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Energy Harvesting and Storage System for Marine Applications

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Abstract**—**Rigorous international maritime regulations are in place to limit boat and ship hydrocarbon emissions. The global sustainability goals are reducing the fuel consumption and minimizing the emissions from the ships and boats. These maritime sustainability goals have attracted a lot of research interest. Energy harvesting and storage system is designed in this study based on hybrid renewable and conventional energy systems. This energy harvesting and storage system is designed for marine applications, such as, boats and small ships. These systems can be utilized for mobile use or off-grid remote electrification. This study analyzed the use of micro power generation for boats and small ships. The energy harvesting and storage system has two distinct systems i.e. dockside shore-based system and on-board system. The shore-based system consists of a small wind turbine, photovoltaic (PV) panels, small gas turbine, hydrogen generator and high-pressure hydrogen storage tank. This dockside system is to provide easy access to the boats and small ships for supply of hydrogen. The on-board system consists of hydrogen storage tanks and fuel cells. The wind turbine and PV panels generate electricity to operate electrolyzer. A small gas turbine is used as a supplementary power system to contribute in case the hybrid renewable energy system does not provide the required energy. The electrolyzer performs the electrolysis on distilled water to produce hydrogen. The hydrogen is stored in high-pressure tanks. The hydrogen from the high-pressure tank is filled in the low-pressure tanks on-board seagoing vessels to operate the fuel cell. The boats and small ships use the hydrogen fuel cell to provide power to electric propulsion motors and for on-board auxiliary use. For shore-based system, a small wind turbine with the total length of 4.5 m and the disk diameter of 1.8 m is used. The small wind turbine dimensions make it big enough to be used to charge batteries yet small enough to be installed on the rooftops of dockside facility. The small dimensions also make the wind turbine easily transportable. In this paper, PV, sizing and solar flux are studied parametrically. System performance is evaluated under different operating and environmental conditions. The parametric study is conducted to evaluate the energy output and storage capacity of energy storage system. Results are generated for a wide range of conditions to analyze the usability of hybrid energy harvesting and storage system. This energy harvesting method significantly improves the usability and output of the renewable energy sources. It also shows that small hybrid energy systems have promising practical applications.

Keywords**—**Energy harvesting, fuel cell, hybrid energy system, hydrogen, wind turbine.

I. Introduction

THERE are many different ways to generate energy. Since renewable energy is gaining popularity, research on renewable energy sources are being conducted for applications in every field. Wind energy is renewable and can be effectively utilized all year long. There are different methods to capture wind but none is more efficient, economical, low on maintenance and easy to handle than capturing wind energy using horizontal-axis wind turbine [1].

Solar PV converts sunlight directly into electrical energy. Direct current electricity is produced, which can be used, stored or converted to alternating current. Solar PV systems operate in an environmentally benign manner, have no moving components, and have no parts that wear out if the device is correctly protected from the environment. By operating on sunlight, PV devices are usable and acceptable to almost all inhabitants of our planet. PV systems can be sized over a wide range, so their electrical power output can be engineered for virtually any application [2]. This report discusses the exergy and energy analysis to study the performance of an integrated renewable energy system for domestic electricity and hot water consumption requirements.

Wind and solar are considered preferred renewable energy sources because of their abundance and ease of availability [3]. Hybrid renewable energy systems (HRES) are considered more reliable and economical compared to single source renewable energy system with 26%-40% saving as compared to only PV systems [4]-[8]. However, wind turbines and PV panel poses an integration challenge due to the unstable output patterns dependent on weather conditions [9], [10]. To counter the fluctuation problems, it is desired to store energy in any suitable form, before being used to power an electrical appliance. Batteries, for small scale applications, have low efficiency when compared to other forms of storage [11].

A combined fuel cell, wind turbine and PV panel energy system would be an effective way to generate renewable energy as they have minimal environmental impact with no hazardous emission and have no or very low noise. The proton exchange membrane fuel cell (PEMFC), in its elemental form, uses hydrogen and produces DC power [12]. For the required conditions, proton seems to be the best solution. Since the PEM fuel cell emission is water, the energy produced through fuel cell is environmentally clean, have extremely low emission of oxides of nitrogen and sulfur, and have very low noise.

The added advantage of using hydrogen is that it can be used to store energy from wind and solar radiation, without having to electrically deal with the fluctuation [13]-[16]. A combined hybrid system shows to be a promising way to generate renewable energy with relatively decent exergy efficiencies [17]. Such combined hybrid systems have been used for off-grid applications in which the surplus energy, from wind and solar, was used for hydrogen generation which

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was stored for later use [18]. The results showed that such systems can be managed and their output is promising overall [19]. Incorporating compressor to compress hydrogen changes the system performance. Increase in PEMFC pressure and temperature increases the fuel cell power and heat output [20]. A fuel cell not only produces electric power but it also emits heat. A PEMFC evaluation and analysis yields the maximum power and heat generation from Nexa 1200 fuel cell reaches 1200 W and 1500 W respectively [21].

For HRES, hydrogen production can be achieved by operating electrolyser/hydrogen generator either through wind turbines or PV panels. Hydrogen storage device is required to store hydrogen before being used in fuel cell since the overall wind-electrolyser system efficiency varies significantly [22]. The stored hydrogen can either directly be fed to the fuel cell or can be compressed before being fed to the fuel cell. Compressed hydrogen tends to produce higher power and heat [21]. At different locations for variable solar flux, a system comprising of PV panels, PEMFC, electrolyser and a compressor to power a building has shown that the requirement can be met using these systems [23]. Such a combined hybrid system can work effectively to produce the desired heat and power requirements for a regular household [24]. Even if a simple wind turbine-PV panel system is used, the energy demand can be met, without the use of fuel cell, for small residential applications [24]. This hybrid system is especially effective when operating an electric motor. Electric motors are lighter than internal combustion engine. However, when batteries are added to it, the entire system becomes relatively heavy [25]. Even hybrid boats show promising results with fuel reduction of 40% over long endurances [26]. The fuel cell based boats have proven to be reliable to operate [27].

II. System Description

An integrated renewable energy system is designed and analyzed that stores energy for later use. The integrated HRES is designed to provide power to boats. It is primarily aimed at marina and harbor of cities since hybrid renewable energy based electric power system eliminates pollutions and toxic emissions.

Wind turbines and PV panels take energy from wind and sun, respectively. The combined energy produced by wind turbines and PV panels go directly to power the electrolyzer. The electrolyzer produces hydrogen and oxygen gas using the distilled water. The hydrogen and oxygen are stored in large tanks. Hydrogen is provided to the electric boat users to power the PEMFC.

The PEMFC produces the electric power to run the electric motor for boat's propulsion. The stored oxygen can either be sold for medical applications or be discharged in the air. The backup power can either be a combustion engine or the grid line connections. The proposed system is designed to be made small and compact. The small size allows it to be installed easily and can be utilized by boat operators. It is modular hence multiple systems can be installed to increase the capacity of the power system. The schematic of the system is shown in Fig. 1.

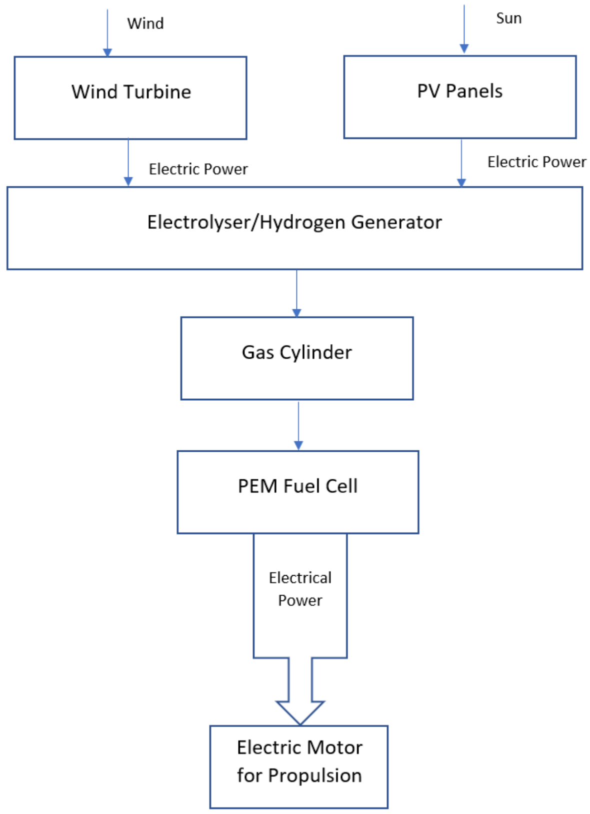

Fig. 1 Schematic of the HRES for electric boats

For the baseline, PV efficiency of 17% is considered for the study. A basic parametric study is conducted to determine the size, area and wind speed to generate the required power, for each source. The HRES is modelled to be powered by a renewable energy network of wind turbine and solar panels. The wind turbine modelled in this study is a small 2 kW wind turbine, it is described in Table I.

TABLE I
Wind Turbine Rotor Parameters and Their Values [28], [29]

Parameter	Value
Airfoil	NACA 63-418
Aspect Ratio – *AR*	6
Span – b	1.52 m
Planform Area – *S*	0.25 m^2
Chord - c	0.27 m
Rotor Area – A	7.54 m^2
Material	*Glass-reinforced plastic*
Surface Area	1.71 m^2
Blade Skin Thickness	1 mm
Number of blades	3
Cut-in speed	2.5 m/s

For the HRES, Nexa 1200 fuel cell with Heliocentris HG60 hydrogen generator is modelled. Nexa 1200 is a PEMFC designed to produce around 1200 W of electrical power at hydrogen consumption rate of 15 L/min [21]. Heliocentris HG60 hydrogen generator is a compatible hydrogen generator that produces hydrogen at 1 litre/min while consuming 480 W of electrical power [30]. The parametric study is conducted for the total output range of 100 W to 3 kW. With hydrogen flow rate requirement of each fuel cell known [31], the necessary power is modelled to run the required number of hydrogen generators.

III. Analyses

The power available in the flow captured by the wind turbine can be described as follows,

$$P_{flow} = \frac{\rho}{2} v_0^3 A \quad (1)$$

where A is the rotor area and V_0 is the free-stream velocity. Like any real system, is has an efficiency associated with it. Betz limit calculates that only 59% of the power extraction is possible [16]. Equation (1) can be rewritten to incorporate the efficiency as follows,

$$P_m = P_{flow}\,\eta = \frac{\rho}{2} v_0^3 A\,\eta \quad (2)$$

The mass and energy balance equations of the integrated hybrid energy system is also presented in this section. The equations for energy efficiencies are also described in this section.

For Fuel Cell:

The mass balance is given as follows:

$$\dot{m}_H + \dot{m}_O = \dot{m}_{water} \quad (3)$$

The energy balance with enthalpy can be written as follows:

$$\dot{m}_H h_H + \dot{m}_O h_O = \dot{m}_{water} h_{water} + \dot{W}_{ele} + \dot{Q} \quad (4)$$

The efficiency with and without fuel cell heat is as follows;

$$\text{Without heat: } \eta = \frac{\dot{W}_{ele}}{\dot{m}_H h_H} \quad (5)$$

$$\text{With heat: } \eta = \frac{\dot{Q}_{FC} + \dot{W}_{ele}}{\dot{m}_H h_H} \quad (6)$$

IV. Results and Discussion

The system studied in this paper is designed to be used to provide energy to electric boats. The power requirements of electric boats are studied first to determine their requirements. Power requirement of a boat changes with the change in speed and size. As expected, bigger the boat, grater the power requirement to counter the drag in the water is. Similarly, the faster the boat moves, greater the power requirement is. Four different small electric boats are studied and their power requirements with respect to the speed are listed in Fig. 2. Apart from showing the increase in power requirement with the increase in size and speed, the graphs also show that the small boats usually do not exceed 3 kW power requirement. In fact, during the low speed cruise, the power requirements for small electric boats do not even exceed 1 kW.

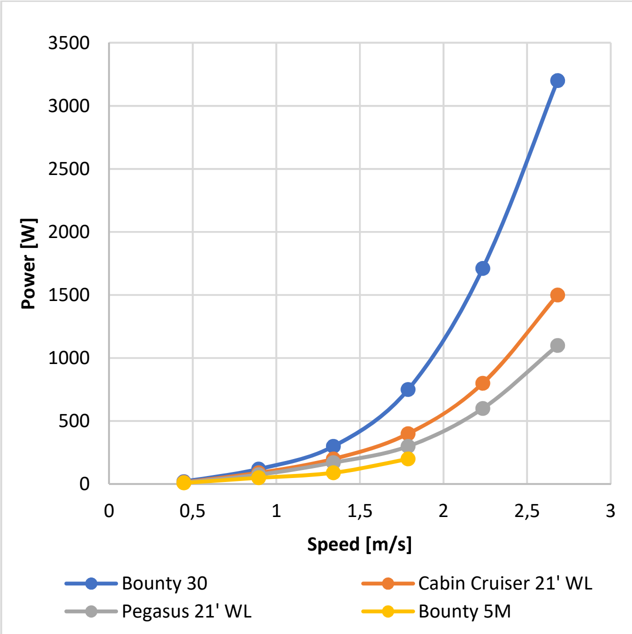

Fig. 2 Different electric boats' power requirement with respect to their speeds [32]

The study in this paper is conducted to model the HRES to provide energy to electric boats using PEMFC. Using Nexa 1200 fuel cell, power output against mass flow rate is also plotted as shown in Fig. 3.

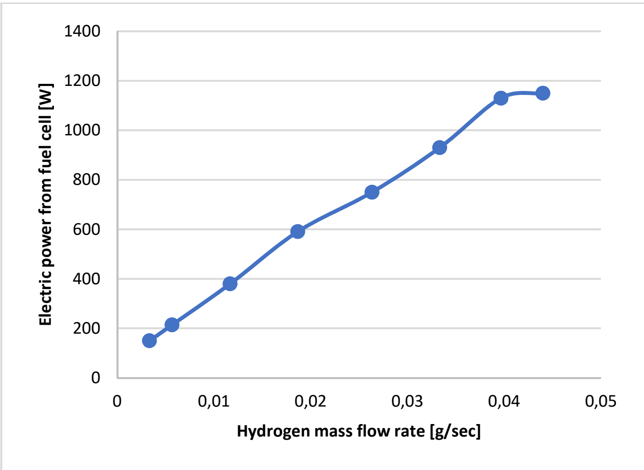

Fig. 3 Nexa 1200 fuel cell power output and hydrogen requirement

Each fuel cell can produce maximum electrical power of 1200 W consuming hydrogen gas at 0.44 g/sec. When compared with the electric boats studied in this paper, number of required Nexa fuel cells can be determined as shown in Fig. 4. This helps understand and estimate the hydrogen producing electrolyzers for the HRES.

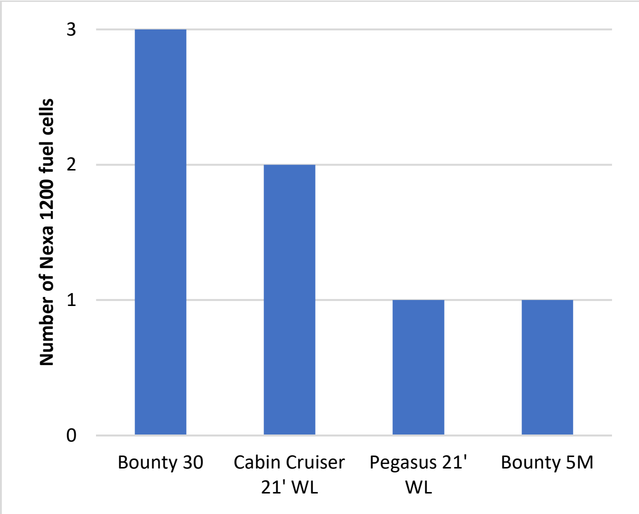

Fig. 4 Number of Nexa 1200 fuel cells required to each studied electric boat

In order to operate the PEMFC on-board the electric boats to run the electric motors, hydrogen is produced using the Heliocentris HG60 hydrogen generator. Fig. 5 shows the required number of Heliocentris HG60 hydrogen generator.

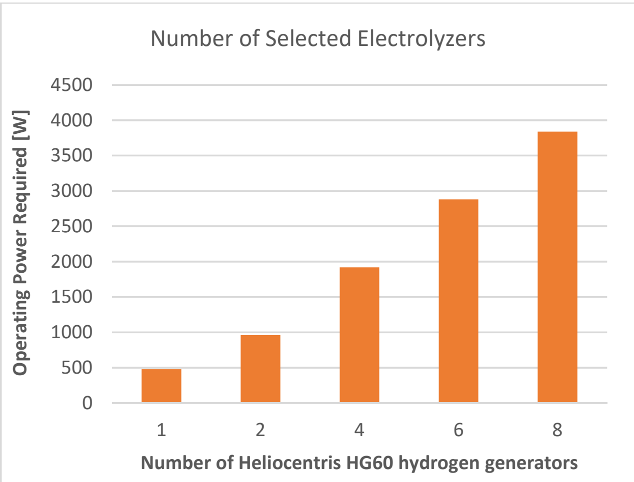

Fig. 5 Required number of Heliocentris HG60 hydrogen generator

Each hydrogen generator produces hydrogen at 1 liter/min while consuming 480 W of electric power. In order to have complete and continuous availability of hydrogen for the electric boat users, multiple hydrogen generators are proposed. Multiple hydrogen generators also help reduce the charging refill time. This reduced refill time helps commercial boats to maintain low turn-around time increasing the efficiency and usage of the electric boats. Fig. 6 shows the refill time of a 50 liter cylinder with respect to number of hydrogen generators.

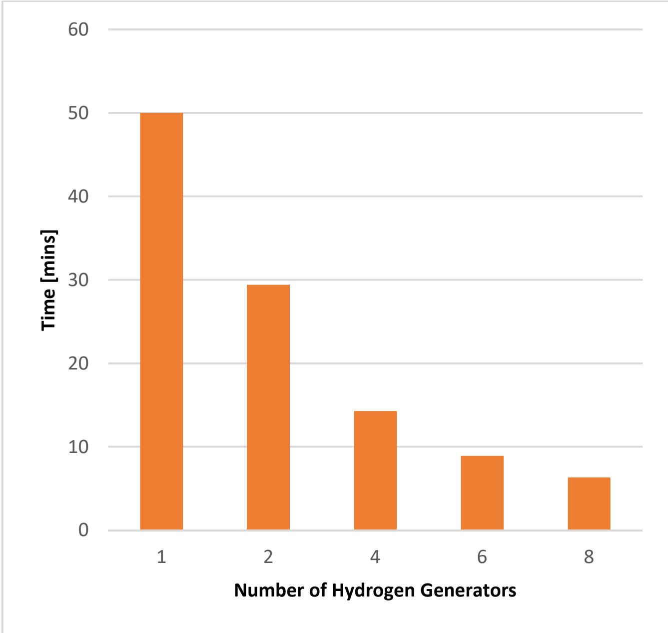

Fig. 6 Time required to refill a 50 liter gas cylinder

V. Conclusions

This paper studies a small HRES to be installed in marinas and harbors to provide energy to electric boats. The HRES produces hydrogen using a hydrogen generator. The hydrogen generator is powered by PV panels and small wind turbine. The produced hydrogen is stored in the tank to be filled by the tank on board the electric boats. The hydrogen is used as an energy carrier to run the PEMFC. The PEMFC produced electric energy to operate the boat's electric motor. This study concluded that;

- Two small wind turbines can sufficiently provide the required power.
- PV panels covering 10 m^2 are required for the system to complement the power requirement and be available as a backup.
- For safe and continuous operations, eight hydrogen generators are required to be installed and operated.
- Using eight hydrogen generators, a 50 liter cylinder takes about 6 minutes to refill.

References

[1] S. Zafar, M. Gadalla, S.M. Hashemi, An Investigation into a Small Wind Turbine Blade Design, 11th International SET Conference (2012), Vancouver, Canada, 415

[2] I. Dincer, M.Rosen. EXERGY Energy, Environment and Sustainable Development. London: Elsevier, 2007.

[3] M. K. Deshmukh, S. S. Deshmukh, Modeling of hybrid renewable energy systems, Renewable and Sustainable Energy Reviews 12 (2008) 235-249

[4] S. Ahmada, M.Z. Abidin Ab Kadirb, S. Shafiea Current perspective of the renewable energy development in Malaysia Renewable and Sustainable Energy Reviews 15 (2011), 897–904

[5] T.R. Mtshali, G. Coppez, S. Chowdhury, S.P. Chowdhury, Simulation and modeling of PV-wind-battery hybrid power system (2011) IEEE Conferences

[6] M.A.M. Radzi, N.A. Rahim, Rural Electrification in Malaysia: Progress and Challenges, Conference Paper for human security (2011) Tokyo, Japan

[7] E. Dursun, O. Kilic. Comparative evaluation of different power management strategies of a stand-alone PV/Wind/PEMFC hybrid power system, Electrical Power and Energy Systems 34 (2012), 81–89
[8] Lanzafame R, Messina M, Horizontal axis wind turbine working at maximum power coefficient continuously, Renewable and Sustainable Energy Reviews 16 (2012) 3364–3369
[9] H. Kim, N. Okada, K. Takigawa. Advanced grid connected PV system with functions to suppress disturbance by PV output variation and customer load change, Solar Energy Materials and Solar Cells 67 (2001) 559–569
[10] N. C. Nair, N. Garimella, Battery energy storage systems: Assessment for small-scale renewable energy integration, Energy and Buildings 42 (2010) 2124–2130
[11] M.Y. El-Sharkh, A. Rahman, M.S. Alam, P.C. Byrne, A.A. Sakla, T. Thomas, A dynamic model for a stand-alone PEM fuel cell power plant for residential applications, Journal of Power Sources 138 (2004) 199-204.
[12] P.C. Ghosh, B. Emonts, H. Janßen, J. Mergel, D. Stolten Ten years of operational experience with a hydrogen-based renewable energy supply system, Solar Energy 75 (2003) 469–478
[13] D. Ipsakis, S. Voutetakis, P. Seferlis, F. Stergiopoulos, C. Elmasides Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage, International Journal of Hydrogen Energy 34 (2009) 7081–7095
[14] H. Mahmoudi, S.A. Abdul-Wahab, M.F.A. Goosen, S.S. Sablani, J. Perret, A. Ouagued *et al.* Weather data and analysis of hybrid photovoltaic-wind power generation systems adapted to a seawater greenhouse desalination unit designed for arid coastal countries, Desalination 222 (2008) 119–127
[15] B.D. Shakya, L. Aye, P. Musgrave Technical feasibility and financial analysis of hybrid wind-photovoltaic system with hydrogen storage for Cooma, International Journal of Hydrogen Energy, 30 (2005), 9–20
[16] M. Calderón, A.J. Calderón, A. Ramiro, J.F. González, I. González, Evaluation of a hybrid photovoltaic-wind system with hydrogen storage performance using exergy analysis, International Journal of Hydrogen Energy 36 (2011) 5751–5762
[17] M. Eroglu, E. Dursun, S. Sevencan, J. Song, S. Yazici, O. Kilic, A mobile renewable house using PV/wind/fuel cell hybrid power system, International Journal of Hydrogen Energy 36 (2011) 7985–7992
[18] M.S. Alam, D.W. Gao, Modeling and analysis of Wind-PV-Fuel cell hybrid power system in HOMER, Second IEEE Conference on Industrial Electronics and Applications (2007) 1594-1599
[19] T.A.H. Ratlamwala, M.A. Gadalla, I. Dincer, Thermodynamic analyses of an integrated PEMFC–TEARS-geothermal system for sustainable buildings, Energy and Buildings 44 (2012) 73–80
[20] A. Yilanci, I. Dincer, H.K. Ozturk, Performance analysis of a PEM fuel cell unit in a solar–hydrogen system, International Journal of Hydrogen Energy 33 (2008) 7538–7552
[21] E. Akyuz, Z. Oktay, I. Dincer, Performance investigation of hydrogen production from a hybrid wind-PV system, International Journal of Hydrogen Energy 37 (2012) 16623–16630
[22] A. Ganguly, D. Misra, S. Ghosh, Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse, Energy and Buildings, 42 (2010) 2036–2043
[23] S. Ozlu, I. Dincer, G.F. Naterer, Comparative assessment of residential energy options in Ontario, Canada, Energy and Buildings 55 (2012) 674–684
[24] S. Cao, A. Hasan, K. Sirén, Analysis and solution for renewable energy load matching for a single-family house, Energy and Buildings 65 (2013) 398–411
[25] A. Tapko, "The Use of Auxiliary Electric Motors in Boats and Sustainable Development of Nautical Tourism – Cost Analysis, the Advantages and Disadvantages of Applied Solutions", Transportation Research Procedia, Vol. 16, pp. 323-328, 2016.
[26] M. Soleymani,A. Yoosofi, M. Kandi-d,"Sizing and energy management of a medium hybrid electric boat", Journal of Marine Science and Technology, vol. 20, pp. 739-751, 2015.
[27] C.H. Choi et. al., "Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat", International Journal of Hydrogen Energy, vol. 41, pp. 3591-3599, 2016.
[28] Zafar, S., Gadalla, M., Hashemi. S. M., 2012, “An Investigation into a Small Wind Turbine Blade Design”. SET-2012-415. 11th International SET Conference. Vancouver, Canada.
[29] Zafar, S., Gadalla, M., 2013. “Design and Evaluation of a Rooftop Wind Turbine Rotor with untwisted Blades”. ASME Power 2013-98217. ASME Power 2013. Boston, Massachusetts, USA.
[30] Heliocentris Energiesysteme GmbH, Hydrogen generator Technical data, http://www.heliocentris.com/academia-angebot/produkte/trainingssysteme/h2-versorgung/wasserstoffgenerator-hg/technical-data.html (2013).
[31] Heliocentris Energiesysteme GmbH, Technical Data, Nexa Fuel Cell Power Module, http://www.heliocentris.com/fileadmin/user_upload/12_Clean_Energy_Products/Datenbl%C3%A4tter/Datenblatt_Nexa1200_EN_1109.pdf (2013).
[32] Lynch Motors, "Design of Electric Derives for Boats", 2019, https://lynchmotors.co.uk/technical-reports/boats/electric-drives_boats.html