

Zero-Emissions, Off-grid, Autonomous Houseboat – a Case Study of Selected Locations in Europe

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ABSTRACT

The aim of this study was to assess the feasibility of creating a prototype of a self-sufficient houseboat that is capable of prolonged independence from power grids and freshwater sources. In this design, electricity demand is met by a photovoltaic installation, and the energy is stored in batteries. Fresh water for living needs may be obtained from many sources, depending on the environmental conditions, such as through purifying outboard water, desalinating seawater, and collecting and storing rainwater. No waste production of the vessel can be achieved in two ways: waste can be treated and discharged into a body of water, or processed into fertiliser for later use in agriculture. Four possible locations were analysed: Rome, Lisbon, Gdańsk and Stockholm. The findings reveal that the length of time for which the unit is autonomous and emission-free depends on the geographical location of the facility. In periods when there is overproduction of energy, the system can produce hydrogen, donate energy to the grid, use it for the needs of its own movement, or perform other useful work, e.g. cleaning or aerating the water body on which it is floating.

Keywords: Floating house, off-grid, autonomous, zero-emission, green shipping, self-sufficient, carbon-neutral, water treatment, wastewater treatment, sustainable

INTRODUCTION

With global warming and the climate crisis, the need for sustainable approaches to design and construction is constantly growing. Buildings significantly contribute to the world's overall energy and carbon emissions, and have become a focus of strategies for sustainable growth. Technological advancements have intensified the pace of research on the energy performance of buildings, including residential ones,

in regard to aspects such as life cycle energy minimisation [1], energy flexibility [2], and the efficiency of off-grid systems [3,4]. The pressing challenges arising from population growth on a global scale have also transformed the landscape of housing solutions at the scale of whole cities, revealing that urban regulations [5], the use of advanced materials [6] and renewable energies are important steps toward creating energy efficient and even off-grid communities [7].

At the same time, growing concerns about climate change and rising sea levels are important factors that necessitate

a search for alternative ways of living on the waterfront, where land-water boundaries have altered [8] or are subject to cyclical changes to accommodate natural processes [9]. Numerous research studies have focused on planning scenarios for waterfront territories, and have identified typologies of public spaces and buildings that can resist flooding [10,11]. These studies indicate the need for flexibility and adaptability [12,13], and for immediate actions such as retrofitting of existing structures to increase their resilience [14]. One of the outcomes of this trend is a growing interest in floating architecture [15,16]. In response to predictions of global warming, the United Nations has proposed the world's first floating city design scheme, called Oceanix City [17]. Floating architecture is increasingly often regarded as an opportunity to develop new flood-resistant and carbon-neutral housing settlements on water [18].

The trend towards building on water has also undergone growth in recent years as one of the consequences of the global pandemic, which affected many aspects of life. One of the observed trends during periods of isolation was towards an "escape to nature" and physical activity away from large population centres. This brought about an even greater increase in demand for recreational and residential watercraft, and in 2020–21, yacht yards were unable to fulfil the growing number of orders. Consequently, a significant increase in the number of residential floating vessels has been observed over recent years. These may have a purely stationary nature, acting as floating houses, or may be specialised floating houses that can undergo voyages, such as British narrowboats, which are adapted to narrow inland waterways. In Eastern and Central European countries, floating houses are becoming increasingly popular, despite mounting legal problems. The available data reveal that the number of registered floating buildings in Poland grew from one in 2003 to 48 in 2017 [19].

It should also be noted that in large Asian coastal cities located in estuaries, people have been living on vessels adapted to this purpose for centuries. One such place is the city of Srinagar in Kashmir (India), where people have lived on boats on a freshwater mountain lake for a long time, despite the unfavourable mountain climate [20]. Today's floating buildings, which are located in many places in Europe and worldwide, often meet high aesthetic and functional standards, and are supported by highly effective technological solutions, and this has contributed to the relatively high initial cost of floating structures. However, technological advancements in the areas of photovoltaic systems, miniature wind power plants, and various types of batteries are having a significant impact on the development of new, more efficient and gradually cheaper technologies that are becoming widely available.

Scientists are also carefully studying the possibility of achieving energy autonomy in onshore systems operating outside the power grid. Studies have delved into strategies for reducing costs through energy efficiency optimisation [21], hybrid renewable energy operations [22], energy management [23,24], and advancements in photovoltaic technology [25]. Researchers have analysed the possibilities of effective storage

and use of electricity [26–28], and a substantial part of this research concerns offshore structures; this is due, among other factors, to the need to store significant amounts of electricity on vessels with a hybrid drive [29,30]. The problem of energy management on a vessel has been noted, and work is currently being carried out on schemes for rational energy management [31,32].

Floating architecture objects are hybrid in nature, and can therefore be analysed from different perspectives, i.e. both as buildings and as floating structures. In Europe, the Netherlands has a long tradition of the construction and mass use of floating houses, with about 2,400 floating houses in Amsterdam alone (and approximately 100,000 in the whole of the Netherlands). All of these are connected to the municipal power grid, and since 2005, there has also been an obligation to connect to the municipal sewage system.

The aim of this study, carried out as part of a wider research project, was to analyse the possibility of building a prototype vessel with a residential function (i.e. a houseboat) which would be as self-sufficient and autonomous as possible, meaning that it can remain independent for a long period without being connected to the power grid or a source of fresh water. In this paper, an autonomous, emission-free, off-grid vessel is understood as one that is disconnected from external networks, and can therefore be self-sufficient for any length of time. The term 'external networks' typically means electrical networks, but in the case of a floating object it is extended to water and sewage systems.

MAIN TECHNICAL ASSUMPTIONS AND CONSIDERATIONS

When analysing an off-grid floating building, the question of connecting it to coastal technical infrastructure (sewage, water supply, and electricity networks) may appear to be irrelevant; it should be noted, however, that this issue can be interpreted in different ways depending on the technical and legal definitions of terms such as off-grid, autonomy, floating building or connection, which are often specific to particular countries (Table 1).

To meet the electricity demand of the vessel, the possibility of using fuels even periodically supplied from outside (diesel, gas, wood, etc.) was excluded. It was assumed that the floating object would generate the electricity necessary for the operation of devices (e.g. a heat pump operating in the heating system) only through photovoltaics, and would store this energy.

The problem of water and sewage systems must be considered separately. Despite the technical possibility of introducing full recirculation of domestic water, as used in space bases, for example, it is unlikely that such expensive solutions will be used in a residential or recreational facility. It is therefore assumed that even with partial recirculation, it will be necessary to obtain water from outside the vessel and to discharge wastewater outside the vessel, unless a full-circulation sewage treatment system is installed. In order

Tab. 1. Formal requirements in Poland for the consumption of electricity and water and the production of wastewater in an “off-grid” or “zero-energy” facility, depending on the legal definition of the facility (source: current authors)

	Off-grid ship or stationary house boat		“Zero energy” ship or stationary house boat
	Floating stationary home (house boat)	Ship	
Electrical installation	No requirements		Notification of construction works needed for the construction of the grid connection, two-way meter and agreement with the grid operator
Water installation	No requirements for intake and discharge up to 5 m ³ /day; Water law permit from 5m ³ /day	No requirements	Notification of construction works needed for the construction of connections
Sewage installation		Prohibition on the discharge of untreated sewage, need for a high degree of treatment	

not to violate the principle of zero emissions, this exchange must take place within the immediate environment, with no connection to external infrastructure. In terms of water acquisition, the most interesting avenue seems to be the use of outboard water after purification (which can be supplemented by collecting rainwater). After using the water for sanitary or other household purposes, the generated wastewater should be treated to a degree that would allow it to be pumped overboard without harming the environment and users of the facility. This would involve a number of legal issues that are specific to local conditions both in different countries (national regulations) and in different berths (local regulations, e.g. port regulations).

For example, in Poland, an analysis of the legal situation depends on the adoption of the definition of a ‘non-emission’ and ‘off-grid’ facility. If we consider such a floating facility to be a structure that must meet the requirements of the Construction Law [33] and the Water Law [34], the user will be exempt from the obligation to obtain a legal water permit only if the amount of surface (outboard) water taken on and the amount of sewage discharged overboard (after treatment in the treatment plant) will not exceed 5 m³ per day on an average annual basis. This condition does not apply if we consider the object to be a watercraft, whether a stationary object [35] or a houseboat [36,20]. In this interpretation, the withdrawal of water is not limited by regulations, while the possibility of discharging sewage overboard depends on the degree of its treatment. In principle, according to local and port regulations, domestic sewage cannot be discharged into inland and port waters, and must be discharged ashore, which would limit the full autonomy of the boat. Hence, to ensure a fully off-grid autonomous facility, it would be necessary to clean this water to a high degree, to make it analogous to cooling water, which is commonly pumped overboard. Similar considerations apply to each berth of the off-grid facility, based on national and local building and ship regulations.

An autonomous facility is often understood in the literature as a net-zero energy facility, i.e. a facility that produces at least as much energy as it consumes, which is assessed and balanced over a specific, relatively long period, usually one year [37]. In this case, the building does not need to store energy, as it is

permanently connected to an external electricity grid to which it can send a surplus and from which it can draw electricity when consumption exceeds production. For a building that is permanently connected to the network, the difference between an architectural object built on land or a water vessel is not crucial. In both cases, the connection installation will consist of two parts: a land-based part, running through the quay from the external network to the two-way meter, which formally acts as the connection, and a surface-based part, running above or below the water from the meter to the facility. This is a situation analogous to a ship (boat) berthed in a port (marina).

Regardless of the definition of a floating object that is adopted, Polish legislation requires that for the installation of connections on land, notification must be made of the intention to carry out construction works, or a legal water permit and a building permit must be obtained in the case of simultaneous construction of coastal infrastructure. In both cases, it is necessary to conclude an appropriate contract with the power grid operator. For the water and sewage system, sanitary safety issues do not allow for the construction of two-way connections. Such a facility will be connected to external networks in a traditional way: it will draw water from the water supply on the quay and pump sewage to the local sewage system, although retention and recirculation solutions may reduce the load on the connections and external network. In both cases, the formal issues of connection construction are analogous to those of electrical installation. When locating a zero-energy facility in other countries, these aspects should be reconsidered in terms of their differences in legal status; for example, in the Netherlands, a stationary facility must have a mooring permit (known as a *ligplaats*) and discharge sewage to the municipal sewage system.

The aim of the research undertaken here was to carry out an analysis, taking the proposed watercraft as an example, of the possibility of achieving net zero energy and off-grid autonomy at four selected locations in Europe. We assumed that it would be possible to easily change the location of the floating house using its own power, especially in the summer season, when it was expected that there would be significant overproduction of electricity from the photovoltaic

installation. It was also assumed that the excess energy could be used in other ways, such as for hydrogen production or purification of the water in which the object is moored.

METHODS

Our approach to designing an autonomous houseboat was based on a model simulation of a fully self-sufficient object. The autonomous houseboat project, as a combination of the concepts of an autonomous house and an object placed on the water, is subject to the requirements of both of these concepts. Hence, for research purposes, general assumptions were made regarding the climate and location of the facility, the number of users, and the boundary dimensions of the facility (Fig. 1).

both the maximum steerability of the vessel and a relatively comfortable usable area, i.e. about 40 m² of living space. The available usable space limits the number of permanent users to four people. To explore the design possibilities for the autonomous houseboat, analyses and simulations of the technical systems required to support the houseboat were carried out while analysing the available hulls, both in terms of their stability and the possibility of placing the necessary technological systems. As part of the study, calculations and simulations were performed for three basic hull shapes: denoted here as ship, cuboid, and cat (catamaran). These calculations were supported by choosing suitable parameters to implement water supply systems, sewage disposal and collection, rainwater management, electricity supply, heating, utility water heating, and the ventilation and air conditioning of rooms. Based on the outcomes of modelling

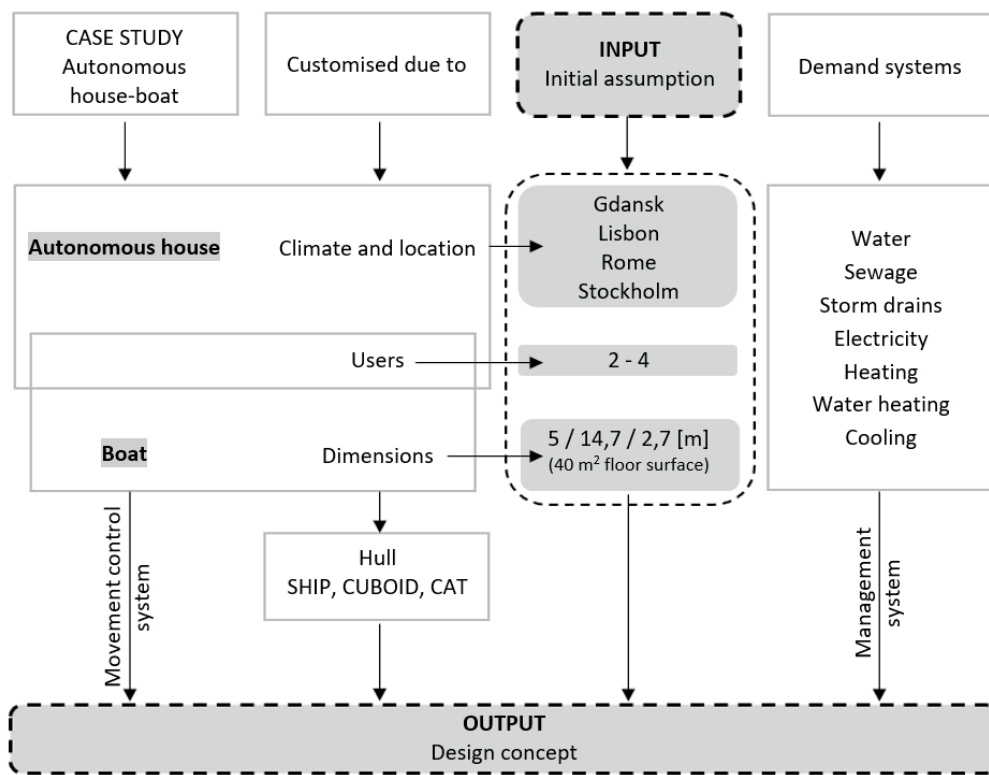


Fig. 1. Process flow diagram: from the initial assumptions for the case study to the design concept

Four cities (in alphabetical order: Gdansk, Lisbon, Rome and Stockholm) were chosen as possible locations. These cities were previously selected as living labs in the H2020 SOS Climate Waterfront program realised in 2019–2023. Their locations in different parts of Europe provide opportunities to consider the self-sufficiency of a facility under widely differing geographical and climatic conditions. Due to constraints arising from locations within the selected areas, often in the vicinity of the city centre and at post-industrial quays, the following boundary dimensions of the facility were adopted: width 5 m, length 14.7 m, and height up to 2.7 m above the water surface. These dimensions ensure

and simulation with the above parameters, a design concept of an autonomous houseboat was developed, as presented in the next section.

CASE STUDY DESCRIPTION AND DESIGN GUIDELINES

DESIGN GUIDELINES FOR A HOUSEBOAT

It was assumed in this study that the floating house should accommodate two to four people. Detailed data are presented in Tables 2 and 3 below.

Tab. 2. Assumptions for living conditions

No.	Parameter	Description
1	Number of users: two (comfortable) to four (maximum)	Two bedrooms, each sleeping two people
2	Usable area: 36–40m ² Volume: 90 m ³	Area suitable for the number of users
3	Location: Gdańsk, Poland Lisbon, Portugal Rome, Italy Stockholm, Sweden	Four different locations in different climate zones

GUIDELINES FOR USERS

It was assumed that the residents would be aware of the problems of energy and waste management, would accept the challenge of living in an emission-free, autonomous house, would be ready for the challenges arising from restrictions on the consumption of water and electricity, and would accept a room temperature in the range 19°C (winter) to 25°C (summer).

GUIDELINES FOR HULL DESIGN

Three versions of the hulls were proposed (Fig. 2) representing the three main types currently used for residential units. They all had the same maximum overall dimensions, but differed in terms of their shape and topology, and thus in their buoyancy, stability and dynamic characteristics. Version A (“ship”) was based on a ship’s hull, and was intended for a version of the unit that would move during its life cycle. Version B (“cuboid”), took the form of a rectangular float, which is often found in solutions of stationary floating objects (SFOs). Version C (“cat”) was based on a catamaran-type hull, a popular choice for light mobile objects (Table 3, Fig. 2).

Tab. 3. Main parameters of the hull of the floating object

Characteristic	Symbol	Value
Float and superstructure length	L [m]	14.7
Breadth	B (b) [m]	5.0 (1.25)
Depth	D [m]	1.5
Superstructure height	H [m]	2.7
Draft	T [m]	0.5
Vertical centre of gravity	VCG [m]	2.25

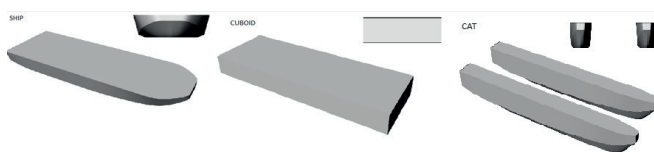


Fig. 2. Diagram showing hull variants: (a) single-hull version with small draft; (b) cuboid (stationary); (c) catamaran (low resistance but greater draft)

GUIDELINES FOR WATER, STORMWATER AND WASTEWATER SYSTEMS

The design of the water and sewage system should involve the construction of a minimum volume of tanks and the maximum use of water, including reuse, and should be divided into rainwater, greywater and blackwater. It is also possible to build an external tank that does not burden the boat’s structure and does not take up space on the boat, as an outboard tank. It is recommended to use natural water treatment systems, such as green walls and floating treatment wetlands (FTWs). Guidelines for FTW design are summarised in Table 4.

Tab. 4. Specific design parameters that should be taken into account in the starting phase of a floating treatment wetland

Parameter	Solution	References
Techniques and materials for constructing floating rafts	<u>Artificial materials:</u> polyethylene (PE), polypropylene (PP), polyurethane (PU) or polyvinyl alcohol foam (PVA), polyurethane foam, thermos-fused high-density polyethylene (PE), cork & polyurethane paste (PU), Polyurethane foam (PU), Recycled polyethylenterephthalate (PET), High density polyethylene (HDPE), polyethylenterephthalate (PET) <u>Natural materials:</u> bamboo, wood & cork Remarks: – Floating rafts should be anchored to prevent excessive drift – The anchoring should be adjusted to accommodate the changing position of the tank’s post-treatment wastewater (WW) mirror	Karstens et al. (2021) [38]
Water depth	General remarks: – The minimum depth of WW should be greater than the expected depth at which most plant roots develop (maximum root depths for emergent wetland vegetation range from 57 to 87 cm) – The maximum water depth is related to the purification efficiency, since if the design water depth exceeds the depth of the hanging root-mat, then a certain portion of the flow will bypass beneath the root-zone with limited exposure to treatment	Tanner and Headley (2011) [39]

Parameter	Solution	References
Coverage ratio	Coverage varies greatly from less than 10% to 100%; recommended range is 5–45% for lakes, ponds, and reservoirs Remarks: – Coverage over 50% may prevent atmospheric reoxygenation and result in lower dissolved oxygen (DO) concentrations in water – The shadow provided by the floating bed may be beneficial in preventing the overgrowth of phytoplankton algae	Shen et al. (2021) [40]
Planting media	Plants that are established on floating rafts without growth media are forced to take up nutrients and other elements directly from the water-column, which results in better performance. A planting substrate may be required in some cases to establish plants on a floating raft. Lightweight, low-nutrient media that do not impose a high oxygen demand when saturated with water and provide a good substrate for root development are preferred. Materials such as coarse peat, coconut fibre, pumice, perlite, soil, bamboo charcoal, sand, compost, and peat moss are suitable choices.	Pavlineri et al. (2017) [41]
Plant species	Selection criteria for plant species: native and non-invasive species, perennial plants, terrestrial plant species, wetland plants or plants with the ability to thrive in a hydroponic environment, plants with aerenchyma tissue <u>Emergent macrophyte species:</u> <i>Iris pseudacorus</i> , <i>Typha latifolia</i> , <i>Carex acutiformis</i> , <i>Acorus calamus</i> , <i>Phragmites australis</i> , <i>Glyceria maxima</i> <u>Free-floating species:</u> <i>Pistia stratiotes</i> , <i>Common water hyacinth</i> , <i>Salvinia</i> , <i>Salvinia molesta</i> , <i>Limnobium</i>	Wang et al. (2014) [42]
Hydraulic design	Consideration should be given to the dimensions of the system (length, width, and depth), which should be adapted to achieve the desired effects. Individual floating units must be configured with the goal of minimising the risk of short-circuiting paths and dead-zones, and maximising the interaction between water and hanging root-mats. Transverse bands of floating mats with complete connectivity from one side of the basin to the other and oriented perpendicular to the flow direction are preferred if possible.	Pavlineri et al. (2017) [41]

ONBOARD CONSTRUCTION SAFETY AND SECURITY

The factors taken into consideration during the design phase were the draft, the displacement, the shape of the upper part, and the height of the vertical location of the centre of mass of the entire structure (VCG). Three hulls, referred to here as ship, cuboid, and cat, were checked in terms of their stability and safety. Initially, we assumed the location of the VCG as 0.75 m above the deck, based on current regulations [43].

RESULTS

ARCHITECTURAL SOLUTIONS

A floating building with an approximate usable floor area of 40 m² was proposed, which was functionally aligned with the standards for floating architecture [44]. Within this space, in addition to the living room, kitchenette, and bathroom, there are two comfortable double bedrooms equipped with the necessary storage space. In addition, the roof of the building can be used as a second deck, and provides space for relaxation and observation of the area. The main floor is located above the water surface. High panoramic windows provide adequate illumination of the interior and also allow for an unobstructed view of the surrounding, which increases the comfort of users [45].

The use of lightweight and durable materials with high thermal insulation parameters, the production and disposal of which has the lowest possible negative impact on the environment, is a key factor influencing the environmental impact over the life of the facility [1,46,47]. The possibility of controlling the unit from different places via a mobile control console was also taken into account. This makes it possible, for example, to limit the height of the vessel by temporarily or completely dismantling the wheelhouse on the roof. At the development stage of the architectural design, we assumed that the unit would be equipped with a significant number of photovoltaic panels, which form the main source of electricity, and a system for collecting rainwater. Green walls are inserted along the side facades and a wetland module is integrated into the form of the floating object to enable the introduction of nature-based solutions for water treatment and to facilitate relaxation.



Fig. 3. Image of the proposed houseboat: version with a mono-hull adapted for travel



Fig. 4. Image of the proposed houseboat: view of PV roof and wall panels, green walls and an ecological floating treatment wetland

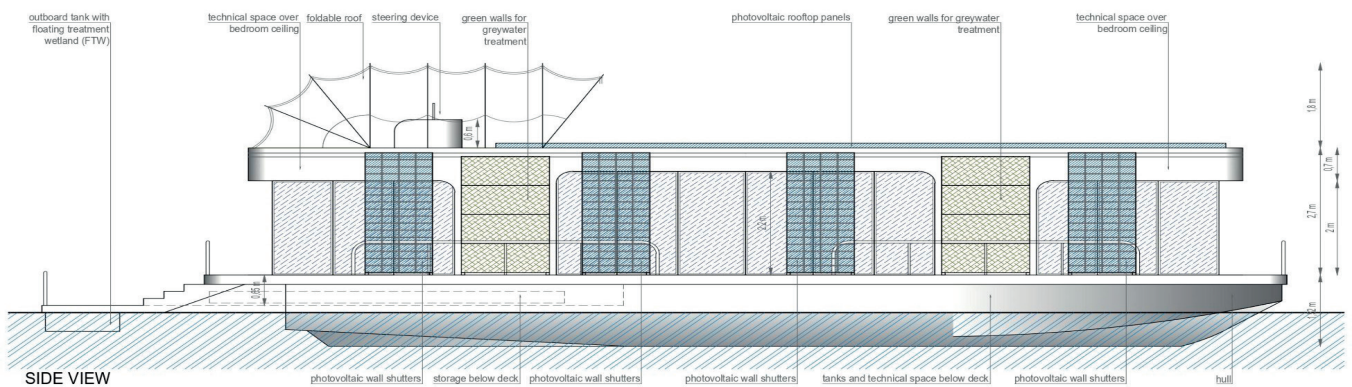


Fig. 5. Side view: technical diagram with description

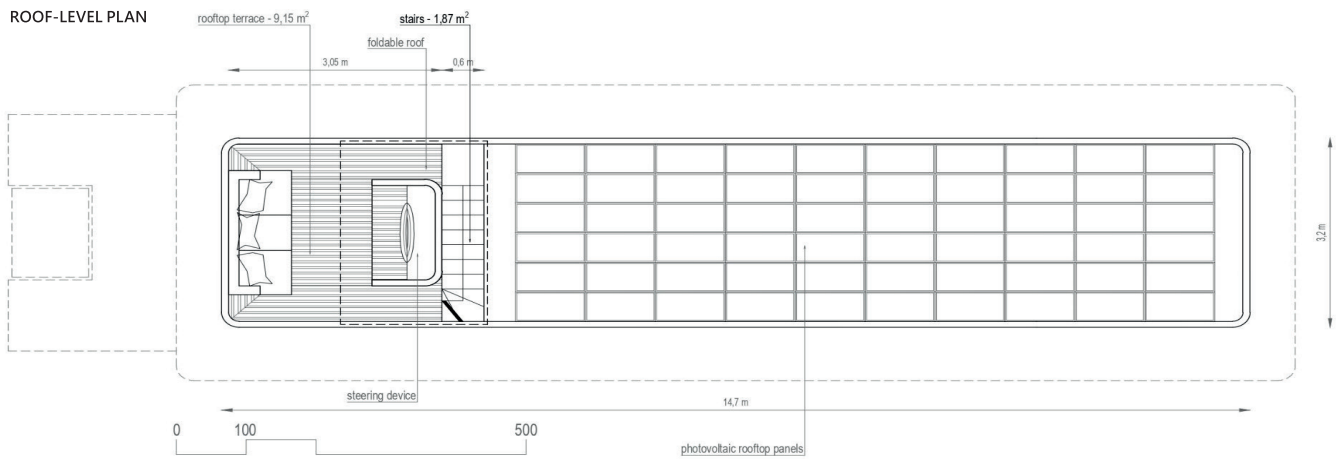


Fig. 6. Roof-level plan: technical diagram with description

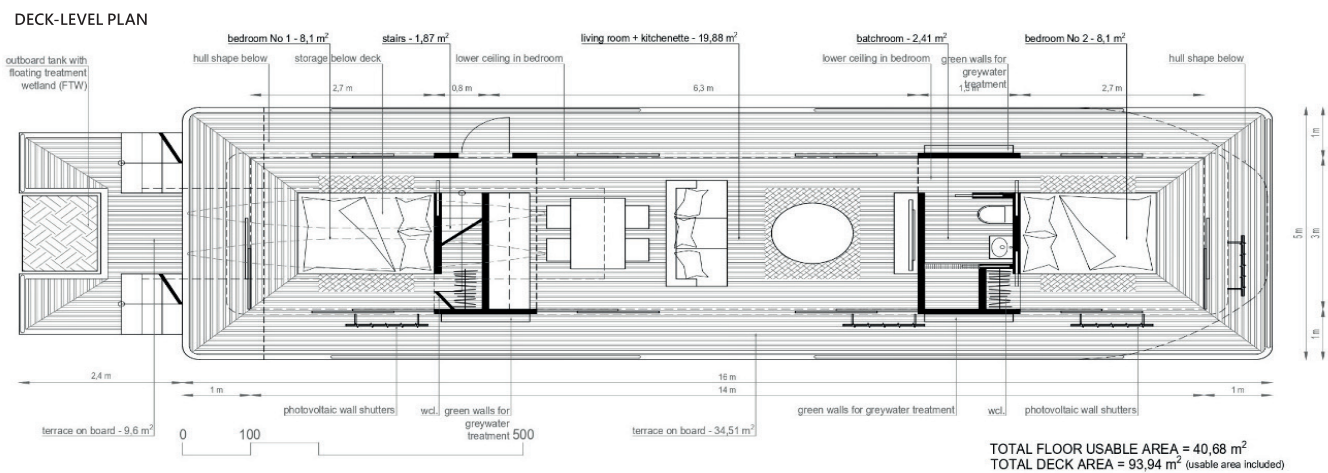


Fig. 7. Deck-level plan: technical diagram with description.

HULL AND SAFETY ON BOARD

One of the most important design problems for floating architectural objects is stability. The stability determines the usability of a floating house as a residential unit, regardless of whether it is autonomous or not. Insufficient stability, or a loss of stability, may lead to flooding of the vessel, damage to its elements as a result of excessive tilting, or even overturning.

In the area of floating architecture, this issue is particularly important, since these vessels are available to users with no training or experience. Under the current regulations, a quantitative description of stability [48], which is a measure of safety, is understood as:

- the angle of heel due to wind and crew,
- the freeboard margin that should be maintained when the object is in an upright position, and
- the freeboard margin that should be maintained when the object is heeling [48,49].

The main premise is that flooding of the deck, which can be treated as the floor of a living space, is not allowed.

As a result, we can apply a certain simplification, and the basic value tested in the design process is an initial metacentric height. The theoretical basis for this approach was described in [49,50].

The hydrostatic and stability properties were considered over a range of displacement from about 8t (corresponding to the empty hull weight) to above 37t (loaded) for a vessel with a draft of 0.5 m. This range was chosen to represent both the extreme shapes and weights, and the extremes in the vessel's operating conditions, from the lightest to the heaviest scenarios. These values could be refined to a narrower range depending on the specific project. Here, we provide generalised values that apply to a wide variety of solutions. The individual variants differ significantly both in terms of the available displacement (Fig. 8) and the initial stability properties, represented by the initial metacentric height (Fig. 9). An increased volume of the float and a cuboid shape correspond to a lower metacentric height (GM - a measurement of the initial static stability of a floating body).

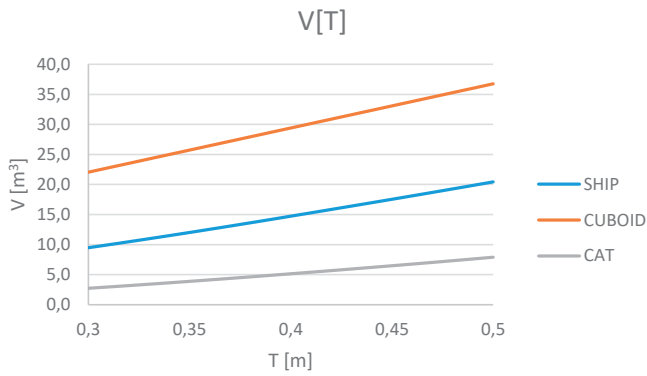


Fig. 8. Displacement vs draft

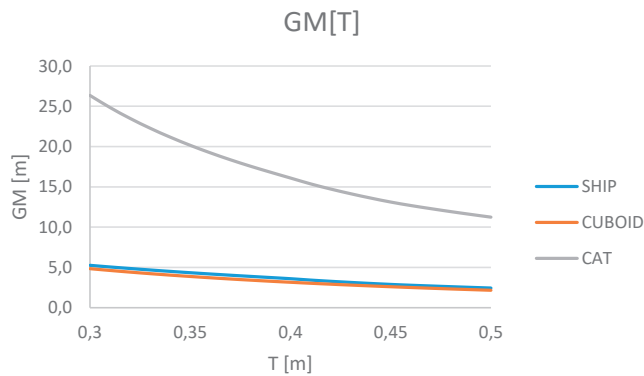


Fig. 9. Initial metacentric height vs draft

Loads that cause dangerous situations for a floating house result from the movements of residents inside the building and the impact of the wind on the above-water part. The values of the heel angles were checked for the three versions of the hull and for the proposed architecture of the living areas (Table 5).

Tab. 5. Stability properties

Wind area	55.1	m ²	
Heeling arm	2.6	m	
Wind pressure	250	Pa	
Wind moment	35.8	kNm	
Crew	4	person	
Weight	0.3	t	
Shifting arm	2.5	m	
Crew moment	7.35	kNm	
Total heeling moment	43.2	kNm	
	RM_SHIP	RM_CUBOID	RM_CAT
T [m]	0.50	0.50	0.5
DISPL [t]	20.4	36.8	7.9
GM [m]	2.44	2.17	11.24
fiwind [°]	4.18	2.63	2.36
fiCL [°]	0.86	0.54	0.48
fitotal [°]	5.04	3.16	2.84

The hull variants meet the safety criteria established by the regulations [36] (Fig. 10).

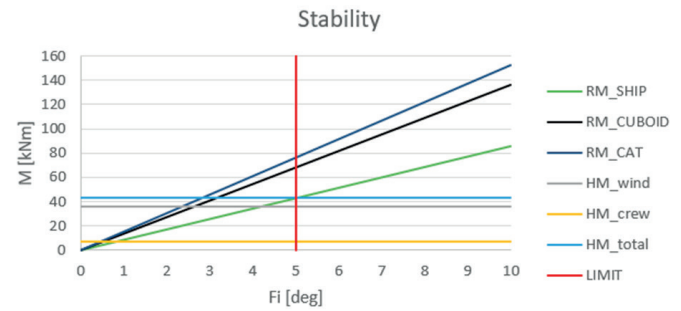


Fig. 10. Stability curves

Each solution is characterised by different volume, mass and stability properties, which are closely related to each other. For example, CAT has the best stability properties, but the smallest available displacement, and not every hull-material solution will be acceptable for such a hull. The limit may be the average accepted level of comfort (maximum heel angle) or another operational factor. In addition to stability, the operational properties should be taken into account, such as the purpose of the vessel and its location, when selecting a type of hull.

The following properties of the float should be taken into account in the design process:

- **Displacement:** This ensures adequate buoyancy in the design draft (the conditions of the location often limit the draft).
- **Capacity:** This is the available usable volume in the hull; autonomous systems require sufficient volume for batteries, tanks, and treatment plants.
- **Stability:** This is the resistance to the external heeling moment.
- **Manoeuvrability:** This relates to operability over a range of small changes in localisation, and requires the possibility of mounting steering devices, such as a conventional rudder, a bow thruster, and outboard engines.
- **Mass:** This is the weight of the float structure, where the smaller the area of the shell, the lower its weight, the larger the area of the flat areas, and the greater the number of stiffeners required.
- **Mobility:** This refers to the ability to change the location of the vessel, both in terms of sailing it and the possibility of mounting the drive and the steering system.

The results of our survey of the usability properties for the three hulls are shown in Table 6 and visualised as a polar diagram in Fig. 11. Depending on the relative importance of the various design assumptions and constraints, the vessel may take different final forms; the final design always represents a compromise.

Tab. 6. Usability properties

HULL	Displacement	Capacity	Stability	Manoeuvrability	Mass	Mobility
SHIP	2	2	3	1	2	1
CUBOID	1	1	2	3	3	3
CAT	3	3	1	2	1	2

1 - good 2 - moderate 3 - weak

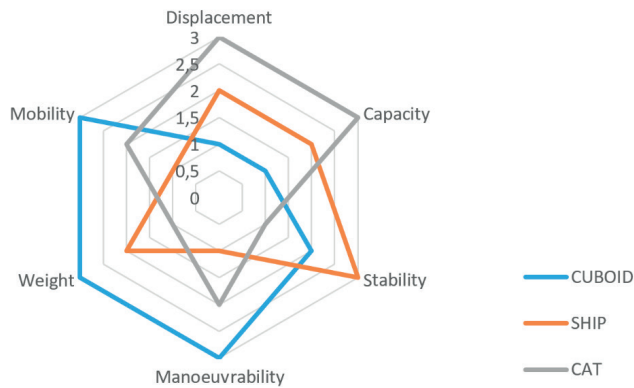


Fig. 11. Usability aspects of the three hull variants

ENERGY PRODUCTION, STORAGE AND DEMAND UNDER VARIOUS ENVIRONMENTAL CONDITIONS

New technologies enable the increasingly effective production of green energy, and its efficient storage and consumption. In particular, energy-efficient, lightweight and durable photovoltaic panels and lithium batteries are now available. These can be supported with ICT and automation systems to ensure a high level of reliability and safety, with limited losses associated with the conversion of energy between direct current (batteries) and alternating current (energy receivers). The aim of the entire complex system of generating, storing and receiving energy is to provide the residents with an appropriate level of comfort. One of the main problems involves ensuring adequate thermal and sanitary comfort. Due to cultural differences or individual characteristics and needs, the requirements of those using a floating house may vary. Nevertheless, it is important to note that achieving full autonomy for the facility may necessitate residents to make certain adjustments and alter their habits, particularly in regard to room temperatures and the use of very hot water for sanitary purposes. Hence, the location of the facility becomes crucial for climatic considerations.

Environmental conditions

The selected locations have very different climatic conditions (Fig. 12), and it was anticipated that the systems required by the unit would differ in the various areas of operation.

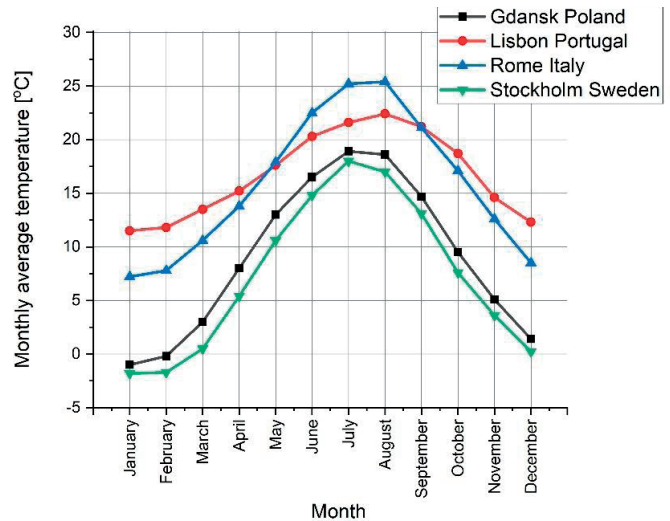


Fig. 12. Monthly average temperature [https://weather-and-climate.com]

Energy generation, storage and consumption

The proposed energy system has a modular structure (Fig. 13), meaning that it can be easily configured based on the needs and financial capabilities of the ship-owner. It is important that the facility is designed to last for at least 30 years; after this period, the need to renovate the residential area and installations must be taken into account. Hull repairs will consist of removing the paint coating and applying a new one, as in the case of ship hulls, which should take place approximately every 10 years. The proposed modular structure with a main DC bus as the axis is a typical solution. It is worth noting that rapid progress in electronics may cause the ship-owner to seriously consider significant changes to the energy system after only a few years of operation.

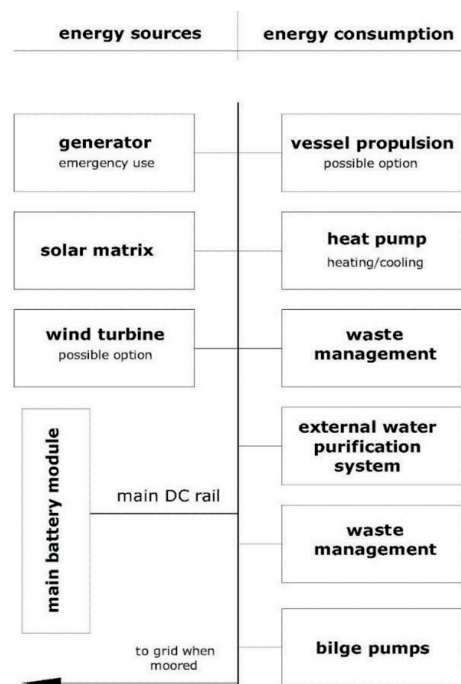


Fig. 13. Energy distribution in the proposed houseboat

Electrical energy sources

When designing the energy system, classic silicon photovoltaic panels with parameters typical of devices available on the market were used (Table 7). When arranging the array of panels on the vessel, it was assumed (Table 8) that the panels on the roof would be installed horizontally, without the possibility of changing the angle of their position. In addition, it was assumed that one of the vertical walls of the facility would be covered with panels that could provide an additional source of energy, especially if the vessel is optimally moored in relation to insolation. The calculations made it possible to estimate the amount of energy that the entire energy system could generate (Fig. 14). It was found that two pairs of locations (Gdańsk and Stockholm, and Rome and Lisbon) allowed for the generation of similar amounts of energy. This is due to the different climatic zones, with differences in insolation potential and other thermal properties (Fig. 14).

Tab. 7. Solar panel data sheet – Monocrystalline/N-type

	Parameter	
1	Size [mm] (L × W × H)	1700 × 1016 × 40
2	Weight [kg]	18.5
3	Maximum power [kWp]	350

Tab. 8. Solar array data based on solar panels currently available on the market

Roof array – flat surface with rain water draining system below		
Array size data:	Size: 10.2 x 5 m	Total power: 18.9 kWp
Array slope 0°	9 × 6 panels	
Side array – flat vertical surface – assumed surface		
Array size data:	Size: 3 × 5.1 m	Total power: 3.1 kWp
Array slope 90°	3 × 3 panels	

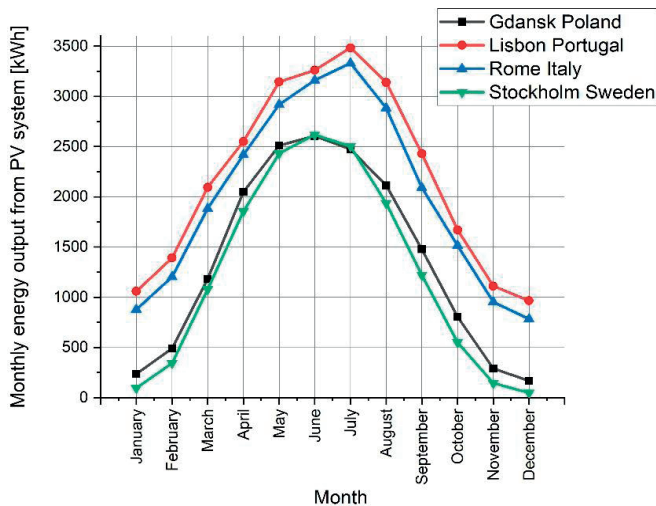


Fig. 14. Monthly energy output from a flat PV system at a fixed angle [https://re.jrc.ec.europa.eu]

Heating and air conditioning systems, energy balance

Calculations of the energy balance were based on the assumed average demand for electricity for a family or crew of four. It was also assumed that the devices installed on the vessel were characterised by low energy consumption. The

greatest demand for energy occurs in the winter months, and the main energy recipient is the heating system. Calculations of energy consumption were carried out for the simplest, cheapest and most energy-intensive heating system based on resistance heat sources. The results for such a system are very promising (Table 9, Fig. 15), and reveal a generally positive monthly energy balance with the exceptions of the months of January and February, which are problematic for the two northern locations with a harsher climate.

Tab. 9. Average monthly energy balance [kWh] [https://re.jrc.ec.europa.eu]

	Gdansk Poland	Lisbon Portugal	Rome Italy	Stockholm Sweden
January	-0.906	1240.044	968.7892	-181.535
February	308.7228	1576.155	1299.011	131.1688
March	1143.238	2310.116	2037.712	1023.648
April	2152.418	2730.077	2589.227	1911.124
May	2665.598	3323.964	3117.074	2566.712
June	2797.224	3423	3344	2803.263
July	2708.11	3664	3533	2747.778
August	2366	3383	3136	2162.742
September	1673.559	2758.85	2398.85	1368.302
October	865.972	1985.703	1795.446	537.6036
November	170.0136	1362.928	1120.784	-24.5404
December	-37.0196	932.3328	893.936	-210.463

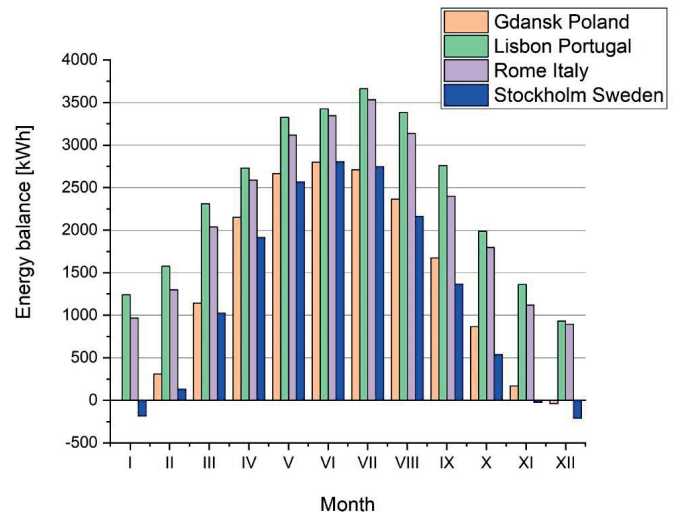


Fig. 15. Average monthly energy balance [kWh]

WATER SUPPLY AND SEWAGE SYSTEM

To implement the design guidelines, a system was designed consisting of seven tanks and four water and sewage installations.

The first installation is a drinking water system. Tank 1 stores water of sufficient quality for drinking, which is

intended for direct consumption, cooking, washing dishes and showering. Although the use of treated rainwater for showering was initially considered, it was decided to use drinking water for sanitary reasons, possible allergies and accidental water consumption. The second system is the greywater installation, which is designed to collect water after a shower, treat it and reuse it for flushing the toilet. When there is no more treated greywater, the tank is replenished from a third system, which is used to collect rainwater from the deck (Tank 6) and from Tank 5 for cleaning the deck and flushing the toilet. The fourth installation is used to discharge excess treated greywater and rainwater to an outboard treatment tank for these waters (Tank 7). From there, Tank 5 (and, indirectly, Tank 4) are refilled. A diagram showing the installation scheme is shown in Figure 16.

for cooking was 0.5 L, and the water required for washing dishes was 1 L per person per day, giving a total consumption of 3.5 L of drinking-quality water per person per day. The production of grey waste water from showering and hand washing was 5 L per person per day, and flushing the toilet required 1 L per person per day. This level demand resulted in the production of greywater in the amount of 5 L per day per person. Blackwater production includes not only wastewater from the toilet, but also from washing dishes. This is due to the significant amount of contaminants (food residues, fats) that are difficult to clean using a simple system. Calculations of the water demand for a four-man crew are presented in Table 10. We also present the results of a simulation of a 14-day voyage without the possibility of water intake from the water supply network and discharge of sewage in the port.

The last column of Table 10 shows the selection of tanks (tank volumes adapted to available commercial products). Tank 1 would be filled in port before departure, without adding water during the cruise. Tank 2 would be filled during the voyage and emptied at the port after the voyage. Tank 3 contains a daily volume of greywater production. Tank 4 is used for collecting treated greywater (20% loss for treatment processes), excess for treatment in the outboard tank 7 with floating treatment wetland (FTW). Tank 5 regulates the uneven inflow of stormwater, provides for the needs of a four-person crew for five days, and is initially filled with drinking water quality. Tank 6 was designed to collect rainwater flowing from

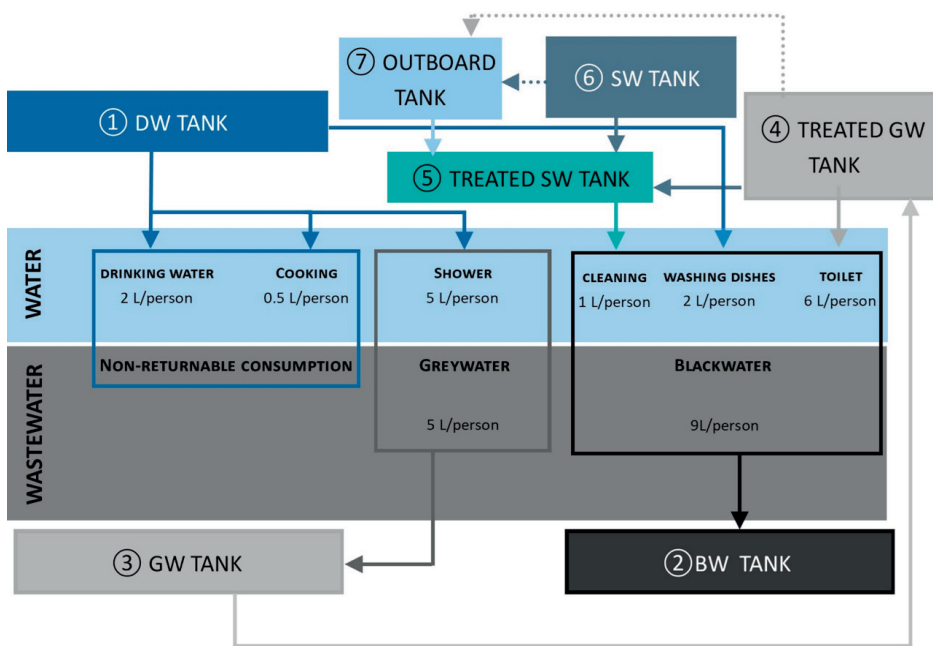


Fig. 16. Diagram showing the water supply and wastewater system together with the assessment of water demand and analysis of wastewater production (solid line - constant water/sewage flow, dotted line - emergency discharge of wastewater, DW - drinking water, BW - blackwater, GW - greywater, SW - stormwater)

The water stored in Tank 5 (treated stormwater and freshwater) is first passed to the treatment unit, which filters out impurities from the water and then disinfects it. Treated greywater (Tank 4) is passed to an extensive treatment unit that applies mechanical and biological filtration as well as UV-C disinfection. A stream of water from an outboard tank is also directed to this extensive treatment system.

The volume of the tanks is determined through planning and analysing the demand for water. Table 10 shows some values presented in the literature. Data on water consumption are drawn from the authors' experience. Additionally, there are guidelines for users on the need to save water, as referenced in the literature [51,52]. Water consumption was assumed to amount to 2 L, while the water required

for cooking was 0.5 L, and the water required for washing dishes was 1 L per person per day, giving a total consumption of 3.5 L of drinking-quality water per person per day. The production of grey waste water from showering and hand washing was 5 L per person per day, and flushing the toilet required 1 L per person per day. This level demand resulted in the production of greywater in the amount of 5 L per day per person. Blackwater production includes not only wastewater from the toilet, but also from washing dishes. This is due to the significant amount of contaminants (food residues, fats) that are difficult to clean using a simple system. Calculations of the water demand for a four-man crew are presented in Table 10. We also present the results of a simulation of a 14-day voyage without the possibility of water intake from the water supply network and discharge of sewage in the port.

Tab. 10. Calculations of the demand for water and production of sewage and the volume of tanks in the water supply and wastewater system

No	Tanks	Consumption person/day	Four people/day	Four people/14 days	Tank
1	Drinking water	4.5 L	18 L	252 L	260 L
2	Blackwater	9 L	36 L	504 L	510 L
3	Greywater	5 L	20 L	280 L	280 L
4	Treated greywater	3 L	12 L	168 L	170 L
5	Treated stormwater/water from lake/sea	5 L	20 L	280 L	100 L
6	Stormwater/water from lake/sea		—		120 L
7	Outboard		—		300 L

A green wall was planned for the treatment of greywater. The ability of green walls to remove pollutants has been proven in the literature [53] and in the authors' laboratory experiments [54,55]. The minimum size of the green wall was selected to enable the treatment of 20 L of greywater per day. According to analyses carried out by the authors, at least 60% of the water can be reused after treatment with the green wall. The green wall containing 21 plants is 140 cm wide, 35 cm deep, and 45 cm high. Suggested plants include *Carex morrowii* Irish Green, *Liriope Muscari* and *Euonymus fortunei*. Plants should be placed in a substrate consisting of 80% coir and 20% perlite.

OUTBOARD WATER TREATMENT

Outboard water storage takes place in outboard open water tanks (OOWTs) attached to the sides of the vessel. The total volume of OOWTs is assumed to be 280 L of water, allowing the vessel to keep a water reserve for 14 days (for non-drinking water purposes). According to the scheme in Fig. 16, this tank is initially filled with tap water during docking. Due to changes in water quality over time (water stagnation occurs after seven days, causing deterioration of its physical and chemical properties in a closed system), an open tank is supplied with a green infrastructure solution in the form of an ecological FTW. During cruising, the water in the tank is replenished with outboard raw water, treated greywater effluent, and, if desired, collected stormwaters. The general requirement for an outboard water tank is to maintain a water depth of 50–70 cm. The specific design concerns that should be taken into account in the construction of an FTW for a storage tank with plant species specification are presented in Table 4.

The additional water purification function of FTW places in OOWT is for greywater recycled purposes, use of available water sources, as well as to minimise the negative impact on the natural environment. Due to the changing water parameters in OOWT (contamination status of the outboard water, collection of salted outboard water, etc.), different species planted on FTW should be considered as presented in Table 11. The water from an OOWT should never be used as drinking water, due to the potential for negative health effects. To ensure dermal safety, OOWT water should be subjected to additional pre-treatment (via a filter) and disinfection processes (due to the danger from the presence of pathogenic microorganisms in outboard water) before use.

Tab. 11. Plant species used in FTW units and their characteristics

Examples of plant species	Characteristics	References
<u>Freshwater species:</u> <i>Carex sp.</i> , <i>Cyperus sp.</i> , <i>Ipomoea aquatica</i> , <i>Iris pseudacorus</i> , <i>Juncus sp.</i> , <i>Phragmites australis</i> , <i>Typha sp.</i> , <i>Vetiveria zizanioides</i>	Invaluable in removing biogenic substances (nitrogen and phosphorus compounds) for water purification and prevention of excessive growth of algae. Plants ideal for floating islands; do not require any special winter protection.	Pavlineri et al. (2017) [41] Lucke et al. (2018) [56], Du et al. (2021) [57]
<u>Saltwater species:</u> <i>Baumea juncea</i> , <i>Chrysopogon zizanioides</i> , <i>Iris pseudacorus</i> , <i>Isolepis Nodosa</i> , <i>Phragmites australis</i> , <i>Sarcocornia quinqueflora</i>	As above. Good growth of shoots and roots in salt and increasing salt water treatments.	

DISCUSSION

Since the late twentieth century, interest in floating architectural structures has been steadily increasing [58]. Research has spanned various aspects of these structures, including their function [44], urban and social significance [59,60], role in the tourism industry [61], response to sustainability goals [62], and relevance to climate change [63]. Scenario-based approaches have been explored to identify future opportunities and limitations for the development of floating houses [64,65], while technical studies have investigated such diverse issues as energy efficiency gains [66] and prefabrication opportunities [67]. However, the study of zero-emission, off-grid, autonomous houseboats that are suitable for a range of geographic locations is a relatively new area of investigation.

As the research presented above reveals, the design of a fully autonomous houseboat presents numerous challenges, including technological, operational, and innovative issues. The water supply and wastewater systems appear to be critical aspects of off-grid floating facilities. In the proposed study, it was assumed that the houseboat would be equipped with treatment systems for stormwater and freshwater/seawater. The reuse of treated greywater relieves pressure on freshwater supplies. In addition to the water purification function, the use of nature-based solutions in the shape of green walls and an FTW makes the vessel a comfortable environment for the crew [68,69]. It is also possible to treat blackwater in order to achieve the requirements for sewage discharge directly into the water body. This system should include at least four stages of treatment, consisting of sedimentation, physical separation, biozone treatment, and chlorination.

Today, one of the main limitations on the widespread development of off-grid autonomous houseboats is that this requires a substantial initial investment. However, to justify the investment costs, houseboats may be compared to apartment buildings. To minimise their primary energy

consumption requirements, residential buildings have to be upgraded, which involves huge financial outlays on photovoltaics, building insulation, and modern ventilation installations; these are initial costs that later result in lower operating costs. In addition, following technological developments, the cost of solar panel systems for home energy consumption has been decreasing steadily over the last few decades. According to the International Renewable Energy Agency, the price of solar PV modules falls by approximately 75% every 10 years [70]. In the proposed floating house, in order to lower the maintenance and initial investment costs, nature-based solutions were proposed for water retrofitting systems, which are considered cost-effective and bring long-term environmental benefits. Our design for a system of tanks and water/sewage installations allows for the purchase of only 260 L of tap water, instead of almost 1000 L. It is permissible to discharge sewage after a 14-day cruise in the amount of approximately 520 L, representing approximately 66% of the total wastewater production on the boat. This results in significantly lower operating costs for the houseboat. Research studies reveal that the initial costs of floating houses can also be decreased by utilising cost-effective anchoring systems. Among the many possible options, mooring cables appear to be the most cost-effective [71].

The maintenance and durability of autonomous systems could also represent challenging issues, and were taken into consideration in this study. For the green wall and FTW systems, very resistant plants were chosen that can survive difficult conditions of both drought and excess water. When considering energy storage limitations, apart from highlighting the decreasing costs of photovoltaic installations, and especially batteries, it is worth noting that the mass of the system is important but not of primary importance, as in mobile applications; for example, partially used batteries from vehicles can be used as a 'second life', which significantly reduces the costs of expensive energy storage.

The climatic dependency of the off-grid houseboat poses a significant challenge. The autonomy of the vessel relies heavily on its location, and at times on the prevailing weather conditions in a particular year. The lack of full autonomy when located in Stockholm and Gdańsk underscores the limitations of self-sufficient floating houses. This finding suggests that floating settlements worldwide should be individually analysed, especially in less favourable conditions such as locations with limited sunlight. These locations may require supplementary energy sources, such as heat pumps or wind turbines. In addition, connecting the vessel to the power grid via a bidirectional energy flow is a viable option. This allows the facility to draw power from the grid, as a source of clean energy, and to feed excess energy back into the grid. The cost of expanding the energy system to include a grid connection is relatively small compared to the entire investment outlay.

While the ecological footprint of the production, transportation, and installation of the required technologies may be comparable to residential houses on land, the impact of a houseboat on the local aquatic ecosystem should be

carefully studied [72]. If we analyse the water and sewage installation, we see that the impact on water systems is reduced through the use of onboard treatment systems and reduced discharge of blackwater. However, with the rising human impact on coastlines, there is a growing need for tools to identify key marine areas requiring protection and conservation, and to incorporate this knowledge into urban waterfront development processes [73]. For example, in future developments on water, floating houseboats could be grouped together and integrated with arrangements of floating islands as an effective solution for water purification and enhancing environmental aesthetics [74]. Numerous research papers have highlighted the need for an interdisciplinary perspective in terms of integrating marine ecologists into the design process of floating architecture, as this can bring numerous environmental benefits and promote ecological biodiversity [75].

In the context of numerous project proposals for floating housing settlements, one question to be discussed is the potential scalability of the project. The possibility of maximising the usable floor space in a floating vessel is almost boundless, unless there are other limitations related to the hull technology, size of the water parcels or the width of canals or watercourses. In general, the larger the floor space area, the larger the outer shell of the vessel and the higher the possibility of using it for photovoltaic and filtration panels. However, it should be noted that increasing the floor area will not always proportionally increase the surface of the outer shell on which the photovoltaic systems and systems for water treatment are placed. In any case, it should be acknowledged that with an increase in the number of users from four to eight or more, the structure will need to provide the same amount of amenities, such as drinking water, energy, or sewage treatment, per person.

To explore the potential enlargement of the proposed vessel, a cube-shaped floating model was employed for calculations (Fig. 17). It was assumed that this cube could provide the necessary space for a single user, and that the outer surfaces of the walls and roof of the cube would be sufficient to ensure the self-sufficiency of the facility in terms of its ability to generate electricity and provide water treatment (Fig. 18). The usable floor area could be increased to provide space for more users by adding successive identical modules (Fig. 19). Regardless of the direction in which the extension is added (i.e. along the length or width), one outer wall of the cube (one wall unit) is always used to add the next module. In the case where the width of this cube is suitable for letting the floating object pass through narrow water channels, the unit could be expanded primarily in the lengthwise direction (and, when feasible, also in height) (Fig. 20). The increase in the surface of the outer shell in relation to the increase in the floor area can be described as a linear function: $a_n = 5 + (n-1) \cdot 3$ (Fig. 21). When analysing this relationship, it becomes evident that the outer shell area per user decreases nonlinearly with the addition of subsequent modules (Fig. 22). The initial ratio of 5:1 (five units of outer shell surface area per unit floor area) undergoes the largest percentage change when moving from

one to two users (4:1), and then decreases more and more slowly towards a ratio of 3:1. Regardless of the number of users, this proportion does not reach as low as 3 : 1.

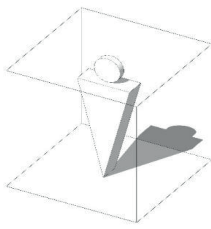


Fig. 17. A cube-shaped floating model module

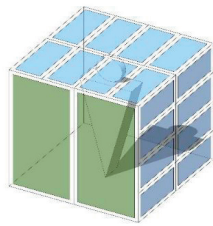


Fig. 18. Diagram showing PV panels and water treatment system

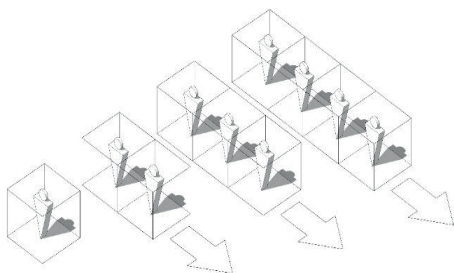


Fig. 19. Direction of possible addition of user modules

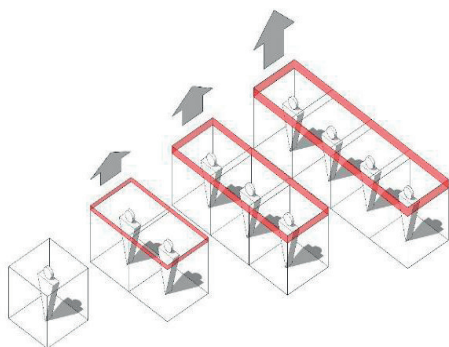


Fig. 20. Direction of possible expansion for the vessel

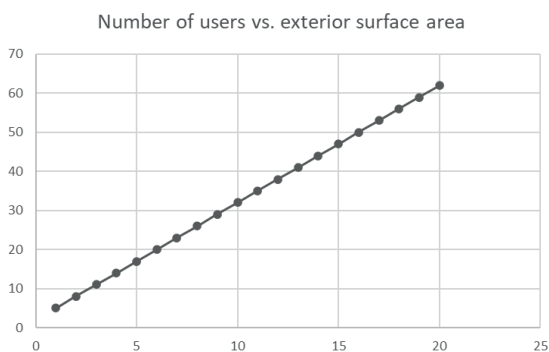


Fig. 21. Number of users vs. exterior surface area.
x – number of users, y – number of parts

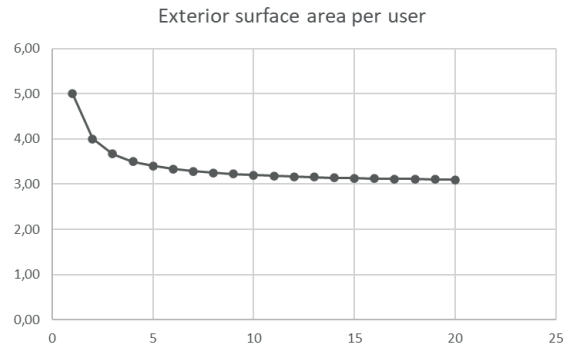


Fig. 22. Exterior surface area per user.
x – number of users, y – number of parts per user

Based on the assumption that a ratio of 5:1 is appropriate to ensure the autonomy of the facility, the height of the facility should therefore be increased, depending on the number of planned users, to maintain this ratio. The chart in Fig. 23 shows that the demand for increasing the outside shell area, under the conditions described above, is the highest when the number of users changes from one to two, and reaches as much as 25%. As the number of modules (users) increases, the demand for an additional outer surface rises at a progressively slower pace, never exceeding about 60% (Fig. 24). If the aim is to find this missing area only by changing the height of the building, then regardless of the number of users, the height will never have to be increased by more than 30% (Fig. 23). When increasing the height of the floating object, particular consideration should be given to issues concerning its stability.

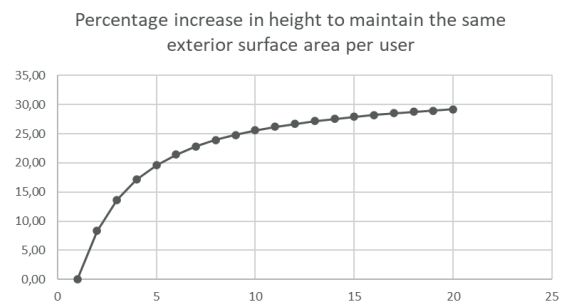


Fig. 23. Percentage increase in height to maintain the same exterior surface area per user.
x – number of users, y – percentage increase of height

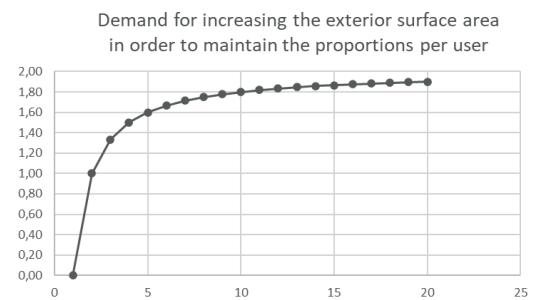


Fig. 24. Demand for increasing the exterior surface area in order to maintain the proportions per user.
x – number of users, y – demand for increasing the external area

The results show that building zero-energy, off-grid floating buildings is feasible. The autonomy and the duration of emission-free operation depended on the geographical location, with Rome and Lisbon showing potential for year-round autonomy, whereas in Gdańsk and Stockholm, autonomy could be achieved for over nine months of the year. However, if the heating system were modified by adding a heat pump, wind turbines or micro-hydro generators, it would be possible to obtain year-round autonomy for all of the analysed locations. In addition, different solutions could be employed for system optimisation [21,76]. Software optimisation packages could be used both to determine the low-cost and low-energy building configuration on the stage of the design and to examine the impact of the technologies used on the operational costs of the building [21,46,47]. It should be noted that the statistical data used in this analysis are based on average values, and do not include extreme cases such as severe winters.

CONCLUSION

This research study has confirmed the feasibility of constructing a prototype vessel with a residential function, which is specifically designed to be self-sufficient and autonomous for extended periods. Off-grid autonomy was achieved through the use of PV-based energy harvesting and nature-based solutions for water treatment.

We designed a sophisticated water and sewage system with seven tanks for water and wastewater (including one overboard), allowing for a reduction of up to 25% in the consumption of drinking water and up to 66% in the production of sewage, which must be subjected to a complex treatment process. The systems used here allowed for year-round independence from external sources of energy in Lisbon and Rome, while in Gdańsk and Stockholm, autonomy could be achieved for more than nine months each year.

The art of design is the art of compromise. Each hull variant considered here offers a different value depending on the evaluation method. This study has broadly demonstrated the multitude of factors that can influence the final outcome of the design process; however, the final choice rests with the designer. Our findings indicate the need to employ additional systems to manage energy deficits in northern countries. Periods of energy surplus allow for diverse applications such as hydrogen production, supplying energy to the grid, supporting the movement of the vessel, or undertaking other tasks such as water body cleaning or aeration.

This study has underscored the potential and limitations of developing environmentally conscious, self-sustaining houseboats and floating settlements that can adapt to different geographical contexts and environmental conditions.

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