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Enhancing Energy Autonomy in an e-Houseboat: Integration of Renewable Energy Sources with Hybrid Energy Storage Systems

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Abstract: This paper explores the development and optimization of a hybrid renewable energy system (HRES) integrated with a hybrid battery energy storage system (HBESS) to achieve energy autonomy for an e-Houseboat. The e-Houseboat is a floating residential unit equipped with advanced sustainable technologies, including photovoltaic panels, wind turbines, and a hybrid battery storage system consisting of lithium iron phosphate (LFP) and lead-acid batteries. The primary goal of this study was to design an energy-autonomous e-Houseboat capable of sustaining energy demands for at least one month without external power sources, regardless of the season. This study included a comprehensive analysis of energy generation potential from renewable sources across different European locations, detailed simulations of the energy storage system, and the development of energy management function for a houseboat automation system. The results demonstrate the feasibility of achieving the desired energy autonomy by leveraging the synergistic benefits of multiple energy storage technologies and optimizing energy management strategies. The experiment demonstrated that the implemented solutions enabled the facility to achieve energy autonomy for a period of 7 months.

Keywords: hybrid battery energy storage system; renewable energy sources; houseboat; energy-autonomous houseboat

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1. Introduction

With the growing challenges of global warming and environmental degradation, the development of innovative and sustainable energy solutions is becoming increasingly important. This also applies to areas such as location-independent or off-grid living. Houseboats, as waterborne dwellings, offer excellent opportunities to achieve energy autonomy, but also present significant challenges. Traditionally, the energy needs and mobility of houseboats have been met by fossil fuels, which contrasts with the growing trend towards environmentally conscious living. An innovative solution to this challenge is the autonomous energy e-Houseboat—a modern residential unit that not only provides comfortable living on water but also minimizes environmental impact by utilizing a hybrid renewable energy system (HRES) and a hybrid battery energy storage system (HBESS), to cover its energy needs independently.

Prior research has focused on the integration of photovoltaic systems, wind turbines, and energy storage systems in various configurations, as well as on optimizing the operation of these systems through the deployment of artificial intelligence algorithms and iterative methodologies. Despite significant progress in this field, there is still a crucial need to further improve these technologies, particularly to meet the demands faced by floating

residential units, which must continuously adapt to rapidly changing environmental conditions. To address these challenges, the present study details the design and implementation of the e-Houseboat prototype, which combines three pivotal components: photovoltaic (PV) panels, wind turbines, and a HBESS composed of lithium iron phosphate (LFP) and lead-acid batteries. This comprehensive approach not only maximizes the utilization of available renewable energy sources (RESs), but also ensures a consistent power supply under demanding conditions, thereby allowing extended periods of energy self-sufficiency.

The primary research problem tackled in this study is the development and optimization of an energy system designed to ensure the e-Houseboat's energy autonomy for at least one month, regardless of the season and weather conditions. This study is particularly focused on the effective management of various energy sources and their storage, with the aim of meeting the high ecological and functional standards required by floating residential units. The findings make a significant contribution to the expanding knowledge base on sustainable energy systems by elucidating the practical applications of hybrid energy storage solutions in mobile and off-grid settings. The results of the study have important implications for the design of future autonomous housing units, especially in particularly challenging environments, such as those without adequate infrastructure, burdened by the so-called "last mile" or water effect.

The structure of this article is as follows: the first part presents a literature review and the latest advances in the field of hybrid energy systems. Then, the motivation and research goals of the e-Houseboat project are discussed. The subsequent sections present the technical details of the project, the functional and design assumptions made, including the methodology for the selection of hybrid energy storage components, the structure of the energy system, and the results of the simulations carried out. The final section of the article discusses the results obtained from the experiment verifying the results obtained in terms of energy autonomy, formulates conclusions, and proposes directions for further research.

2. State of the Art

Articles on HRES highlight their importance in enhancing the flexibility and reliability of power grids through the integration of PV systems, wind energy, and energy storage. The research conducted so far analyzes various configurations and methods to optimize the operation of such installations. Key issues include the impact of different configurations of alternating current (AC) and direct current (DC) on system efficiency, as well as the application of optimization algorithms, artificial intelligence, and iterative methods in energy management. A study describing a hybrid installation shows that it increases power and capacity coefficients, making these systems valuable for energy generation [1]. Similarly, other studies discuss recent advances in HBESS, that can address issues related to the instability of RES, such as cost, lifespan, power density, and dynamic response [2]. Subsequent studies focus on the energy self-sufficiency of residential buildings using HRES [3], while reviews and optimization tools in the literature highlight the need for further research to improve these technologies [4,5]. The conducted research discusses a modern approach to hybrid energy systems that combine wind turbines and PV systems, focusing on the analysis of advanced system architectures, energy converters, methods of integrating energy storage systems, and control strategies. The advantages of wind and solar power synergy are also presented, such as the increased efficiency and stability of the system, as well as the potential to meet a higher energy demand with a lower environmental impact [6]. AI-driven energy forecasting plays a critical role in optimizing energy consumption, facilitating the efficient utilization of renewable resources, and improving the overall performance of HRES [7]. Research on the integration of renewable energy technologies in industrial and regional contexts is also widely distributed. These studies analyze the economic viability

of different renewable energy technologies and the technological and economic barriers to their implementation [8]. In many works, the key focus is on optimizing the size, cost, and reliability of energy production in the context of smart grids and isolated HRES [9,10]. Lithium-ion batteries are a fundamental component of hybrid systems. Research on its use focuses on methods to estimate the state of charge (SoC) and the state of health (SoH), as well as predicting battery degradation using advanced machine learning algorithms and neural networks [11,12]. An analysis of lithium-ion battery degradation under different aging conditions indicates that degradation depends on the order and periodicity of these conditions. The research focuses on two aging modes: calendar (in the absence of load) and cyclic (during current flow), suggesting that degradation may be sensitive to both its order and periodicity [13]. Scientific papers also present open-source models for optimizing the operation of PV systems with batteries, using energy price forecasts to optimize battery charging, and discharging in real-time, demonstrating the significant impact of system configuration on performance [14]. The integration of energy storage systems and RES using artificial intelligence highlights the importance of the proper configuration of BESS, energy management strategies, and the assessment of the state of BESS [15]. Similarly, the integration of energy storage technologies with PV systems to power buildings is an important research topic that draws attention to the global development of these solutions [16]. In addition, to ensure proper operation, it is necessary to optimize the dimensioning and scheduling of BESS and intelligent inverters for the integration of PV systems with distribution networks [17]. Research on the optimal design of hybrid PV systems combined with BESS in residential buildings employs multi-objective optimization algorithms [18]. Other studies describe a hybrid system operating in both on-grid and off-grid modes that provides uninterrupted power supply to critical local loads during network failures, thereby improving system dynamics and power stability [19]. The research also examines the development of the prosumer concept in the energy sector, highlighting the importance of decentralizing RES [20]. In the context of decarbonization and sustainable development, the research analyzes the interaction between RES, water management, and environmental protection [21]. The authors of these articles discuss the latest advances in renewable energy technology, emphasizing its growing importance in the context of climate change [22]. In the marine sector, research explores the integration of RES and battery BESS as a strategy to enhance energy autonomy and mitigate greenhouse gas (GHG) emissions. Studies focus on hybrid energy solutions, such as PEM fuel cells and battery systems for tourist vessels [23], as well as on the optimization of thermal management in BESS for electric ships [24]. Simulation-based approaches, including those using the HOMER tool, have been used to refine HRES configurations in maritime applications. Research examines the optimization of HRES in tugboats, evaluating their energy efficiency and emissions reduction potential [25]. The potential of perovskite solar cells as a new energy source for offshore oil ships is also investigated, highlighting their efficiency and environmental advantages [26]. Comparative studies assess the implementation of HRES in both land and maritime contexts, analyzing their economic and environmental implications [27]. Each study highlights the importance of RES and hybrid installations in the pursuit of more sustainable energy practices and achieving the energy autonomy of the facilities.

3. Motivation

The motivation for the research carried out was to design and develop a prototype e-Houseboat, which is a completely new type of unit in relation to existing solutions on the market and has functional features referring to the best utility and environmental standards.

A houseboat is a residential structure not founded on the ground, but in a water environment (mainly rivers), with the additional possibility of adapting it using its own

propulsion to move on inland waters. This propulsion is usually provided by an internal combustion engine with a propeller. As a market product, it is characterized by its highly customizable nature for a generally demanding and conscious clientele.

The aim of this research was to build a prototype of an e-Houseboat equipped with an electric drive system designed to achieve extended energy autonomy using HRES and advanced ecological solutions. These technologies include a variety of sophisticated installations such as heat pumps, recuperation systems, multi-zone air conditioning, and heating mats. The design envisioned that both the propulsion and the on-board power supply would be powered by electricity generated on-board and stored in a dedicated HBESS. Given the unique nature of this product, maintaining long-term comfort for users is crucial, along with the ability to recharge the hybrid energy storage from AC networks available in marinas.

The following assumptions were adopted:

- Maximizing the energy autonomy of the e-Houseboat—the time between recharging the HBESS should not be less than one month;
- Ensuring user comfort, with particular attention to thermal comfort (maintaining an internal temperature of 20 °C in winter and below 29 °C in summer);
- Using electric motors for propulsion (this allows for quiet operation, and helps ensure emission-free operation, reduced noise levels, and the enhanced handling of the e-Houseboat, related to the operational characteristics of such motors);
- Development of a HBESS utilizing various types of batteries to leverage the synergistic benefits of LFP and lead-acid technologies: high power density and current carrying capacity and low price;
- Enabling the HBESS to be charged primarily via PV installations, in various locations across Europe.

To properly prepare and later conduct a research experiment aimed at verifying the energy autonomy duration of the facility, a specific facility-dedicated concept of energy independence was defined. This definition assumes the ability to meet the current energy demands of the facility using various energy sources installed within the facility. This concept can also be associated with the term "energy autonomy", which, in the case of houseboat-type facilities, has been defined as the absence of a need to connect the facility to an external energy source.

4. Optimizing Renewable Energy and Storage Systems for the e-Houseboat

4.1. Evaluation of the Potential of the Amount of Energy Generated by Designed RES Installations in Selected European Cities

One of the initial stages of the research carried out as part of the implementation of the "electric" and energy autonomous houseboat project involved performing a comparative analysis of the energy production from PV panels and wind turbines at selected locations across Europe. An overview of the designed e-Houseboat is presented in Figure 1.

The test site is equipped with three independent RESs: photovoltaic panels, solar blinds, and vertical axis wind turbines. The total nominal power of the PV panels installed at the reference facility is approximately 7400 Wp, making it the largest RES on-site in terms of capacity. The solar blinds have a nominal power output of approximately 100 W/m^2, resulting in a total power of 700 Wp for an area of 7 m^2. The installed wind turbines have a nominal power of 2000 Wp. To conduct the study, data on annual irradiation and wind speed with a resolution of one hour were collected for the following cities: Bydgoszcz, Oslo, London, Amsterdam, Helsinki, and Bremen. The results of the simulations are presented in two tables. Table 1 shows the energy generated by PV panels and solar blinds in each

month, while Table 2 shows the energy generated by wind turbines in each month. It should be noted that the values in the tables are expressed in kilowatt-h (kWh).

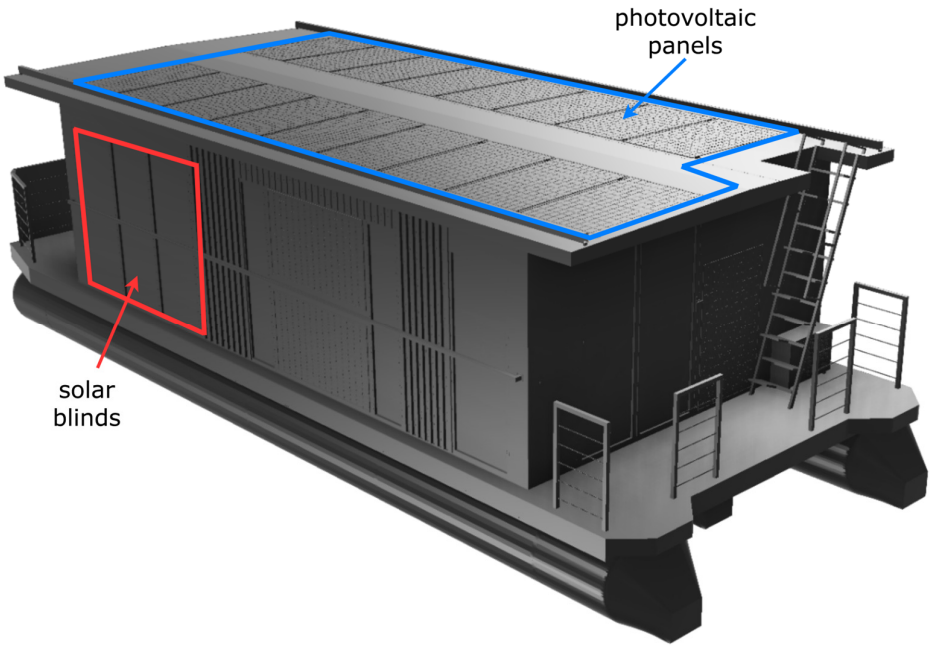


Figure 1. Diagram showing the arrangement of PV panels on the roof and solar blinds on the side of the e-Houseboat.

Table 1. Energy generated by PV panels each month.

City	January	February	March	April	May	June	July	August	September	October	November	December	Sum
Bydgoszcz	114.59	164.27	372.81	493.70	689.01	643.09	603.39	569.46	398.52	209.45	119.87	81.21	4459.36
Oslo	47.32	121.35	322.59	461.86	801.18	837.29	772.78	599.69	346.02	178.42	56.57	24.84	4569.91
London	114.41	201.01	350.34	588.10	759.08	762.70	788.13	701.61	463.89	281.76	151.20	88.51	5250.74
Amsterdam	103.11	223.97	394.45	567.33	757.52	758.89	771.23	655.49	424.47	250.13	128.70	74.71	5110.01
Helsinki	40.39	149.59	303.56	595.29	835.33	890.93	846.82	647.67	366.19	181.01	49.05	19.22	4925.05
Bremen	92.62	197.80	338.83	599.47	781.15	770.64	720.00	652.05	403.79	233.68	121.26	66.94	4978.22

Table 2. Energy generated by wind turbines each month.

City	January	February	March	April	May	June	July	August	September	October	November	December	Sum
Bydgoszcz	160.72	137.97	160.46	143.42	111.36	118.85	102.95	115.93	110.21	175.51	213.16	183.55	1734.10
Oslo	24.59	65.36	76.29	74.84	59.10	85.73	65.44	61.49	71.75	96.97	32.72	109.77	824.04
London	151.80	102.83	183.77	143.33	126.96	114.65	74.76	90.65	124.71	97.67	57.57	124.81	1393.51
Amsterdam	447.63	353.79	306.69	297.95	177.02	153.40	187.11	206.96	193.68	333.82	188.03	343.85	3189.95
Helsinki	170.79	125.40	209.97	102.74	128.91	121.50	158.30	120.55	104.26	178.24	160.76	211.08	1792.50
Bremen	390.59	161.10	214.20	158.08	118.50	147.35	137.82	156.50	241.38	174.44	181.49	206.32	2287.79

The data presented in Table 1 show that the energy produced by PV panels is comparable regardless of geographical location and shows a consistent level of output. There is also an increase in production during the summer months, regardless of location. On the other hand, wind energy production is more variable depending on the geographical location. In Oslo, for example, annual wind energy production is around 800 kWh, while in Amsterdam it is almost four times higher, at around 3200 kWh. Wind energy production is generally higher in the autumn and winter months, regardless of location.

The overall conclusion from this part of the study is that the energy yield of a particular source depends on the extent to which the generation system is exposed to a particular type of energy flow. Due to the nature of the object, the largest active exposure area is possible with photovoltaic technology. Despite the relatively low efficiency of this technology, which

is averaging around 20%, the energy yields from PV panels are significantly higher than those from other generation technologies that can be applied to the unit. The active area of the rotating elements in wind generators is insufficient to match that of PV panels. Consequently, even with higher efficiencies, wind systems cannot compensate for the limited number of installations possible on the e-Houseboat.

To analyze the simulation results for the energy yields of all the RESs, the values of the energy produced were summed. Table 3 shows the total energy yields from all generation systems (wind and solar) for each month. As can be seen in Table 3, the energy yield from RES generators remains relatively constant between different locations, ranging from 5400 to 8300 kWh per year. The highest energy yield is observed in Amsterdam, where it almost reaches 8300 kWh. This significant contribution of wind energy in the region highlights the high potential of wind energy in this part of Europe.

Table 3. Energy generated by RES each month.

City	January	February	March	April	May	June	July	August	September	October	November	December	Sum
Bydgoszcz	275.31	302.24	533.27	637.12	800.38	761.94	706.34	685.4	508.73	384.97	333.03	264.77	6193.5
Oslo	71.92	186.71	398.89	536.7	860.28	923.02	838.22	661.18	417.78	275.39	89.29	134.61	5393.99
London	266.22	303.84	534.11	731.43	886.04	877.35	862.89	792.27	588.6	379.43	208.77	213.33	6644.28
Amsterdam	550.74	577.76	701.15	865.29	934.55	912.3	958.34	862.45	618.16	583.95	316.74	418.56	8299.99
Helsinki	211.18	275	513.54	698.03	964.25	1012.43	1005.13	768.22	470.45	359.25	209.81	230.3	6717.59
Bremen	483.22	358.9	553.03	757.55	899.66	917.99	857.82	808.55	645.18	408.12	302.76	273.27	7266.05

The data suggest that the conditions and assumptions made—recharging the HBESS-based solely on photovoltaic panels—are met in most of the locations studied, regardless of the time of year or weather conditions. The only exception is northern Europe in winter, where very short daylight hours significantly reduce the exposure of PV panels to sunlight compared to other regions. In other locations, the assumptions and design guidelines are consistently met throughout the year.

This study concludes that the achievement of energy autonomy for the operation of the plant depends primarily on the PV modules installed on the site. In addition, given the favorable wind conditions in certain regions, it is also possible to effectively charge the HBESS using harvested wind energy.

4.2. Battery Storage Sizing

The methodology used to select energy storage parameters in autonomous systems is highly simplified and should therefore be considered as an approximation. The industry literature [28] defines the required storage capacity in [Ah] using the formula described in Equation (1). The coefficient equal to 2 is used to avoid the deep discharge of the battery, which could shorten its lifetime and it represents some recommended excess (safety margin).

$$C_{\mathrm{BATT}} = \frac{2 \cdot Q_{\mathrm{DAY}} \cdot F_{\mathrm{RES}}}{V} \quad (1)$$

where

Q_{DAY}—daily energy demand [Wh];

F_{RES}—energy reserve factor: summer period—2.5, and winter period—4;

V—operating voltage of the power system [V].

Slightly more precision in the selection of energy storage capacity for energy-autonomous systems is provided by [29], where the duration of the assumed autonomy of the system (in days) and the allowable discharge depth for the BESS (as a percentage of the nominal value) are considered. This is described by Equation (2):

$$BC = \frac{TWPD \cdot DA}{DOD \cdot BV} \quad (2)$$

where

BC—battery capacity [Ah];
$TWPD$—total watt-hours per day used by appliances [Wh/day];
DA—days of autonomy [days];
DOD—depth of discharge [%];
BV—battery voltage [V].

In practice, the number of pertinent parameters to be considered when selecting an energy storage unit is considerably greater. Such considerations may include the total energy capacity of the storage unit (expressed in Wh), the allowable power output (expressed in W), which determines the unit's ability to handle the required current, the cost of the storage unit, its overall size, and other factors. Furthermore, in energy cluster systems and larger storage facilities, the utilization of multiple energy storage technologies is frequently observed. Therefore, it is essential to conduct a comprehensive selection of these parameters for the various storage and generation technologies.

The research project on the design of an electric and autonomous e-Houseboat resulted in the development of a method for determining the optimal parameters of energy storage units based on a given optimization criterion. The utilization of different battery types enables the advantages of the employed technologies to be capitalized upon. For instance, LFP cells provide high energy density and current-carrying capacity, whereas lead-acid cells are cost-effective and can be easily recycled. A HBESS with a selected capacity can be used effectively as an energy reservoir with varying charge–discharge cycles, thus providing a reliable and adaptable solution for energy storage.

In the presented energy system, LFP batteries are dedicated to handling relatively fast-varying daily charging cycles and high-current loads (e.g., electric propulsion), while lead-acid battery technology serves as a global energy reservoir, enabling a long-term strategic reserve for the e-Houseboat. This approach allows the optimal matching of the number of possible charging cycles for the different technologies, namely LFP (which handles the rapidly varying energy volume component) and lead-acid (which handles the constant component), thereby maximizing the overall operational life of the entire HBESS. The principal objective of this research was to determine the optimal ratio of different types of BESS, such as lead-acid batteries and LFP cells. This approach allows the optimal utilization of the benefits inherent to each battery type, while simultaneously mitigating their respective disadvantages. This research takes into account the rapid advancement of battery technology and the methodology developed is universal, and therefore applicable to different types of batteries that may become available on the market in the future. Furthermore, this study considered the necessity for a periodic and instantaneous large current capacity in the energy storage system, which is required due to the specific load profile of use (e.g., electric propulsion).

As previously stated in Section 2, this research conducted to gain insight into the current state of the art in HBESS design revealed that the majority of designs can be categorized as either experimental and research-oriented systems, utility systems with minimal constraints on size and weight (e.g., PV farms), or systems with strict limitations on both mass and dimensions (e.g., vehicles, bikes). Moreover, these designs frequently address applications requiring extremely high dynamic performance, where a huge instantaneous energy density is required to both power the device and recover dissipated energy (such as during braking and acceleration in vehicles). Consequently, such systems typically consist of battery cells of a single type and may be further enhanced with supercapacitor technology to meet specific performance demands.

To facilitate the research objectives of the HBESS, the energy loads have been categorized according to their operational characteristics. The categories are as follows:

- High-current and low-current loads;
- Frequency of operation, classified as follows:
    - Continuous operation: includes control and monitoring systems of the unit;
    - Infrequently used operation: includes appliances such as washing machines;
    - Frequently used operation: includes essential systems such as lighting and refrigerators;
    - Sporadic or stochastic operation: includes propulsion systems of the unit.

A strategy was adopted in which the amount of stored energy utilized is variable, allowing for fluctuations throughout its structure. This variability allows for the isolation of the dynamic energy component, which is managed using an LFP battery. LFP batteries have a longer lifespan, indicated by the number of charging cycles, in comparison to lead-acid batteries. On the other hand, a bank of lead-acid batteries is used to store energy over an extended period corresponding to the fixed component of the energy volume. This approach enhances the durability and lifespan of lead-acid battery technology, optimizes the performance of LFP batteries, and ultimately aligns the number of supported charge cycles of both battery types with their maximum potential, as defined by their technological capabilities.

4.2.1. Original Method for Determining Battery Technologies Percentage Ratios

The method presented below has been successfully developed and verified based on defined parameters (e.g., amount of energy in kWh, maximum power supply in kW and permissible storage size), to match the size of the energy storage to the hybrid power system, creating its energy autonomy. It also allows for iterative optimization (one by one) according to further defined criteria.

In general, the strategy of that method is based on dividing the optimized parameter into all the n-type similar technologies that are considered with an equal percentage distribution for a given criterion (in proportion: $1/n \times 100\%$). This allows one to determine the minimum or maximum values of the optimized parameter per technology used (in the example presented, dividing 30 kW into two technologies of 15 kW each) that will meet the requirements of the criterion (no less than or no more than). To determine the minimum level of the parameters sought, the static characteristics of the individual battery technologies are used, which determine the available relationships for the model of that. An example of that can be seen in Figure 2.

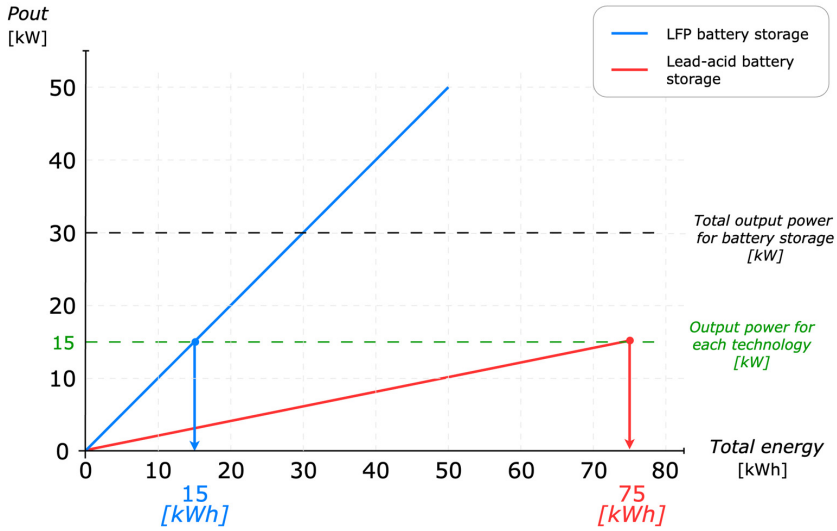


Figure 2. Output power Pout in kW of the battery storage versus its total capacity in kWh.

Therefore, each successive iteration of the method determines the minima or maxima that meet the conditions of the optimization criteria. At the same time, it gives the possibility to select an additional volume of the preferred technology if the condition is met with a margin over the previous iteration. An example of that can be seen in Figure 3, where the volumes of both technologies were increased when the cost condition was easily met.

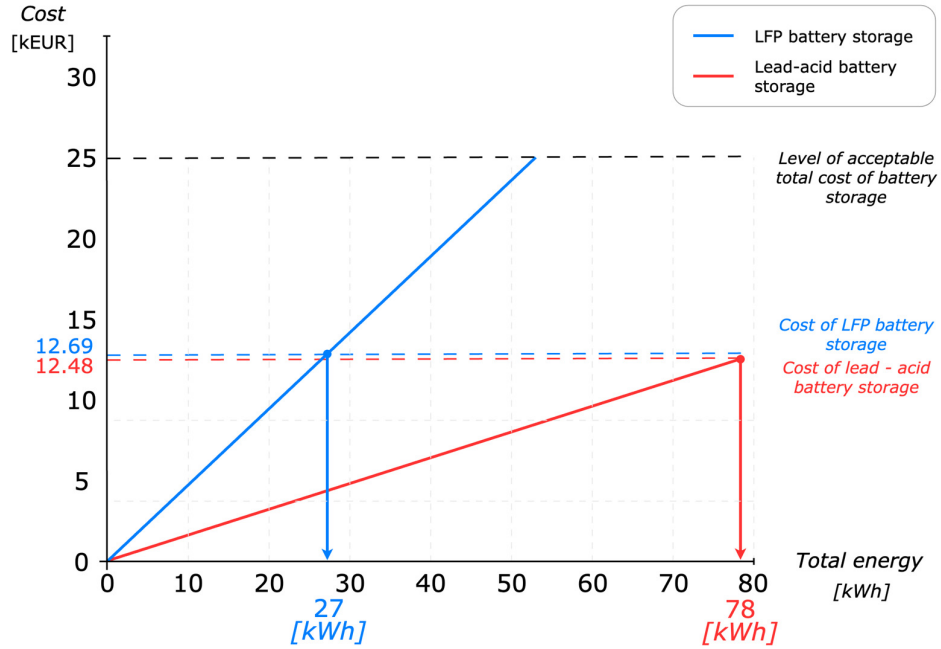


Figure 3. Implementation of percentage distribution in an HBESS using a cost criterion and leveraging the dependency of cell prices on their capacities for different technologies.

Considering the above assumptions of the presented method, it can be concluded that it is universal and scalable and also that additional criteria can be introduced.

For the construction of the prototype storage facility, it was assumed that two technologies with different parameters (energy densities, different weights, and different prices) would be used in order to achieve the following:

- The optimization of cost storage: relatively expensive LFP technology and much cheaper lead-acid technology;
- Optimizing the use of available installation space and improving the mechanical stability of the houseboat unit: different size and weight of lead-acid and LFP technology;
- Increasing the recyclability of the storage and reducing the environmental cost: easy recycling of lead-acid cells and difficult one to lightweight LFP cells;
- Use of two different technologies (lead-acid and LFP) to operate on different charging cycles:
  - Fast-changing and frequent—daily;
  - A slow and relatively infrequent energy buffer—several weeks.

The primary criterion for selecting the battery proportion using two different technologies was to meet the electrical power requirements necessary for the functional operation of the e-Houseboat, including its mobility features. Calculations based on the installed electric drives and other equipment determined that the HBESS would need to provide a minimum of 30 kW of power, referred to as the functional utility criterion. Figure 2 illustrates the relationship between output power in [kW] and electrical capacity in [kWh] for each battery technology (LFP and lead-acid) within the battery bank.

Initially, the relative proportions of each battery technology were optimized. The optimization criterion was to achieve the required output power at the lowest possible

electrical capacity using more expensive and less environmentally friendly technology. It was critical to meet the minimum battery power requirement of 30 kW while avoiding the suboptimal oversizing of the battery bank.

The battery distribution was designed to provide half of the required power (15 kW) from each of the lead-acid and LFP battery banks. Increasing this value (represented by the green dashed line) it would result in an oversized (suboptimal) battery bank, while decreasing it would result in an undersized (insufficient output power) battery bank. These specific values are highlighted with red dots and arrows in Figure 2. As a result, a 75 kWh, 15 kW lead-acid battery bank was selected, along with a 15 kWh, 15 kW LFP battery bank.

During the second stage of optimization, cost considerations were introduced. This involved evaluating the "cost-to-capacity" ratio for battery banks of different technologies within the HBESS. An acceptable cost level for the BESS was established at approximately EUR 25,000, based on the relative costs of other materials and resources required to build the e-Houseboat. The planned configuration included 220 Ah batteries in a 4S1P arrangement for the lead-acid battery bank and 400 Ah cells in a 16S1P arrangement for the LFP battery bank. The unit cost of the energy capacity was estimated to be EUR 160/kWh for the lead-acid technology and EUR 470/kWh for the LFP technology. Figure 3 illustrates the variation in the unit price of a module as a function of the energy capacity (kWh) for each technology.

The costs of the battery banks identified during the first functional optimization phase (Figure 2) were significantly lower than the defined cost limit. Specifically, the cost of the LFP battery bank was USD 7050, while the cost of the lead-acid battery bank was USD 12,000, resulting in a total cost of USD 19,050—lower than the established limit. This cost margin provided the flexibility to significantly increase the capacity of the battery bank, thereby improving the functionality and comfort of the e-Houseboat.

After applying the second optimization criterion (Figure 3), it was determined that the capacities of both battery technologies could be increased to 27 kWh for LFP cells and 78 kWh for lead-acid cells.

However, the design requirements of the e-Houseboat dictate that the batteries be installed inside the floats, as shown in Figure 4. This arrangement is essential to maintain the unit's center of gravity and ensure the effective thermal stabilization of the cells. The proximity to the water provides a natural and efficient cooling resource, which aids in temperature regulation. Space within the eight floats has been specifically allocated for energy storage, with the restriction that only one type of battery can be installed in each float.

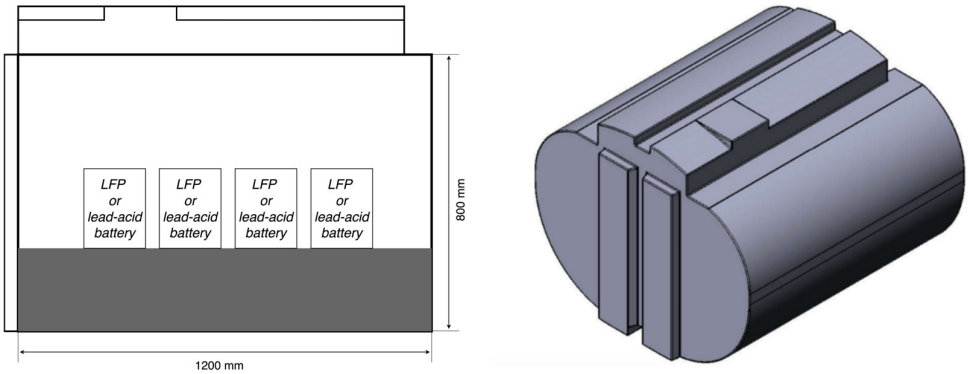


Figure 4. 3D model of a float and technical drawing with a battery layout diagram.

During the customization and optimization process, the total capacity of the HBESS was adapted to align with the available space. The selected battery models allow for the installation of either 10 kWh of lead-acid based batteries or 20 kWh of LFP-based batteries

in a single float. Due to space limitations and design optimization, it was decided to install LFP batteries in the first float, while the remaining seven floats were equipped with lead-acid batteries. This configuration meets all previously established optimization criteria. Figure 5 illustrates the selected battery capacities, marked with red dots and arrows, along with their distribution among the individual floats. The final specifications for the HBESS include an electrical capacity of 90 kWh, an output power of 34 kW, and a total cost of 20,600 EUR.

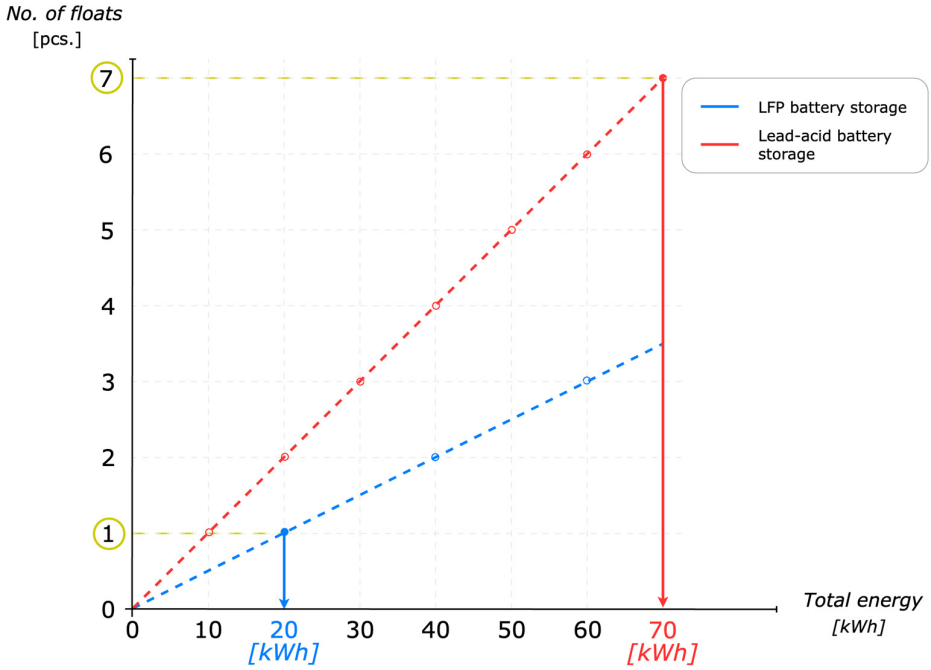


Figure 5. Space availability in quantized units of battery module capacity versus total energy in kWh of the battery storage.

The final contribution of each technology to the capacity of the HBESS was determined to be 22.2% for LFP cells and 77.8% for lead-acid cells.

As previously outlined, the methodology for selecting the components of the HBESS can be adapted to various applications and scenarios by adjusting the relevant parameter values according to the proposed optimization criteria. This approach involves an iterative process of evaluating successive system parameters and optimization criteria, ultimately resulting in an optimal configuration of storage parameters that balances multiple objectives.

It is important to emphasize that all partial system requirements have been carefully considered and met. Subsequent iterations of optimization for specific criteria involve only minor adjustments to the previously established parameters, ensuring that the overall functionality of the system remains uncompromised. This methodology facilitates a comprehensive, multi-criteria verification of the designed system, ensuring its robustness and adaptability.

4.2.2. Energy Fluctuations in Hybrid Battery Energy Storage—Optimization Potential

A fundamental aspect of the HBESS investigation was the estimation of the energy required for the e-Houseboat to achieve autonomous operation. A dedicated energy model of the unit was developed within the SciLab environment. This took into account both electrical and thermal energy demands, incorporating seasonal variations and archived meteorological data. The data on electricity, heating, and cooling energy demand, as well as energy consumption by end-use devices, were generated using the eQuest environment. A simulation was conducted for a structure located on water, with building parameters

(such as thermal transmittance) corresponding to the materials used in the construction of a houseboat. Additionally, meteorological data were exported from eQuest to facilitate further research. The remaining calculations were performed in the SciLab environment, where the data obtained from eQuest were supplemented with information on renewable energy generation. Based on this, the state of charge of the HBESS was computed. Based on this model, the required level of electric power and the energy storage capacity to fulfill the specified functionality, ensuring both operational utility and user comfort, were determined for various potential scenarios.

Figures 6 and 7 illustrate the variability in the stored electrical energy within both energy banks (LFP and lead-acid). Notably, significant fluctuations in the stored energy are observed within the LFP batteries, characterized by a variable derivative. These fluctuations are largely independent of seasonal changes, as evidenced by graphs that represent two contrasting periods.

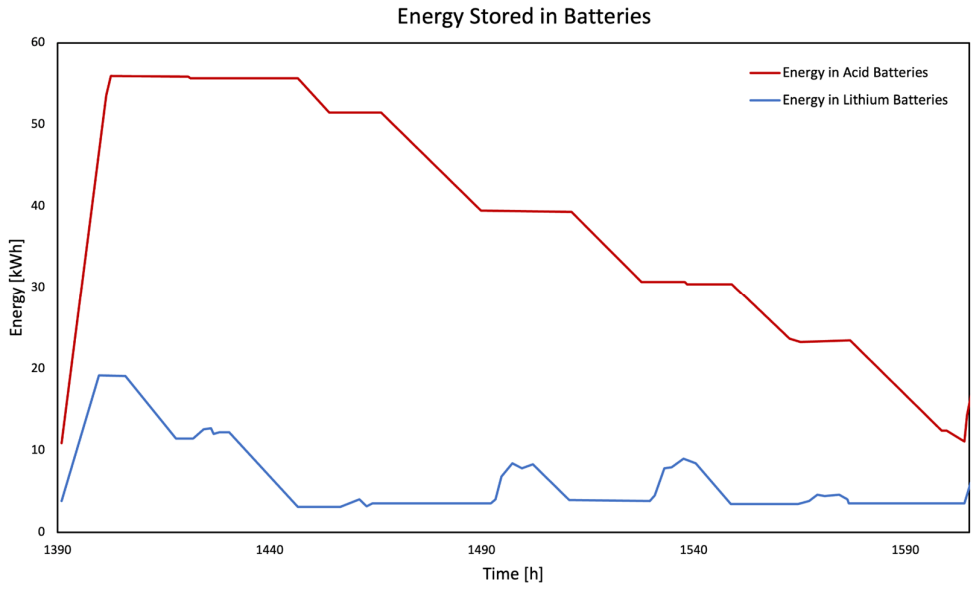


Figure 6. Fluctuations in the energy capacity of batteries during winter (February).

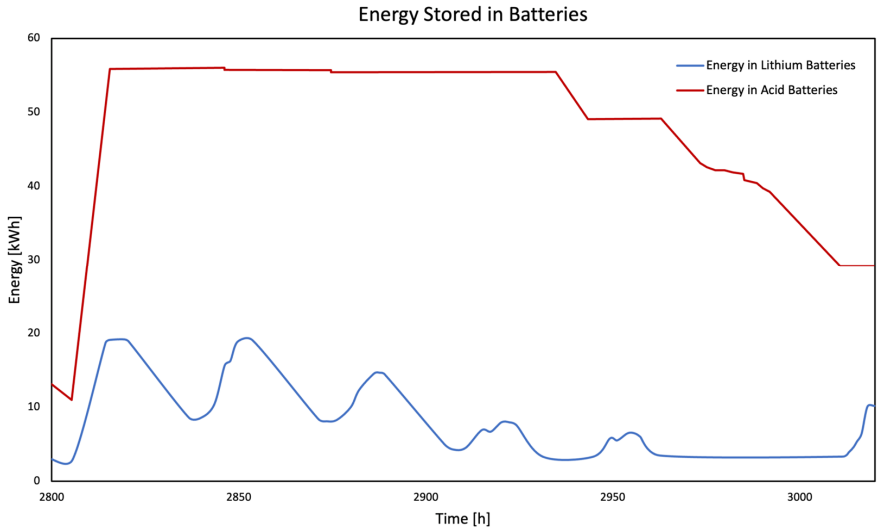


Figure 7. Fluctuations in the energy capacity of batteries during spring (May).

The fluctuations are observed during both winter months (Figure 6, based on simulations from early February for Bydgoszcz) and spring–summer months (Figure 7, based on simulations from late May, also for Bydgoszcz). The primary driver of this variability is the

amplitude of the fluctuations, which correlates with the increased energy generation from the RES. This is particularly evident during periods of higher irradiation in the spring and summer months.

During these months, energy generation frequently exceeds instantaneous electricity demand, resulting in higher energy yields. Simultaneously, the e-Houseboat's overall energy demand declines, contributing to the observed variability in stored energy levels.

The principal disadvantage of lead-acid batteries is their relatively low energy density compared to their weight. However, the high energy output during discharge and the simplicity of recycling are advantages of this battery technology. The voltage variation at the terminals of a loaded battery during discharge, under different discharge current values, follows different characteristic patterns.

The discharge curves for the battery used in this study are shown in Figure 8. Their nearly linear nature allows for a relatively straightforward estimation of the battery's SoC.

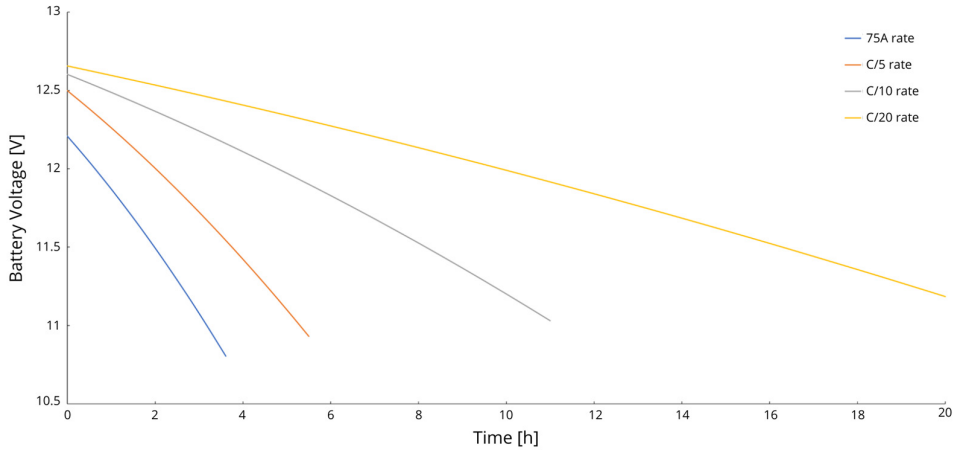


Figure 8. Discharge curves chart for constant load currents.

LFP batteries are becoming increasingly widespread due to their potential to enhance energy density and achieve high voltage in a single cell. This trend is further supported by declining production costs driven by economies of scale. Despite these advantages, LFP batteries remain approximately three times more expensive per unit of capacity compared to lead-acid batteries.

From a systemic perspective, it has been proposed that the energy in HBESS can be decomposed into a time-varying component and a fixed component. This decomposition allows for the efficient management of the charging and discharging processes, thereby ensuring a balanced or approximately equal number of cycles for each energy storage technology. Consequently, this approach significantly extends the overall lifespan of the HBESS while maintaining cost optimization.

Figure 9 illustrates the variation in the number of potential operating cycles for both lead-acid and LFP batteries as a function of the depth of discharge. The data indicate that with appropriate energy balancing, the service life—defined as operational longevity—of both technologies can be comparable.

Moreover, the potential lifespan of lead-acid batteries depends on several factors, including the C-rate (discharge rate relative to battery capacity), the processes of discharge and charging, and the operating temperature. It is assumed that an 8 °C increase in the operating temperature of a lead-acid battery above the standard 25 °C will result in a halving of the number of charging cycles.

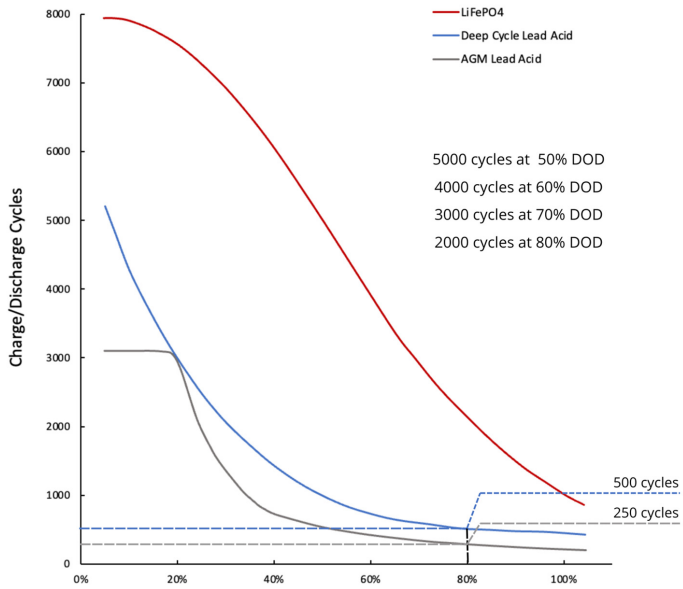


Figure 9. Graphical representation of the number of operating cycles for lead-acid and LFP battery technologies as a function of cell discharge depth.

It should be noted that the storage system was initially conceived as two separate sections: one dedicated to traction and the other to utility. However, this design approach was ultimately rejected. Instead, the overall current capacity was increased by enhancing the storage capacity.

4.3. Architecture and Functionality of the Dedicated On-Board Energy System

The efficiency of the power system in the e-Houseboat unit was defined by its ability to provide the required functionality of the facility while maintaining thermal and utility comfort, as well as ensuring system reliability. A significant focus of the research and design process was the establishment of the dedicated framework, a structure for the e-Houseboat's comprehensive energy supply system. This process involved identifying suitable power sources and generation technologies, selecting appropriate energy storage solutions, and specifying inverters capable of converting energy parameters to align with the desired operational modes.

The optimal battery capacities for each type were determined by a detailed functional analysis that accounted for energy demand, usage profiles, design constraints, and mass distribution. This analysis was followed by a multi-criteria optimization process, as detailed in Section 4.2.

The designed topology of the energy system has been developed and tested with the objective of maximizing battery lifespan and optimizing the allowable number of duty cycles for various battery technologies. This approach is based on the criterion of maximizing the overall storage system lifespan. The structure of the energy system has been designed to support the following functionalities:

- The utilization and operation of multiple types of battery storage units;
- The BESS is capable of being charged from either RES or AC ground grid. Moreover, an external AC combustion generator can function as an emergency power source for on-board systems. The objective is to provide power to the unit's propulsion system, thereby ensuring optimal operational performance;
- When LFP batteries are fully charged, the optional energy flow to lead-acid batteries is provided, and the balance of energy consumed by the on-board equipment and generated by RES remains positive;

- When the LFP batteries are discharged and the immediate power demand is high (e.g., during intensive motor use), energy is provided from the lead-acid batteries.

Figure 10 shows the custom-designed topology of the energy system for the e-Houseboat. The system includes an AC grid connection, a generator, RES, lead-acid and LFP batteries, and inverters. Inverter 1 is connected to the lead-acid batteries, while Inverter 2 is connected to the LFP batteries. Additionally, a charger is integrated with the LFP batteries, enabling them to be charged using the energy generated from RES. The motors are powered by the LFP batteries, ensuring efficient propulsion. The energy flows to the loads are regulated through controlled relays (R1 and R2), allowing for precise energy management. This configuration supports efficient battery charging and discharging, while reliably powering various devices and systems.

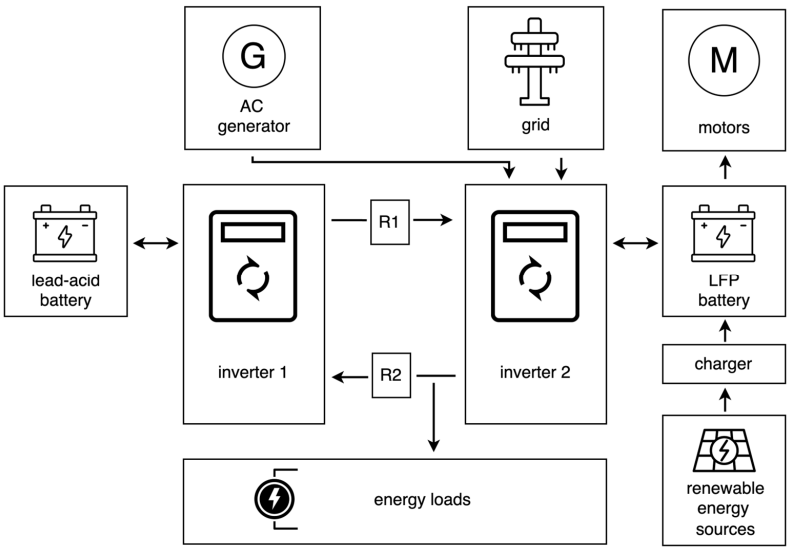


Figure 10. Energy system topology for an autonomous and electrically powered e-Houseboat.

The arrows indicate that the energy transfer within the system can be unidirectional or bidirectional. The functional structure of the e-Houseboat, which comprises multiple load types, critical systems, supplementary AC and DC circuits, generation sources, and storage units, represents a relatively complex power system topology. Additionally, the system supports various operating modes and offers multiple management options. To achieve the defined functionalities, it was necessary to algorithmize the control system, define specific modes of operation, and outline potential options. Consequently, three primary system use scenarios were identified:

- Standard Operation—this scenario involves powering on-board equipment from battery storage units and occurs in two modes:
    - RES and LFP Battery Mode (default)—in this operational mode, energy is drawn from the LFP battery bank and RES. This mode is active when the unit's energy balance is positive, defined as the energy generated from RES and stored in the LFP battery bank exceeding the energy consumed by the loads. Furthermore, the Smart Optimization function can be activated in this state, ensuring that when the LFP bank is fully charged, the lead-acid batteries can be recharged (relay R2 is closed and relay R1 is open);
    - Lead-Acid Battery Mode: in this mode, energy is drawn from the lead-acid batteries, which serve as the system's energy backup. This mode is initiated when the unit's energy balance in the RES and LFP Battery Mode is negative, indicating that the generation from RES is insufficient to meet the energy consumption

requirements and that the energy stored in the LFP bank is inadequate. Furthermore, the Energy-Saving function, integrated into the on-board automation system, is activated in this state. This function reduces the energy consumption of selected loads when the lead-acid battery charge level declines below 50% by implementing periodic limitations on their usage;

- Recharging—this scenario allows the connection of an external AC grid source, which is typically a pole situated in the marina where the boat is moored. In this configuration, relay R1 remains open and relay R2 remains closed;
- Emergency Power—in this scenario, relay R1 remains open, and relay R2 remains closed. In this scenario, power is provided to on-board equipment and consumers from an external emergency generator. No shore power is required, making it suitable for use outside the marina. In this scenario, relay R1 remains open, and relay R2 remains closed.

The system includes two inverters (Inverter 1 and Inverter 2), primarily to guarantee system redundancy and to address technical considerations. It is important to note that different battery technologies require different charging and loading characteristics. However, increasing the inverter power linearly leads to a substantial increase in cost. Inverter 2 is connected to two AC power sources: the grid and an emergency generator. This configuration ensures that only one AC source operates at a time, thereby providing short-circuit protection between the two sources. The logic for controlling the relay to transfer energy between LFP and lead-acid batteries (switching from RES and LFP Battery Mode to Lead-Acid Battery Mode in the standard operational scenario) has been implemented within Inverter 2. The system relays are actuated based on voltage measurements of the LFP batteries, allowing energy flow. While various parameters can be defined to determine the relays' operation, the battery voltage is selected as the primary parameter. The default operational scenario is Standard Operation with the RES and LFP Battery Mode, where the LFP batteries—owing to their significantly higher cycle life and current capacity—supply power to both the motors and AC loads. If the LFP battery voltage exceeds a software-defined threshold of 54 VDC and AC power is disconnected, the system activates the Smart Optimization function. In this scenario, if the lead-acid batteries are not fully charged, energy flows from the solar chargers through Inverter 2 and Inverter 1 to charge the lead-acid batteries. Relay R2 remains closed, while R1 remains open. This setup helps minimize the fluctuation of the charge level of lead-acid batteries, as outlined in Section 4.2.2.

When the voltage of the LFP batteries reaches a level below 45.6 V (approximately 20% of charge) and the unit's energy balance becomes negative, the relay states are adjusted to enable the LFP batteries to charge from the lead-acid batteries. This transition to lead-acid battery mode involves closing relay R1 and opening relay R2, allowing energy transfer from the lead-acid batteries through two inverters to the LFP batteries. Additionally, the relay states are adjusted when the system is connected to an external AC grid—such as at a marina or when a generator is active—or when the LFP batteries are fully charged. If the energy level of the lead-acid batteries drops below 50%, the Energy-Saving function is activated. The HBESS energy flow sequence is designed to match the operating parameters and demands of the on-board energy loads with the capabilities of the battery technologies. LFP batteries are optimized for high-current demands and rapid daily charging cycles, while lead-acid batteries act as a global energy reservoir, maintaining a strategic reserve for the e-Houseboat and storing surplus energy. This configuration reduces the load on the lead-acid batteries, thus extending their service life and minimizing the need for the disposal of environmentally hazardous materials such as lead. Beyond its environmental

advantages, this setup also reduces the overall cost of building e-Houseboat with an electric propulsion system by significantly extending its operational lifespan.

4.4. e-Houseboat Automation System

An integral part of the prototype e-Houseboat unit, which is designed to achieve energy autonomy, is the dedicated automation and control system. This system integrates two key energy subsystems: independent RES (such as PV panels and wind generators), combined with HBESS (lead-acid and LFP batteries), together with a power system connected to the main grid and a backup generator. The integration of these systems took place at multiple levels: the electrical level (AC and DC buses), the high-current level, the control level, and the sensors and communication level, utilizing the specific communication protocols of each device.

The on-board automation system takes advantage of building and industrial automation technologies. The system measures the variables of the process, manages thermal comfort within the e-Houseboat, monitors weather conditions, and tracks the consumption of energy by individual installations, including electrical, heating, hot water, propulsion systems, and energy flow within the facility's energy system. This includes the integration of RES, HBESS, and inverters. Figure 11 illustrates screenshots of the user interface from the custom automation system developed for the e-Houseboat.

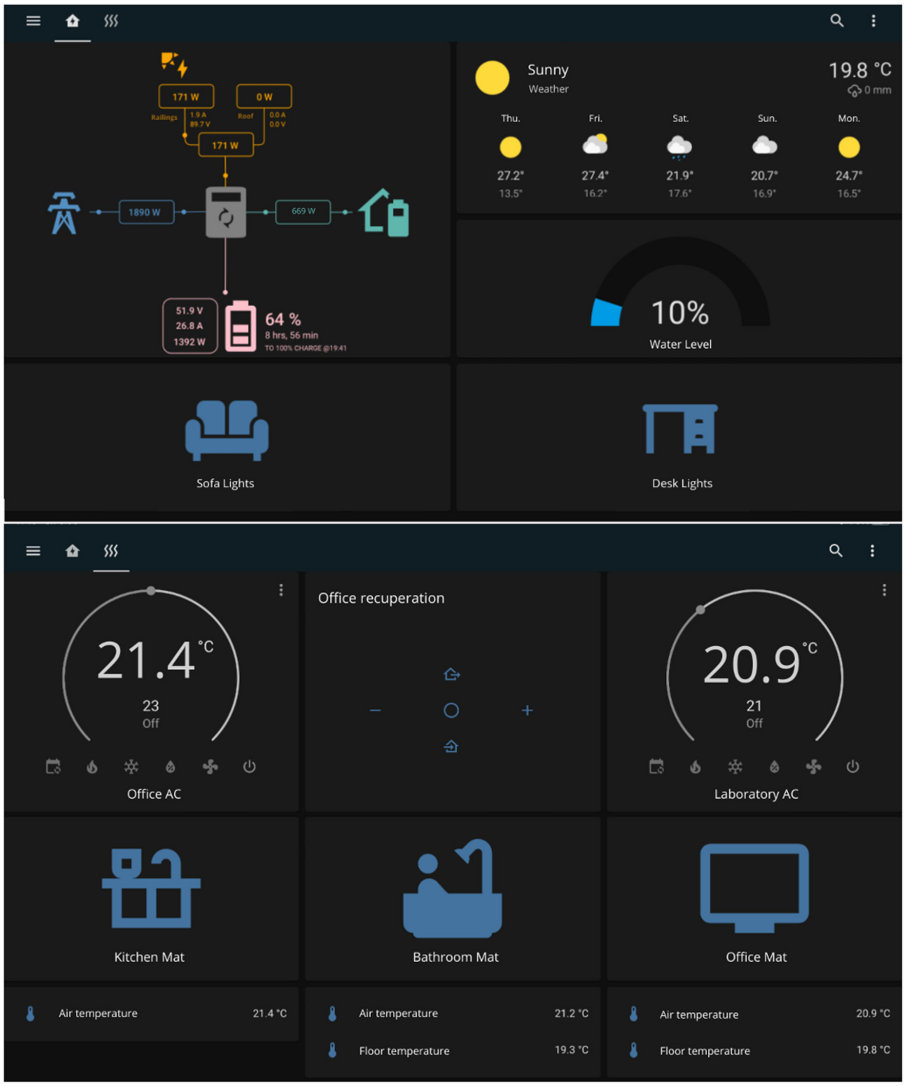


Figure 11. Display of the e-Houseboat automation system interfaces.

The data from the object are logged in a dedicated relational SQL database every 30-s. The data are stored for a period of 9999 days, which equates to over 27 years. This allows for the continuous verification of the e-Houseboat's operation and provides the ability to analyze historical data from the prototype commissioning period.

The developed and implemented on-board interfaces monitor the operation of all subsystems, ensuring both safety and user comfort. Their design follows established best practices and guidelines from the User Interface (UI) and User Experience (UX) methodologies, providing intuitive interaction with the system, clear process visualization, and effective notifications about system status, detected anomalies, and emergency situations.

The EMS system and its user interface, as described in this article, are not the first iteration of this solution. Before being deployed on the e-Houseboat, it was developed and tested in a laboratory environment. During its development, the functionality and operation of the system were continuously consulted with potential users. A series of usability tests were conducted, including heuristic analysis, scenario-based testing, and user sessions with a prototype interface. Based on the collected feedback, iterative improvements were made, focusing on interface layout optimization, enhanced visualization readability, and improved notification systems for errors and anomalies.

Additionally, the system passed stress and reliability tests to identify potential issues related to connection loss, remote access, and communication with various devices (e.g., sensors and actuators). Any malfunctions were promptly diagnosed and resolved, ensuring greater system reliability.

Thanks to these usability tests and an iterative improvement process, the EMS user interface provides high ergonomics and intuitive operation, which was confirmed by positive user feedback in the final deployment phase.

5. Results and Discussion

The primary objective of this study was to achieve a minimum of one month of energy autonomy for the e-Houseboat, regardless of the season and external conditions. To provide a comprehensive evaluation of this objective, the test duration was set at 12 months, beginning on 1 September 2022, and ending on 31 August 2023. During the heating season, the temperature was maintained between 21 and 23 °C, thus ensuring that the temperature remained above 20 °C. During the summer months, if the e-Houseboat was not occupied, the temperature could reach 27 °C. This approach guaranteed that the temperature remained below the maximum limit of 29 °C. The usage profile assumed that the equipment would be used for a minimum of three hours per day. The data collected during the experiment were logged in the previously mentioned database using the on-board automation system. At the start of the verification period, the e-Houseboat's HBESS was fully charged to 100% and disconnected from the external power source. During the long-term energy autonomy tests, ensuring thermal comfort and optimal boating conditions was essential. These conditions included the proper functioning of the RES, adequate visibility, and safe navigation. From 16 November 2022 to 10 March 2023, the weather conditions were not suitable for boating. Due to safety concerns, navigation during the winter months in Bydgoszcz, Poland, was nearly impossible. However, the e-Houseboat was operational for boating during other seasons, with an average of four hours of boating per day. Throughout the energy autonomy test period, the facility was used in a normal manner, with loads and appliances operated according to user needs and in accordance with the recommendations provided by the on-board automation system.

The automation system operated continuously throughout the 12-month prototype testing period. This system was responsible for controlling and managing the unit, as well as monitoring and recording data. Upon the completion of the testing period, the logs and

recorded data were subjected to analysis to evaluate the level of energy autonomy achieved by the prototype unit. The energy management system (EMS) of the on-board automation system developed for the prototype unit showed satisfactory performance during the testing phase, with no significant issues identified. During the one-year testing period, the facility required external recharging only twice. If recharging was required, the facility was connected to an external energy source and charged to 100% capacity. Following a period of several hours during which the e-Houseboat was connected to an external energy source, it was then disconnected. During the recharging process, the facility was utilized in its normal capacity, apart from any activities related to boating. The two instances of recharging occurred in late autumn (2 December 2022) and winter (24 January 2023). The interval between recharges exceeded one month, demonstrating that the e-Houseboat and its EMS met the design objectives. Figures 12–23 illustrate the monthly percentage of charging for the HBESS during the e-Houseboat energy autonomy verification.

In September 2022 (Figure 12), the energy produced by RESs generally met the facility's energy demands. This was due to the relatively mild outdoor temperatures, which reduced the need for thermal energy. From 15 to 23 September, RES production was lower due to increased cloud cover, which reduced the efficiency of the PV panels. Nevertheless, the energy stored in the HBESS was sufficient to cover the facility's energy demand during those days.

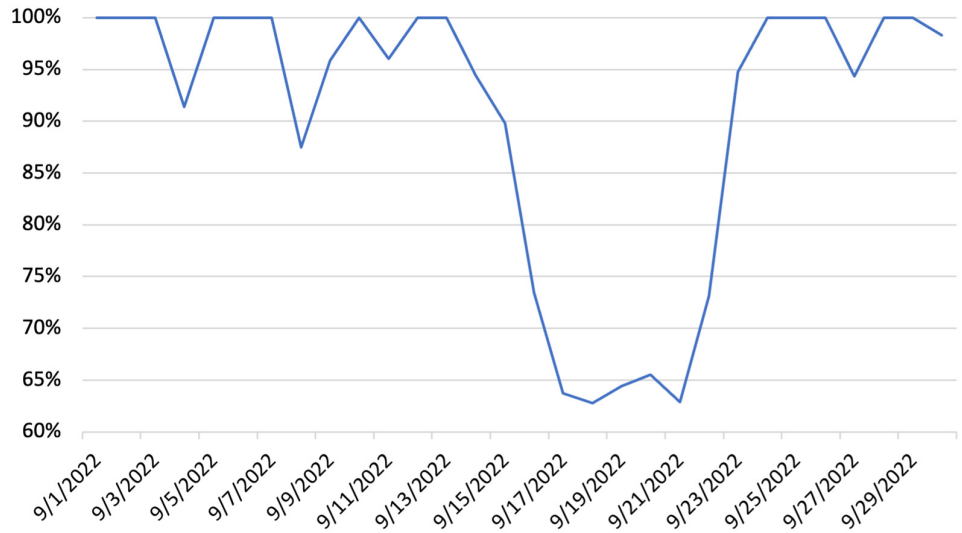


Figure 12. SoC profile for an HBESS—September 2022.

In October 2022 (Figure 13), RES energy production generally covered the e-Houseboat's energy requirements. Relatively mild outdoor temperatures resulted in a reduction in thermal energy demand for the facility. However, between 18 and 25 October, RES production decreased due to increased cloud cover, which decreased the efficiency of PV panels. Despite this, the energy stored in the HBESS was sufficient to meet the facility's demands during this period.

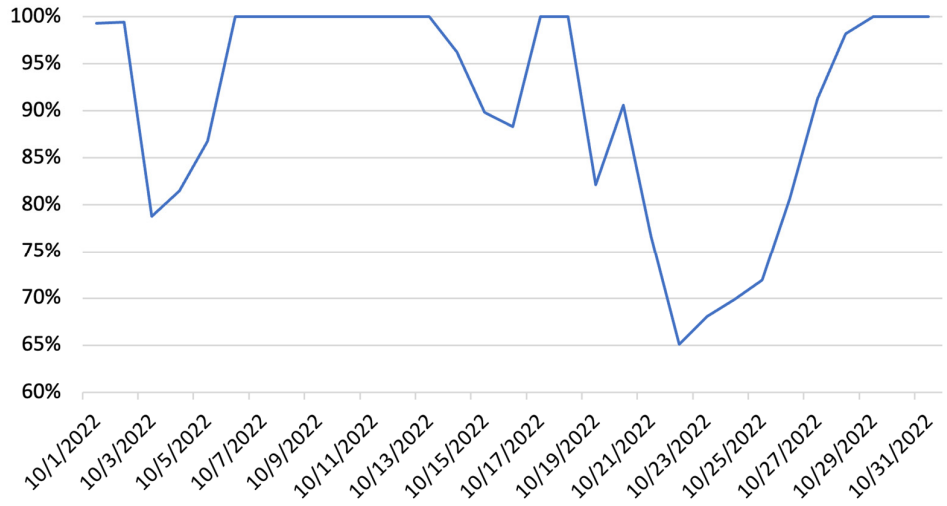


Figure 13. SoC profile for an HBESS—October 2022.

In November 2022 (Figure 14), the observed energy patterns differed significantly from those of the previous two months. During the first part of the month, the yields of renewable energy and favorable weather conditions enabled the HBESS to reach full capacity. However, as the month advanced, the deteriorating weather conditions increased thermal energy demand and significantly reduced energy generation from PV, the primary RES for the e-Houseboat. Despite this, the energy stored in the HBESS was sufficient to maintain the energy autonomy of the facility throughout the month. By the end of November, the level of energy storage had decreased to approximately 7%.

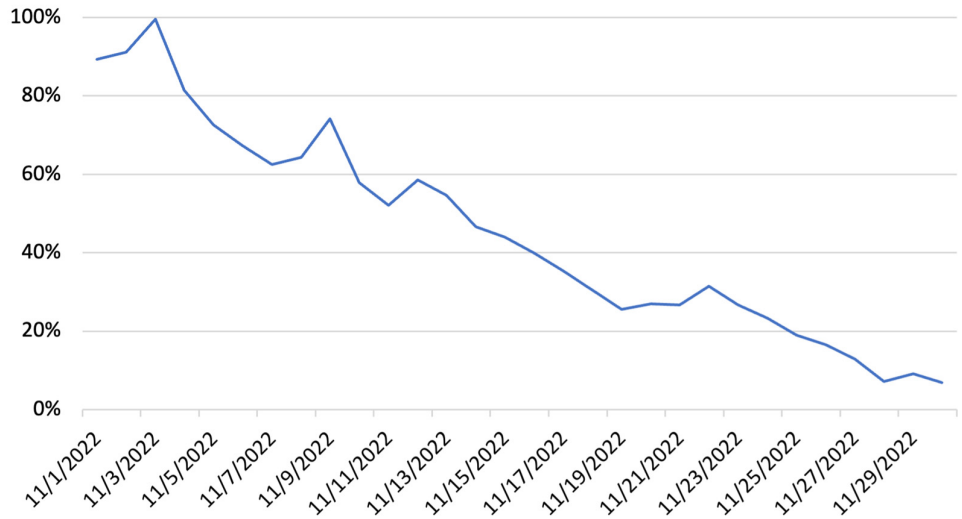


Figure 14. SoC Profile for an HBESS—November 2022.

In December 2022 (Figure 15), the demand for thermal energy increased further, while the energy generation from RESs decreased compared to November. On 2 December, the HBESS reached a critical level, requiring a connection to an external power source to reach 100% capacity. The test resumed at midnight on 3 December, with the HBESS fully charged. From that point onward, the charge level in the HBESS gradually declined. This indicates that energy production from RES was insufficient to meet the e-Houseboat's energy demands. Nevertheless, the HBESS capacity sustained the energy autonomy of the facility for several additional days.

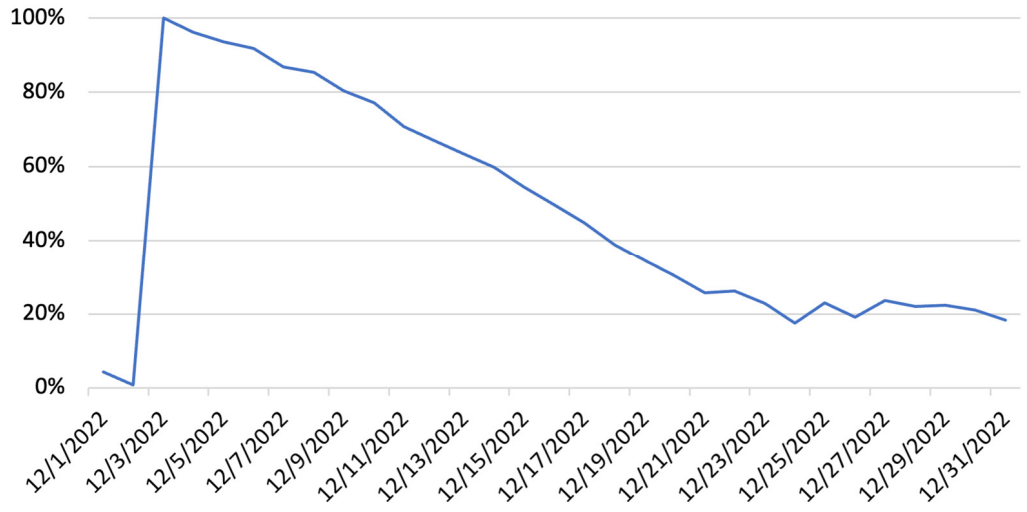


Figure 15. SoC profile for an HBESS—December 2022.

In January 2023 (Figure 16), the charge level of HBESS remained between 20% and 40% for most of the month. This indicates that the energy produced by RES was sufficient to meet the e-Houseboat's demands, with any surplus energy stored in the HBESS. However, from 18 January, still-deteriorating weather conditions caused a gradual decline in the HBESS charge level. By 24 January, the charge level had dropped below a critical threshold, requiring a connection to an external power source for complete recharge. After the recharge, the energy level gradually decreased until the end of the month.

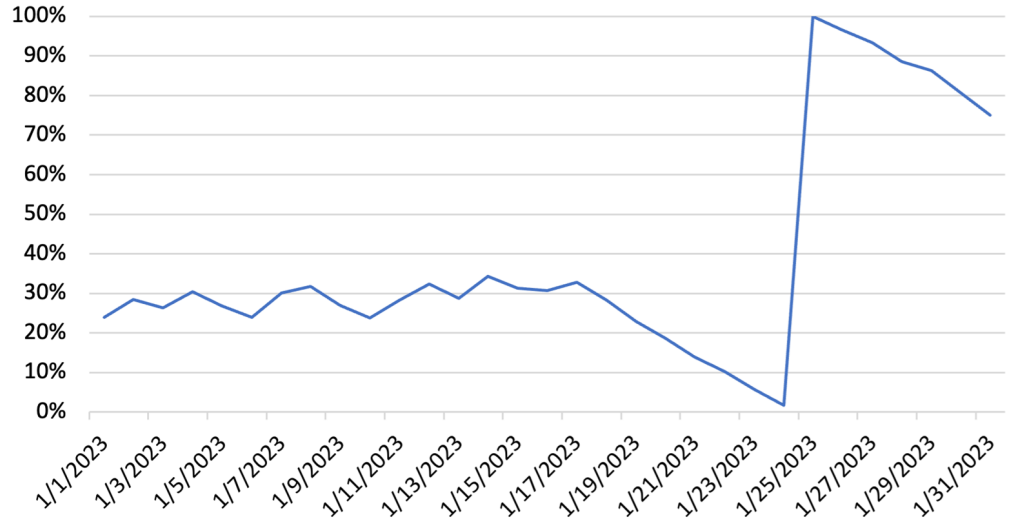


Figure 16. SoC profile for an HBESS—January 2023.

In early February 2023 (Figure 17), the HBESS charge level continued to decline. However, on 7 February, improved weather conditions significantly increased energy production while simultaneously reducing the e-Houseboat's energy demand. From that point, surplus energy from RESs was stored in the HBESS, enabling it to reach full capacity and maintain a charge level close to 100% for the remainder of the month.

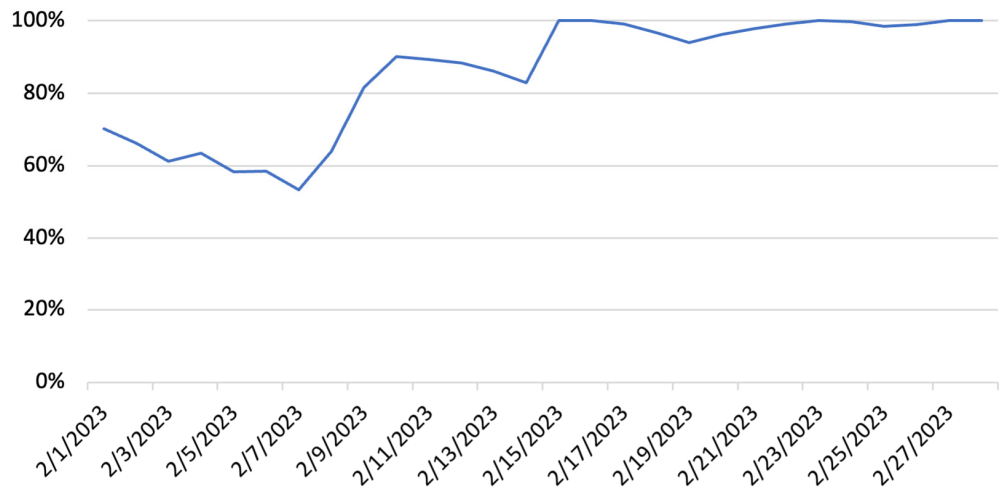


Figure 17. SoC profile for an HBESS—February 2023.

In the early days of March 2023 (Figure 18), the trend of the previous month continued, with the HBESS remaining fully charged and capable of meeting the e-Houseboat's energy demand through current RES generation. However, on 10 March, deteriorating conditions caused the energy level in the HBESS to drop from 100% to approximately 32% over a five-day period. After the weather conditions improved, the RES generation gain became sufficient to meet the facility's demand and recharge the HBESS. At the end of the month, the HBESS reached full capacity.

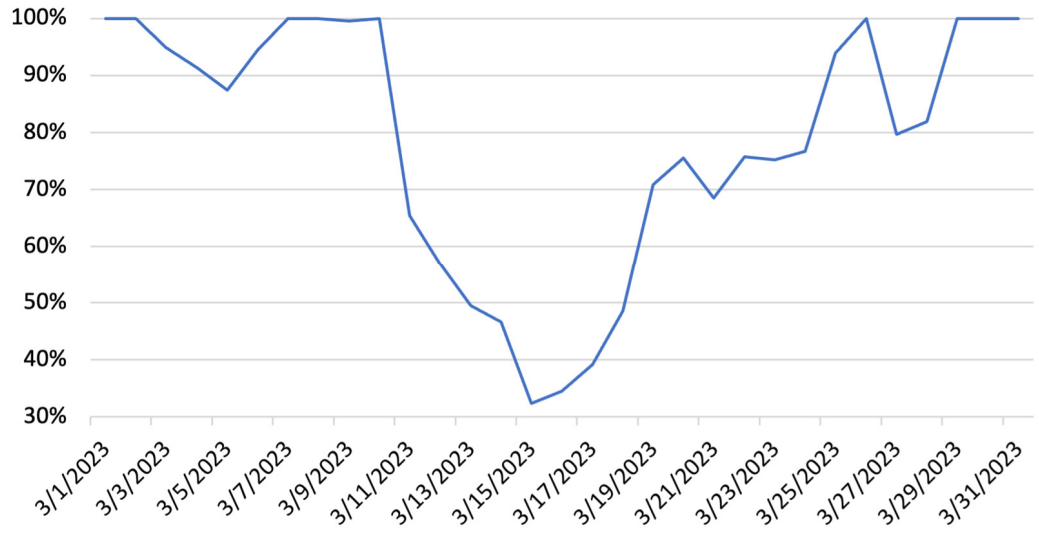


Figure 18. SoC profile for an HBESS—March 2023.

In April 2023 (Figure 19), the HBESS charge level fluctuated between 60% and 100%. This indicates that, in most cases, the energy generated by the e-Houseboat was sufficient to meet its energy demands, with any surplus energy stored in the HBESS until it reached full capacity.

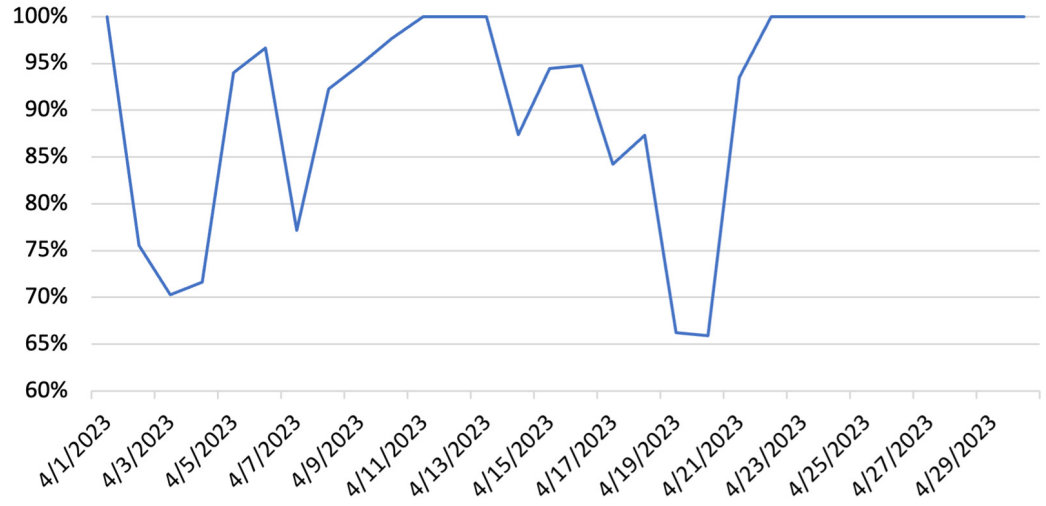


Figure 19. SoC profile for an HBESS—April 2023.

In May 2023 (Figure 20), the HBESS charge level fluctuated between 75% and 100%. This indicates that, in most cases, the energy generated by the e-Houseboat was sufficient to meet its energy demands, with any surplus energy was stored in the HBESS until it reached full capacity.

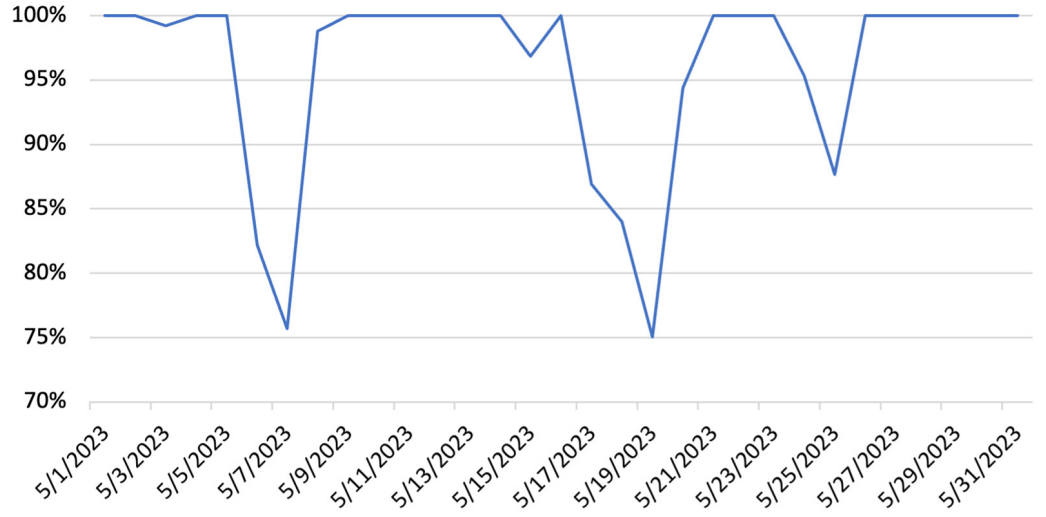


Figure 20. SoC profile for an HBESS—May 2023.

In June 2023 (Figure 21), the HBESS charge level remained at 100% for most of the month, indicating that the energy generated by the e-Houseboat consistently met its energy demands. However, on 24 June, the charge level decreases to 90%, attributed to the reduced energy production of RESs caused by increased cloud cover.

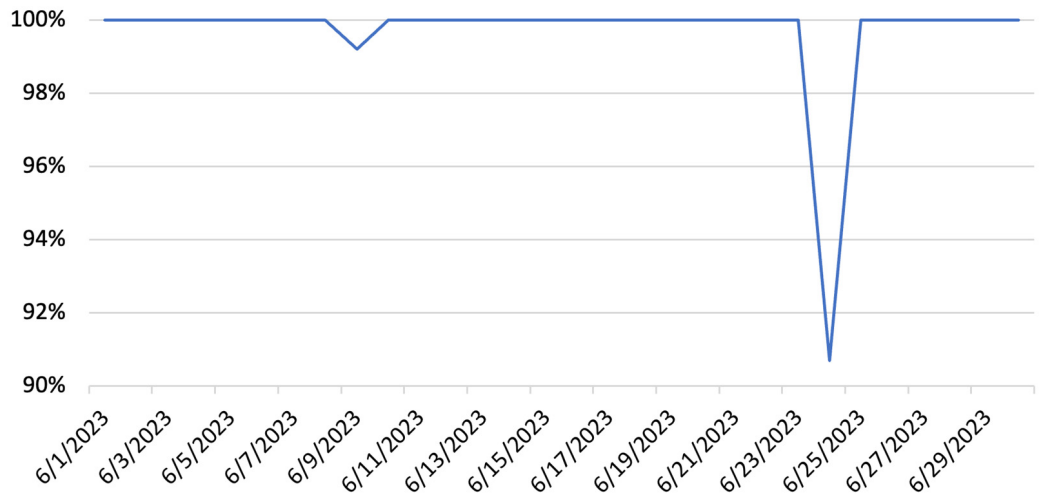


Figure 21. SoC profile for an HBESS–June 2023.

A similar situation occurred in July 2023 (Figure 22), with the HBESS charge level consistently remaining at 100%. In a few days, the charge level dropped below 100%. This was due to reduced energy generation from the RESs and the high external temperatures, which increase the cooling demand for the e-Houseboat.

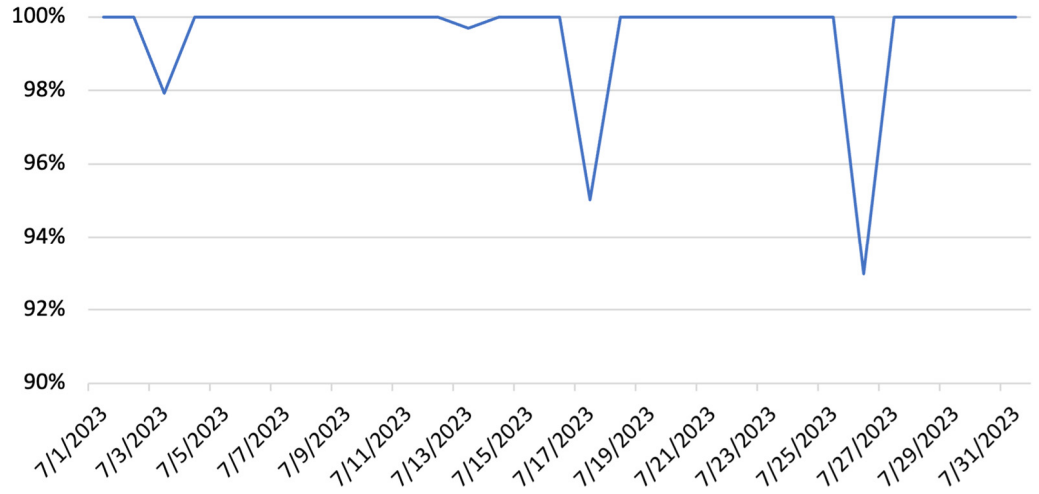


Figure 22. SoC profile for an HBESS—July 2023.

In early August 2023 (Figure 23), the HBESS charge level fluctuated between 60% and 100%. These fluctuations were caused by high external temperatures, which significantly increased the energy demand for air conditioning to maintain internal temperature within the specified range. During the second half of the month, the HBESS charge level remained near 100%, indicating that energy generation from RESs was sufficient to meet the e-Houseboat's energy demands, with surplus energy used to recharge the HBESS.

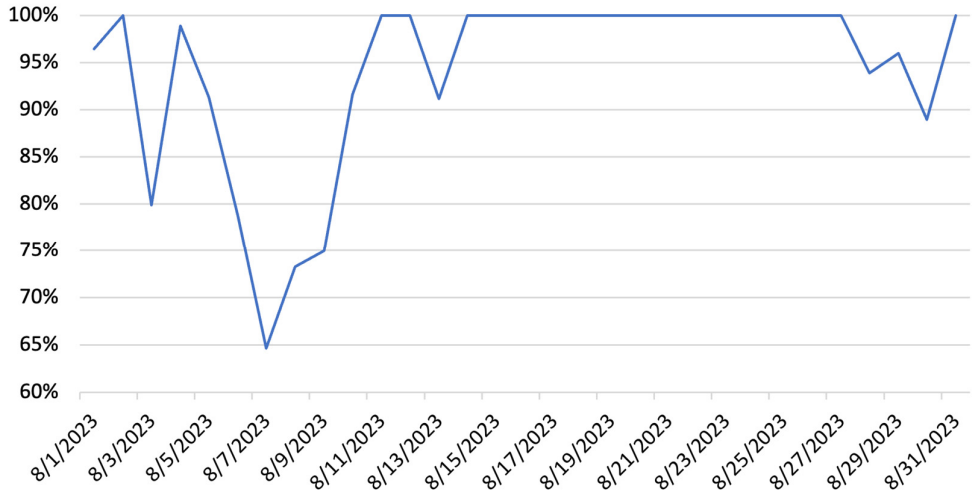


Figure 23. SoC profile for an HBESS—August 2023.

Table 4 presents the monthly parameters that define the maximum charge level, the minimum charge level, the number of days with the battery charged to 100%, the number of days with the battery charged below 20%, and the number of recharges from an external source. Throughout the analyzed period, the 100% charge level was achieved in each month, except for November. In December and January, external recharging was necessary as the battery reached a critical voltage level. During the summer months (May to August), the number of days with the battery charged to 100% exceeded half of the month.

Table 4. Annual analysis of battery charge parameters recorded each month.

Month	Max Charge Level (%)	Min Charge Level (%)	Days at 100% Charge	Days at Less than 20% Charge	Number of Charge Cycles
Sep-22	100.0%	63%	14	0	0
Oct-22	100.0%	65%	13	0	0
Nov-22	99.6%	7%	0	6	0
Dec-22	100.0%	1%	1	5	1
Jan-23	100.0%	2%	1	5	1
Feb-23	100.0%	53%	5	0	0
Mar-23	100.0%	32%	9	0	0
Apr-23	100.0%	66%	13	0	0
May-23	100.0%	75%	20	0	0
Jun-23	100.0%	91%	28	0	0
Jul-23	100.0%	93%	27	0	0
Aug-23	100.0%	65%	18	0	0

The HBESS was designed to use LFP batteries as the primary power source, with lead-acid batteries serving only as an additional energy buffer. During the test period, the system underwent more than 50 recharge cycles from various charge levels, not always reaching 100% capacity. However, because of their specific role in the system, the lead-acid batteries completed only a few full charge–discharge cycles, operating with minimal current loads. To ensure safe and efficient operation, an automated control system continuously monitored key parameters of the HBESS, preventing excessively deep discharges, maintaining safe current levels, and keeping temperatures within optimal ranges.

The estimated lifespan of the lead-acid cells is approximately 1000 charge cycles, while LFP cells are rated for around 5000 cycles, and the overall HBESS system is expected to last 12–15 years. Given this long lifespan, the 12-month testing period did not reveal any measurable signs of battery degradation. A more detailed analysis of aging effects would require extended testing over multiple years.

In its original configuration, the houseboat's energy system relied on 11.5 kWh battery storage, which required daily charging, resulting in an annual energy cost of 2519 EUR

(at a price of 0.6 EUR/kWh). Additionally, the propulsion system consisted of two 10 kW internal combustion engines, which consumed a total of 2000 L of fuel per year. At a fuel price of 1.8 EUR per liter, the annual fuel cost amounted to 3600 EUR. Therefore, the total annual operational cost of the initial system was 6119 EUR, while its environmental impact was significant, with annual CO_2 emissions of 4600 kg.

The initial system infrastructure cost was structured as follows:

- Battery storage (11.5 kWh)—2000 EUR;
- PV panels, inverters, and internal combustion engines (2 × 10 kW)—8000 EUR;

Total initial investment cost: 10,000 EUR.

To improve operational efficiency, reduce environmental impact, and lower running costs, a modern HBESS of 90 kWh was implemented, supplemented by additional photovoltaic infrastructure, inverters, an electric propulsion system, and an EMS. In this new configuration, fuel costs were completely eliminated, and external energy charging was required only twice a year, with each charging session consuming 90 kWh. At an electricity rate of 0.6 EUR/kWh, this resulted in an annual energy cost of only 108 EUR.

The investment cost for the new system included the following:

- HBESS battery storage (90 kWh)—25,000 EUR;
- Additional PV panels, inverters, electric propulsion system, EMS—25,000 EUR;

Total investment cost: 50,000 EUR.

The transition to the HBESS system generates annual operational savings of 6119 EUR (ROI 12.24%), resulting from the elimination of fuel costs and the significantly lower energy consumption. Given these savings, the estimated payback period for the investment is approximately 8.17 years, ensuring that the system pays for itself well within its expected 12 to 15-year lifespan.

Beyond measurable financial savings, the implementation of HBESS significantly improves the mobility and operational autonomy of the vessel by eliminating the need for daily charging and frequent returns to port. This improvement allows the boat to remain on the water for extended periods, allowing longer rental durations and greater flexibility in voyage planning, which in turn increases potential revenue. In the charter industry, extended rental periods are typically associated with higher pricing, directly influencing profitability. Moreover, the shift to an electric propulsion system eliminates engine noise and vibrations, enhancing passenger comfort and making the vessel more attractive in the premium rental market.

Additionally, the maintenance costs for an electric propulsion system are considerably lower than those of internal combustion engines, which require frequent oil changes, filter replacements, and mechanical maintenance. Over time, this reduction in maintenance expenses further supports the financial viability of the investment. Furthermore, annual CO_2 emissions have been eliminated, reducing the boat's environmental footprint by 4600 kg per year. This environmental advantage not only contributes to sustainability goals, but could also provide financial benefits in the future due to evolving regulations on low-emission maritime transport.

Summing up the modernization of the boat's energy system through the implementation of HBESS, combined with an electric propulsion system and EMS, represents a strategic investment that not only eliminates fuel costs and reduces annual operating expenses by more than 6119 EUR but also significantly improves the market value and rental potential of the vessel. While the nominal payback period is 8.17 years, the true economic return may be even shorter, given the added value of increased rental flexibility, premium pricing potential, and lower maintenance costs. Consequently, the implementation of HBESS is

not only a step toward a more sustainable maritime operation, but also a financially sound investment that enhances long-term profitability and competitiveness.

6. Conclusions

A prototype e-Houseboat was constructed for the purposes of this research study, equipped with its own RESs and HBESS. A dedicated EMS was developed and then implemented as part of a customized automation system for the e-Houseboat. It provides comprehensive control over the flow and distribution of various forms of energy within the object. Additionally, a user interface was developed to allow the efficient monitoring of the operation of individual appliances and maintain thermal comfort.

Long-term energy autonomy tests were executed on the prototype. The tests were initiated with the HBESS in a fully charged state and the external power sources disconnected. The results confirmed that the e-Houseboat could sustain energy autonomy for a minimum of one month, regardless of weather conditions or season. During the spring, summer, and early autumn, the RES installation reliably met the e-Houseboat's energy demands, with surplus energy stored in the HBESS to ensure energy autonomy during periods of reduced RES generation. In the late autumn and winter months, the HBESS was discharged on two occasions. The intervals between these discharges exceeded 30 days and occurred in different seasons. Throughout the study, the thermal comfort conditions within the e-Houseboat were fully monitored, with temperatures remaining between 20 °C and 29 °C. The results confirmed that the project's primary assumptions and goals in achieving long-term energy autonomy and enhancing user comfort were successfully achieved. A real achievement was the result of optimizing the EMS and integrating advanced energy storage technologies. The combination of LFP and lead-acid batteries efficiently managed the variability in renewable energy generation, improving the sustainability of the system and reducing operating costs. The developed automation and control system not only optimized energy resource management but also allowed for various operational modes, increasing the e-Houseboat's flexibility. The methodology for selecting energy storage technologies is also applicable to other projects that aim to achieve energy autonomy in mobile and off-grid environments. The findings of this research have significant insights for future projects involving autonomous residential units. They can serve as a foundation for further development of sustainable energy technologies for mobile and floating units.

In the presented solution, over 70% of the energy comes from lead-acid batteries, which are widely used in various industries, including electromobility. These batteries are easier to recycle compared to other types of batteries, such as LFP batteries, which significantly facilitates their subsequent disposal. We also consider the possibility of regenerating and replacing only those cells that have lost their efficiency. This approach allows for a significant extension of the system's lifespan, reducing the need for complete battery replacement, which is more sustainable and environmentally beneficial.

Although the functional and design objectives were successfully achieved, the authors recognize the need for further research and development to improve HBESS. Future research should focus on the following areas:

- Optimizing the volume of energy storage and generation systems to match the individual usage profile of the facility based on long-term process data. This will allow empirical adjustments to energy resources to meet user needs, which is not feasible without a reference object;
- Developing predictive models (e.g., energy generation forecasts based on meteorological services and/or on-board environmental parameters monitoring stations) to accurately estimate future energy generation levels. This will improve user comfort

and validate identified parameters, such as the thermodynamic model of the facility, the actual efficiency of the generation and storage systems, and usage profiles;
- Developing methods to assist users in managing and utilizing energy efficiently within the e-Houseboat using an interface designed according to User Experience (UX) and User Interface (UI) principles. This will increase user awareness and maximize the overall effectiveness of the EMS;
- Creating mechanisms to integrate e-Houseboat EMS with the open energy market, allowing for cost-effective energy purchases during marina stays and potentially enabling the resale of excess energy to the grid as the market evolves. This integration could support local energy network stability, balance, while aligning with smart grid principles.

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Abbreviations

The following abbreviations are used in this manuscript:

RESs	Renewable energy sources
HBESS	Hybrid battery energy storage system
HRES	Hybrid renewable energy system
BESS	Battery energy storage system
EMS	Energy management system
LFP	Lithium iron phosphate (LiFePO4)
PV	Photovoltaic
SoC	State of charge
SoH	State of health

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