in the automotive industry, possibilities of the electric storage and propulsion on passenger's vessels are future steps. Electric propulsion, in combination with solar powering, is a new stress-free experience of comfortable sailing, where the only noise and vibration come from wind and waves.

2. iCat project

From the very beginning, the iCat project coped with compromising among multiple often conflicting goals such as size, capacity, maritime properties, seakeeping, manoeuvrability, maintainability, reliability, passenger comfort, low noise, low costs and attractive appearance. The concept required modularity in design and production for flexible modifications for different service purposes at densely inhabited coastal areas and islands as well as for protected lakes and coastal nature reserves with tourist ambitions.

The basic platform obtained from these multidisciplinary considerations is the concept of Catamaran shape single deck solar-powered vessel, with integrated solar cells in the shelter deck, modifiable for different operational profiles.

The first application of the concept was on the series of three vessels for Mljet National Park: babyCat1, babyCat2 and babyCat3. These vessels were carefully tested in different operational and service conditions, providing important experiences for future development.

Following the encouraging resting and practical experiences, the next vessel developed from the basic iCat concept was the solarCat with higher battery capacity and higher solar power appropriate for more distant and demanding coastal and inter-island operations.

3. Design

3.1 Design requirements and regulations

The iCat vessels were designed and built according to contract for referent Rules and Regulations of 2013 including statutory certification requirements of Croatian Register of Shipping (CRS) for passenger ships [1], the classification requirements of the CRS [2] and the CRS general requirements [3]. Particular requirements e.g. pertaining on their environmental impact or facilities for boarding passengers with disabilities were applied. Here it is important to note that where the available requirements were not appropriate for small passenger ships such as it is the iCat series, special considerations were necessary in agreement with CRS. The most recent documents for future applications are [5] [6] [7].

In the absence of national rules, such as for example the rules for installation of lithium-based batteries on board one may seek guidance by referring to DNV-GL [4] rules or the most recent [8]. The justifiability of requirements prescribing equipment components for ships with very limited areas of navigation, such as area 6, 7 or 8, should be reconsidered [3]. The requirement for the installation of additional backup propulsion is not justified if a ship, e.g. a catamaran, already has two fully independent propulsion systems at N+1 redundancy level.

3.2 solarCat Design

Designed to be operated by 2 crew members, the vessel would achieve a significant saving in operating expenses. Small crew, small consumption and zero-emission of the vessel design is the result of joint R&D activities of iCat Ltd, The University of Zagreb and Končar Institute.

3.3 General arrangement

Description: Catamaran shape single deck solar-powered vessel with exposed shelter deck with integrated solar cells. The general arrangement is presented in Fig. 1.

Basic ship data:

- Δ=15 t
- L_{OA}=14,95 m
- B=5,00 m
- H=1,58 m
- T=0,68 m
- $V_{cruising}$=6 knots
- V_{max}=9,5 knots
- Passenger capacity 54+2
- Crew 2 members

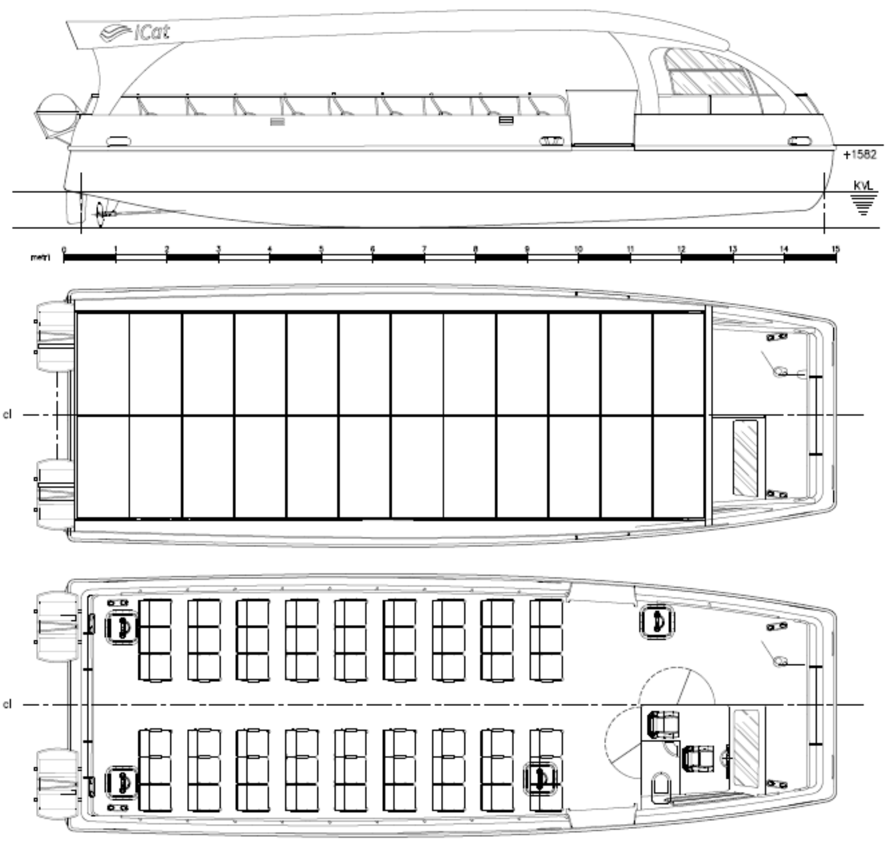

Fig. 1 solarCat – General Arrangement Plan

3.4 Hull

Comparing FRP (fibber reinforced plastic) in vacuum infusion technology with aluminum in welding technology in the preliminary design stage, considering jointly strength, technology (welding thin aluminum materials) and hull surface finishing (additional plastering and painting needed in some cases), all of which contribute to additional weight, the conclusion was that the savings in hull weight, vessel immersion, ship resistance and finally the fuel consumption could be up to 30%.

A Midship section is presented in Fig. 2. Hull assembly process is presented in Fig. 5.

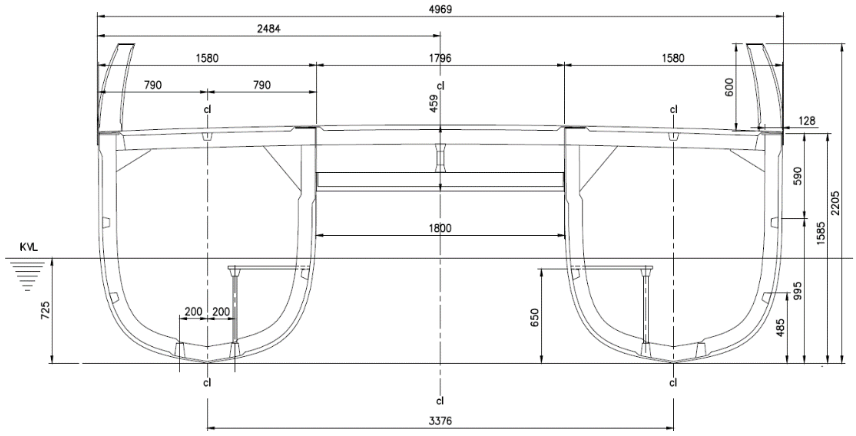

Fig. 2 solarCat – Midship Section

3.5 Propulsion

Electric motors, LiFePO4 batteries and solar power plant make the heart of catamarans. Electric energy is generated by the photovoltaic solar cells, stored in lithium batteries and used by the permanent magnet motor (Fig. 3). In normal daily operations, with cruising speed up to 6 knots and sailing time up to 12 hours, there is no need for the additional power supply, where all the energy needed for the propulsion is generated on-board. Additionally, more energy can be accumulated by the shore chargers, usually overnight.

Fig. 3 solarCat – Engine Room

3.6 Photovoltaic Solar Panels

Photovoltaic (PV) Solar Panels are integrated with the exposed shelter deck (Fig. 4) of the vessel, following deck structure and aerodynamic shape of the vessel. Solar panel cooling is provided between panels and deck construction, where front and aft end opening defines natural airflow.

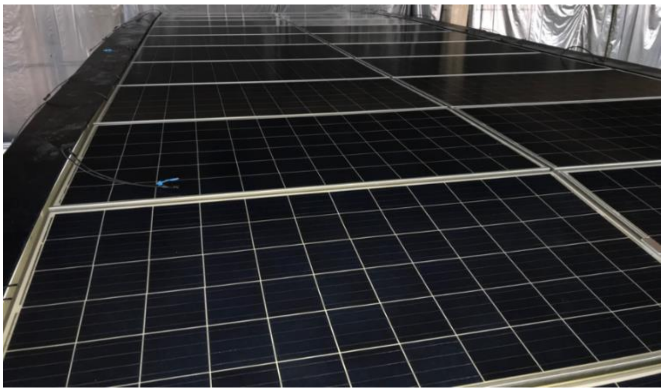

Fig. 4. solarCat – Photovoltaic Solar Panels integrated in the vessel’s exposed shelter deck

3.7 Outfitting

Ergonomic passenger seats with mesh cover are chosen for the high level of comfort for passengers. Solid bulwark, in combination with handrails, protects passenger deck from splashing or dropping personal belonging over the deck.

Weather protection is secured by the foldable rain covers below rooftop on each side.

Mooring is defined by the front and end bollards for the overnight mooring and side bollards for the fast mooring during short berthing for the boarding of passengers.

Anchoring line defines 25 kg Delta anchor on 10 mm anchoring chain and 1,7 kW anchoring winch. Considering low height under the deck in a central position, the winch is allocated to the side of the vessel with anchor basket in the hull. Outfitting process is presented in iCat shipyard in Zagreb in Fig. 6.

4. Materials and production

The first step was the preparation of moulds. The production of moulds was outsourced to specialized factories in Poland and transported to the shipyard location in Zagreb, Figs. 5, 6.

Glass-reinforced plastic in vacuum infusion technology provides a high level of strength of the material with a low weight of the vessel.

Certified Laboratory for Polymers and Composites at the Faculty of Mechanical Engineering and Ocean Engineering in Zagreb confirmed Average Fiber ratio in solid laminate of 67,97% on test specimens. High glass content is result of vacuum technology. No appropriate CRS rules existed for vacuum technology at that time only for hand-layout technology.

The test results are placing vacuum infusion laminate strength on the level of standard construction steel in shipbuilding as shown:

- Average Bending Strength 334,9 N/mm^2
- Average Tensile Strength 247,6 N/mm^2

Launching of a completed vessel is presented in Fig. 7.

Fig. 5 solarCat –Hull assembly

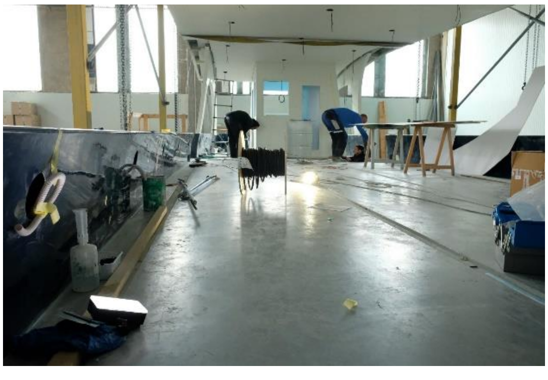

Fig. 6 solarCat – Outfitting

Fig. 7 babyCat – Launching

5. Testing and trials

Since the solarCat is a newbuilding within to the EU project, and sea trials will be carried out after the project ends, testing results have been taken from the syster's vesseles babyCat2 and babyCat3, which are in the operations for more than a year. BabyCat2 (Fig. 8) was tested in the summertime with long days and high solar insolation, while babyCat3 (Fig. 9) was tested in the wintertime with short days and low solar insolation.

Propulsion, energy storage and production comparison are given in Table 1.

Table 1 Propulsion, batteries and power data

Vessel	Engine	Battery Capacity	Instaled Solar Power
solarCat*	2 x 12 kW	2 x 32 kWh	8,9 kWp
babyCat2	2 x 12 kW	2 x 25 kWh	7,5 kWp
babyCat3	2 x 12 kW	2 x 25 kWh	7,5 kWp

*solarCat has 28% more capacity in batteries, and 19% more instaled solar power.

5.1 Test results babyCat2 – "Antun Tonko Martić"

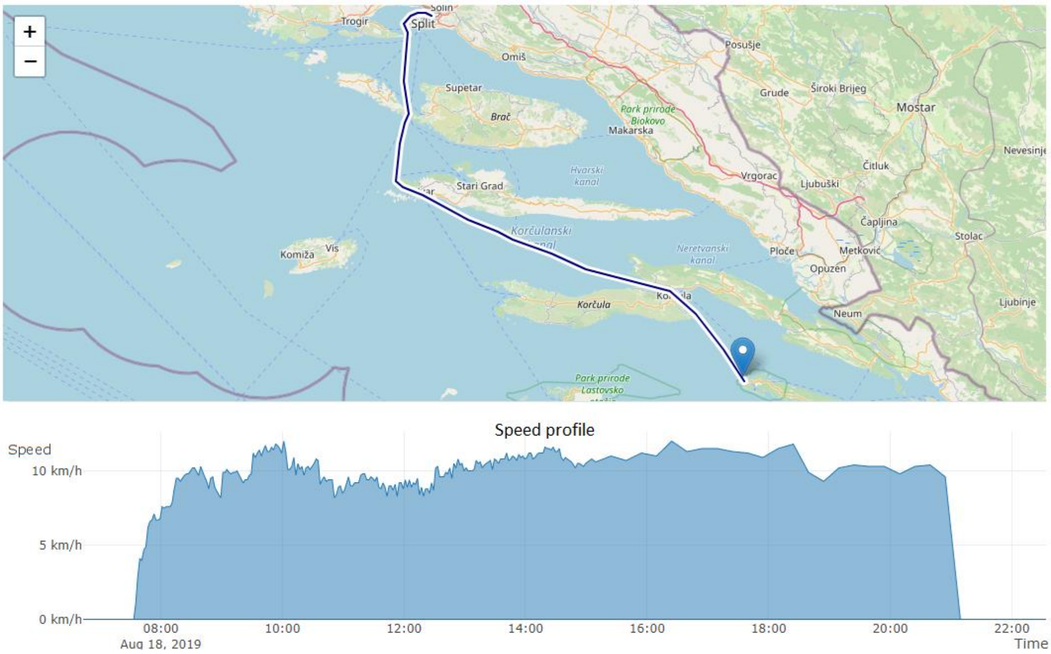

Fig. 8 babyCat2 sailing route and speed profile between Split and Pomena

Battery capacity testing was on 18th August 2019. At departure, batteries were at 100% State of Charge (SOC), and the following testing results achieved:

Location: Split – Pomena

Departure: 7.30 am; Arrival: 9.00 pm; Sailing Time: 13,5 hours

Sailing Distance: 75 NM; Average Speed: 10 km/h (5,5 knots); Batteries at Arrival: 55% SOC.

5.2 Test results babyCat3 – "Pero Seršen"

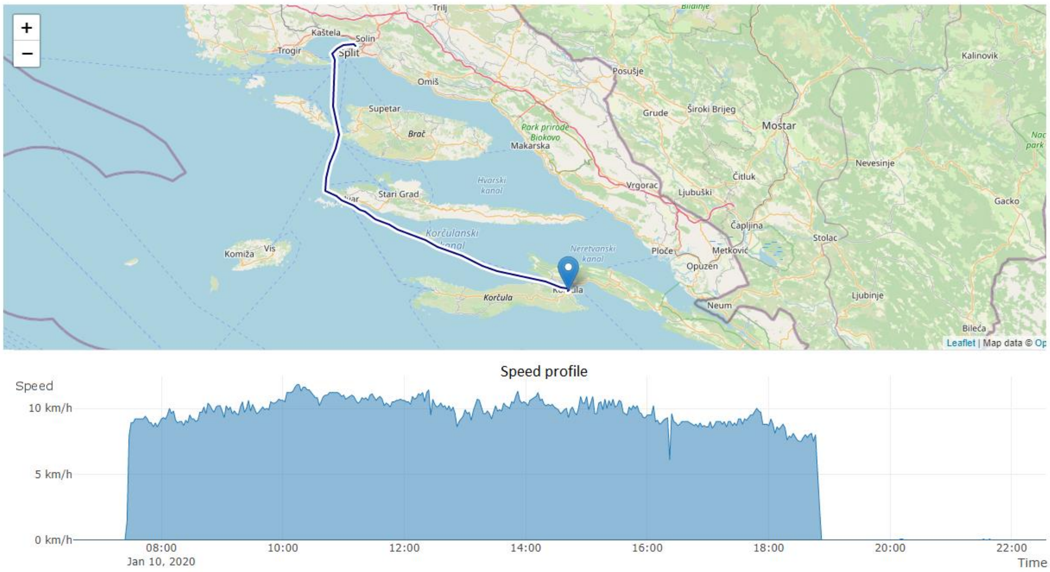

Fig. 9 babyCat3 sailing route and speed profile between Split and Korčula

Battery capacity testing has been done on January 10th 2020. At departuture batteries have been at 100% State of Charge (SOC), and following testing result have been acchieved:

Location: Split – Korčula

Departure: 7:30; Arrival: 19:00; Sailing Time: 11,5 hours

Sailing Distance: 62 NM; Average Speed: 10 km/h (5,5 knots); Bateries at Arrival: 10% SOC

Presented testing of the vessel in different conditions (summer vs winter) shows that there is a significant difference in photovoltaic energy production. However, both testings show that presented vessels have whole day sailing autonomy.

Concerning batteries and solar panels, solarCat would have extended sailing autonomy of 30-50% relative to babyCat, which comes to the 100 NM of sailing autonomy.

The installed solar power cannot be much more increased, while battery bank can be increased 4 times without significant effect on draft and wetted surface and subsequently negligible effect on prevailing viscous resistance at relatively low.

6. Exploitation and maintenance

Although electric propulsion components require significantly less maintenance, hull maintenance and hull and propeller protection by antifouling paint are still required.

In general, compared to conventional vessels, maintenance is less expensive and less demanding.

From the engine side, on permanent motors only bearing can be replaced if they wear off. Other works would consider parts replacement and not regular services.

Batteries must be checked twice per year, balanced and reprogramed if needed. The same is with battery chargers. Whole electric installation must be checked and tightened regularly.

Operational costs are defined by the price of the electric energy if shore chargers are in function and no other expenses are required.

Valuable practical experiences with solar-powered passenger ferries (babyCat1-3) (Fig. 10) came from a continuous yearlong service in Mljet National Park.

7. Practical experience

Since the beginning of the regular services in Mljet National Park (Fig. 10) vessels were only electrically powered and exclusively by solar power with minimal maintenance. The vessels are safely operational by two crew members: the captain and the sailor. No accidents or damages have been encountered.

Crew training

Operation electric vessel is slightly different from the conventional one. Therefore, the crew must be trained for some new skills and habits. There is no oil check, but installation and battery check must be done as a daily routine. Batteries, chargers functionality, fuse conditions and general inspection should be done each day. However, there is an online app where battery condition is available. The experience shows that the crew easily acquire new requirements.

Fig. 10 Solar Powered Passenger Ferry (babyCat1) in service in Mljet National Park

7.1 Safety of the Lithium battery on vessels

Most of the parts and main components of the vessel are well known and used on the vessels worldwide for years. While LiFePO4 batteries are relatively new in ship applications, with limited regulation for their application. When design of babyCat and solarCat vessel have started, Croatian Register of Shipping as classification body, emphasized that application of LiFePO4 batteries must be done with additional safety analysis, where Risk assessment and Classification of the space have been made additionally.

From the communication with Register of Shipping, it have been noticed that safety of the vessel is mostly related to the type of batteries on board, where lithium batteries are rather new technology and as such, Notification Bodies (e.g. Registry of Shipping) is still developing rules and defining a condition of lithium battery usage on board. Like with each new technology it will take some time before notification Bodies will come to the level of trust to the lithium batteries.

Lithium batteries have several technology options, where on solarCat Lithium Iron Phosphate (LiFePO4) [Fig.11] have been chosen and used. It have been considered as relatively safe with thermal runaway at 270°C,.

Thermal runaway defines a point of no return, where the battery would burn out without possibility to be cooled down. If that happens, it is important to leave the battery in thermal runaway to burn out, and taking care that no other battery is affected by the fire.

Summary Table for the LiFePO4 batteries:

- Voltage 2,5-3,65 V/cell
- Capacity 90-120 Wh/kg
- Charge rate 1C
- Discharge rate 1C
- Cycle Life 2000 – 5000
- Thermal Runaway 270°C

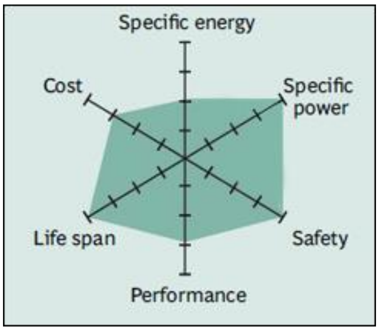

Fig. 11 LiFePO4 – Performance Ration

Safety measures defined for the solarCat vessel by the designed and Croatian Registry of Shipping are defined on several levels:

- Battery BMS as the first level of protection shutting down the batteries
- Monitoring and Alarm system where main battery parameters are monitored with possibilities to shut down the system with an emergency switch
- Fire Extinguishers for the direct fire
- Sprinkler system for the battery compartment to cool down space if the fire starts
- Firefighting water buckets

7.2 Seakeeping

Catamaran hulls were optimized for the minimum wetted surface in order to reduce the dominant viscous resistance of the hull at normal speeds also having small underwater lateral hull area. The seakeeping properties at higher and lower speeds of such catamaran arrangement in calm sea conditions are satisfactory.

Emphasized keels and more weight on board are added in order to improve seakeeping and maneuverability at lower speeds of light catamarans with high lateral area exposed to strong side winds and cross waves when more power might be required.

In this specific conflating conditions two independently controllable electric engines of 2x12 kW were found sufficiently reliable to provide the sustainable seakeeping and maneuverability properties at high and low speeds in wind and waves.

7.3 Manoeuvring

Low draft, twin engines, direct-drive and bow thruster provide excellent manoeuvring of the vessel. The solarCat can be rotated around the centre of buoyancy.

The propeller should be chosen by the preferences, a smaller one (16”-18”) for the higher sailing efficiency, and a bigger one (18”-19,5”) for better manoeuvring.

8. Future developments and plans

Even though batteries and engines are protected against overheating and fire, temperature, voltage and current should be regularly monitored. Lithium batteries are self-protected with Battery Management System (BMS). However, a marine application would ask for additional features as: in case of overtemperature, overvoltage or overcurrent, battery shutdown is not acceptable, while warning would be needed. Onboard monitoring and alarm system are required by the Notification Body.

Further development of battery technology with improved capacity, cycle life and charge/discharge rate will make electric energy enough for shore shipping vessels. Taking an example, coastal ferry transportation service will be achievable with electric vessels.

The iCat Project described in this paper has proven self-sustainability of the electric vessels on low speed. Next step will be testing of a high-speed vessel in marine applications.

9. Conclusion

The three delivered vessels babyCat and the solarCat as muscled sister vessel are the first steps of iCat shipyard, aiming to set line of electric powered coastal ferries. The vessel trials on typical coastal and inter-island service routes approved the seakeeping and manoeuvrability abilities. A year-long experience of vessels in commercial service has been confirming the presupposed advantages of electric vessels defined by the higher efficiency of a propulsion system, high efficiency of the propulsion in all speed range, low maintenance costs, low or no fuel cost, zero emissions, low vibrations and noise. The three firstly delivered vessels have proven, in service, the expected self-sustainability of electric propulsion while the next step is to build longer range and faster electric-powered vessels. The ambition is to build and maintain in operations a fleet of self-sustainable passenger vessels for coastal areas and islands, enabling solar power for commercial transportation services.

Acknowledgement

The project “solarCat” KK.01.2.1.0021 is supported by the EU Operational Programme Competitiveness and Cohesion 2014 – 2020. The goal was to design, build and test solar-powered vessel prototype for coastal service and to bring new company product to the market.

Along with “solarCat” project, iCat Ltd has been awarded several other EU projects, set up ship-design and ship-building company:

- EU project “SolarCat” KK.03.2.1.05.0228- a setting-up facility for GRP production
- EU project “iCat shipyard” KK.03.2.1.06 – outfitting facility with tools for GRP production
- EU project “iCat international” KK.03.2.1.07.0026 – international promotion of the company

Few smaller-scale EU projects have been awarded for academia collaboration.

Mljet National Park was a supportive and great partner, where the first 3 vessels were tested.

Croatian Register of Shipping, support in new technologies for application on vessels as solar-power and lithium batteries were mutually challenging.

The Ministry of Sea Transport and Infrastructure, recognising the importance of the electric vessel in future coastal and inter-island transport development.

The University of Zagreb, the Faculty of Mechanical Engineering and Naval Architecture, through many years of support and collaboration.

Končar Institute, as the first institution helping us to implement electric energy as propulsion.

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