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# 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)*

<table>
<tr><th rowspan="2"></th><th colspan="2">Off-grid ship or stationary house boat</th><th rowspan="2">"Zero energy" ship or stationary house boat</th></tr>
<tr><th>Floating stationary home (house boat)</th><th>Ship</th></tr>
<tr><td>Electrical installation</td><td colspan="2">No requirements</td><td>Notification of construction works needed for the construction of the grid connection, two-way meter and agreement with the grid operator</td></tr>
<tr><td>Water installation</td><td rowspan="2">No requirements for intake and discharge up to 5 $m^3$/day; Water law permit from 5$m^3$/day</td><td>No requirements</td><td rowspan="2">Notification of construction works needed for the construction of connections</td></tr>
<tr><td>Sewage installation</td><td>Prohibition on the discharge of untreated sewage, need for a high degree of treatment</td></tr>
</table>

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 $m^3$ 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).

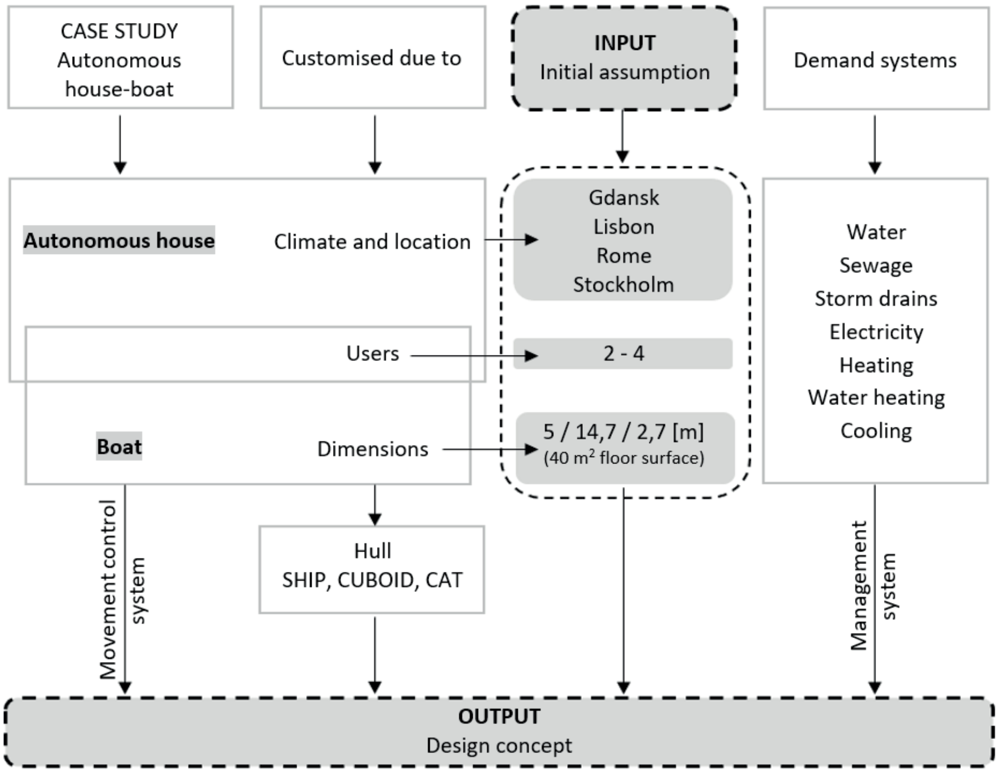


*Fig. 1. Process flow diagram: from the initial assumptions for the case study to the design concept*

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 both the maximum steerability of the vessel and a relatively comfortable usable area, i.e. about 40 $m^2$ 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 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: 36–40m² Volume: 90 m³ | 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 |

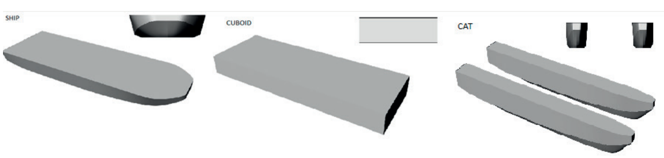


*Fig. 2. Diagram showing hull variants: (a) single-hull version with small draft; (b) cuboid (stationary); (c) catamaran (low resistance but greater draft)*

## 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)<br><u>Natural materials:</u> bamboo, wood & cork<br>Remarks:<br>– Floating rafts should be anchored to prevent excessive drift<br>– 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:<br>– 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)<br>– 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<br>Remarks:<br>– Coverage over 50% may prevent atmospheric reoxygenation and result in lower dissolved oxygen (DO) concentrations in water<br>– 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<br>Emergent macrophyte species:<br>*Iris pseudacorus, Typha lafifolia, Carex acutiformis, Acorus calamus, Phragmites australis, Glyceria maxima*<br>Free-floating species:<br>*Pistia stratiotes, Common water hyacinth, Salvinia, Salvinia molesta, Limnobium* | 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 m$^2$ 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*

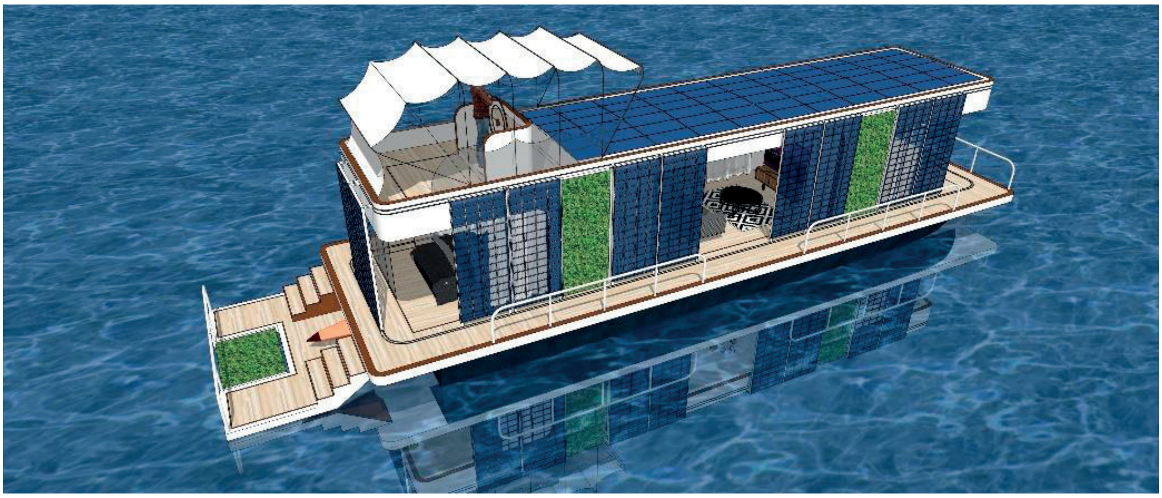

*Fig. 4. Image of the proposed houseboat: view of PV roof and wall panels, green walls and an ecological floating treatment wetland*

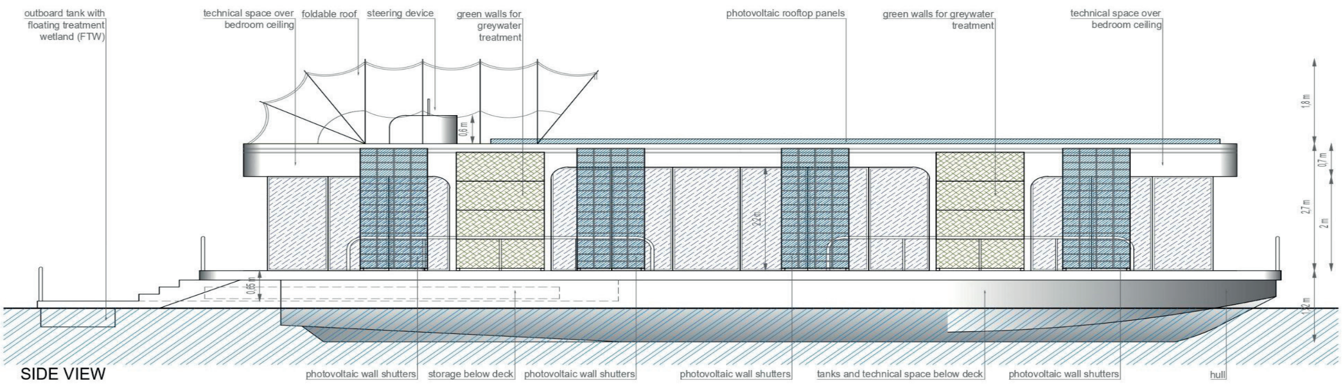


*Fig. 5. Side view: technical diagram with description*

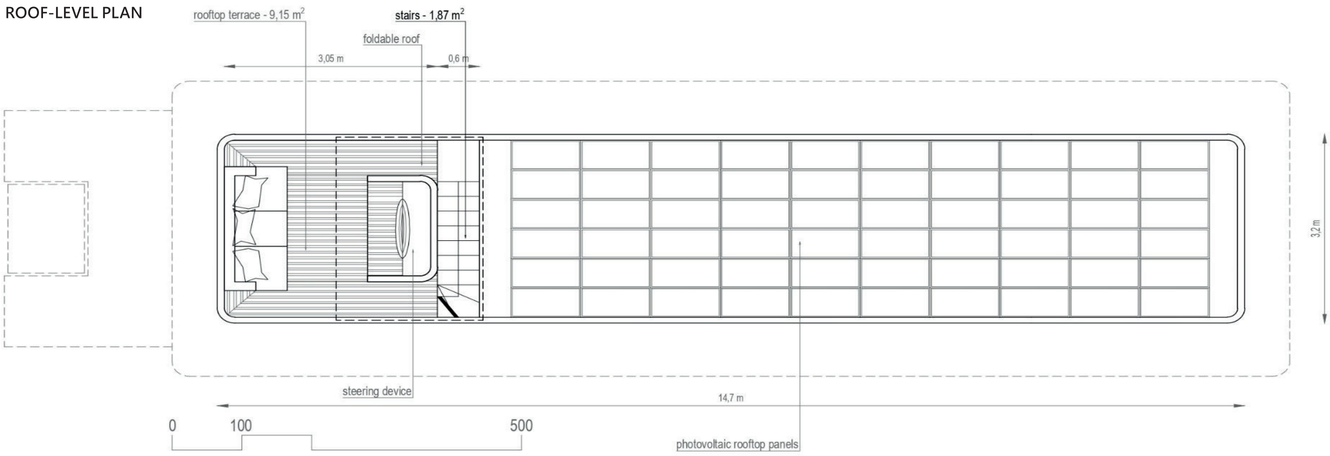


*Fig. 6. Roof-level plan: technical diagram with description*

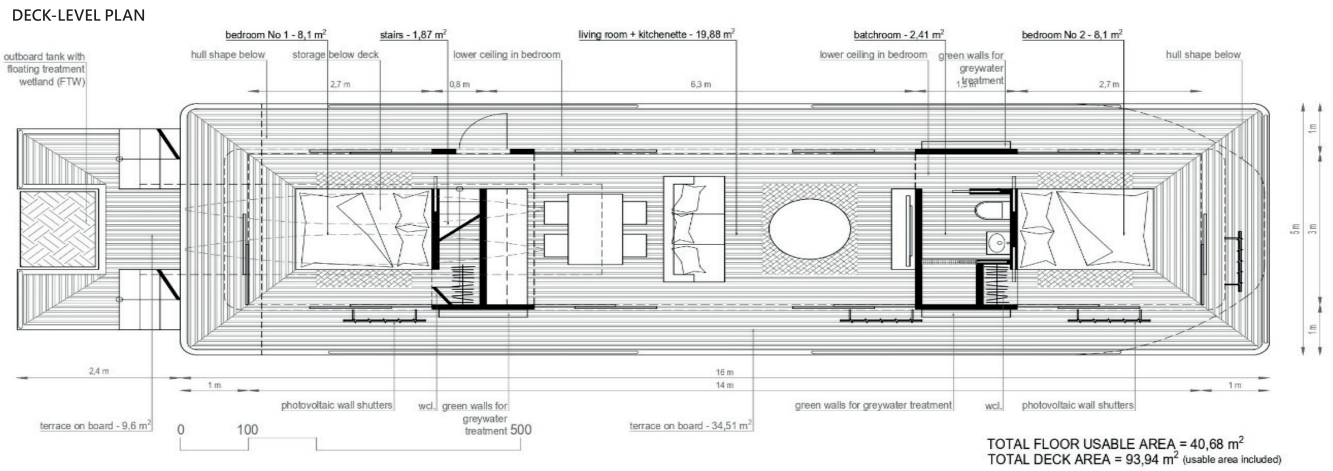


*Fig. 7. Deck-level plan: technical diagram with description.*

## 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).

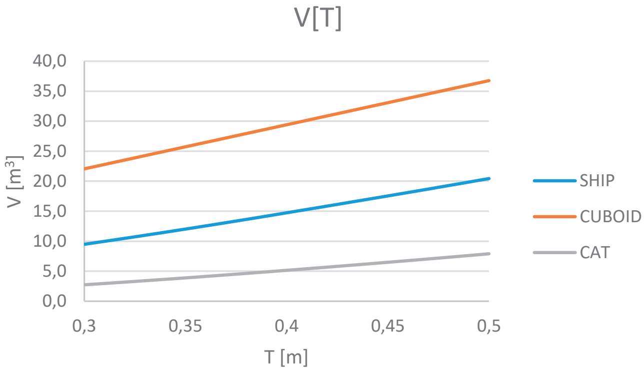


*Fig. 8. Displacement vs draft*

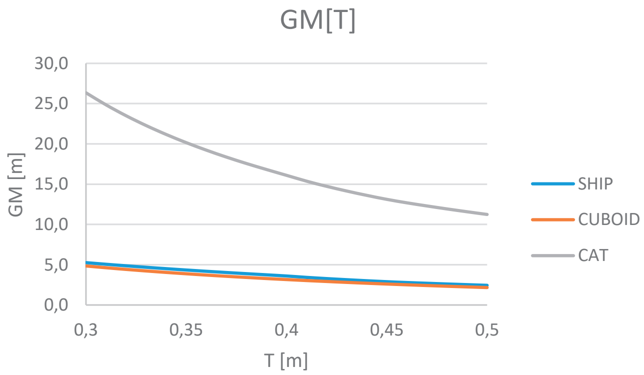


*Fig. 9. Initial metacentric height vs draft*

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).

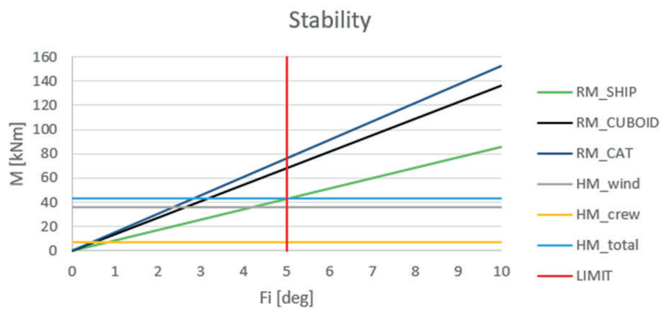


*Fig. 10. Stability curves*

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 | | | | | | |

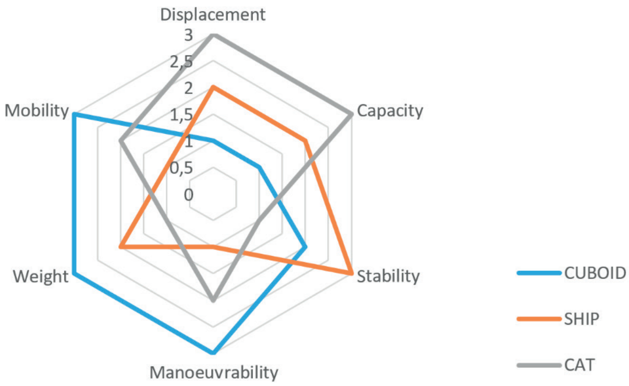


*Fig. 11. Usability aspects of the three hull variants*

## 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.

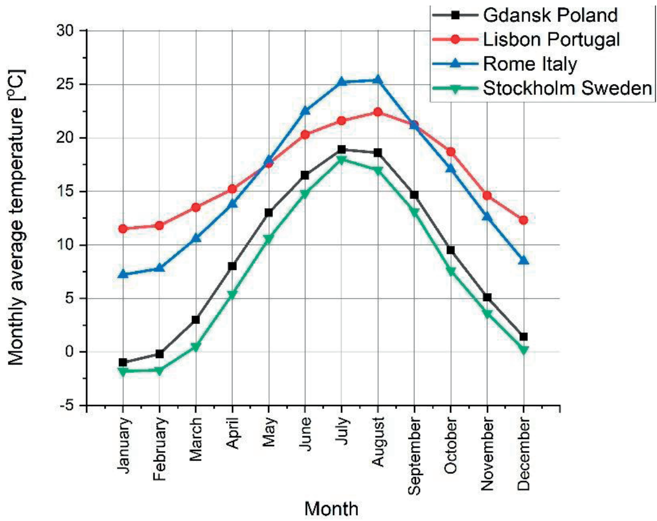


*Fig. 12. Monthly average temperature [https://weather-and-climate.com]*

### 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.

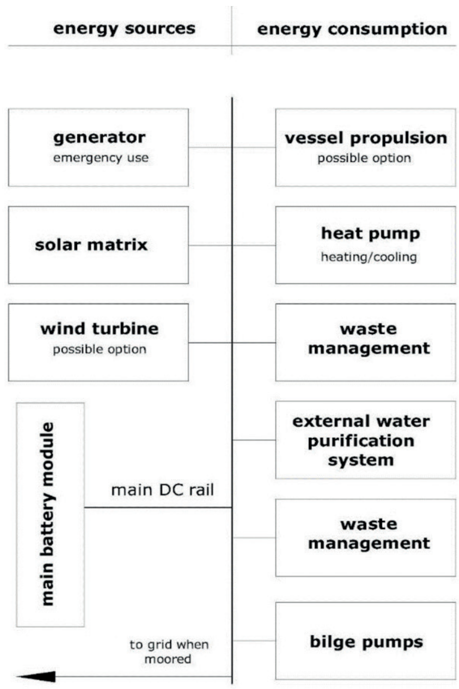


*Fig. 13. Energy distribution in the proposed houseboat*

**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:<br>Array slope 0° | Size: 10.2 x 5 m<br>9 × 6 panels | Total power: 18.9 kWp |
| Side array – flat vertical surface – assumed surface | | |
| Array size data:<br>Array slope 90° | Size: 3 × 5.1 m<br>3 x 3 panels | Total power: 3.1 kWp |

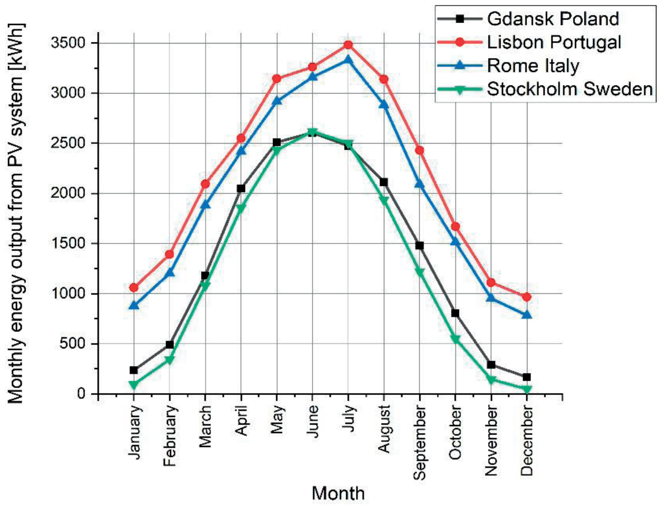


*Fig. 14. Monthly energy output from a flat PV system at a fixed angle [https://re.jrc.ec.europa.eu]*

**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 |

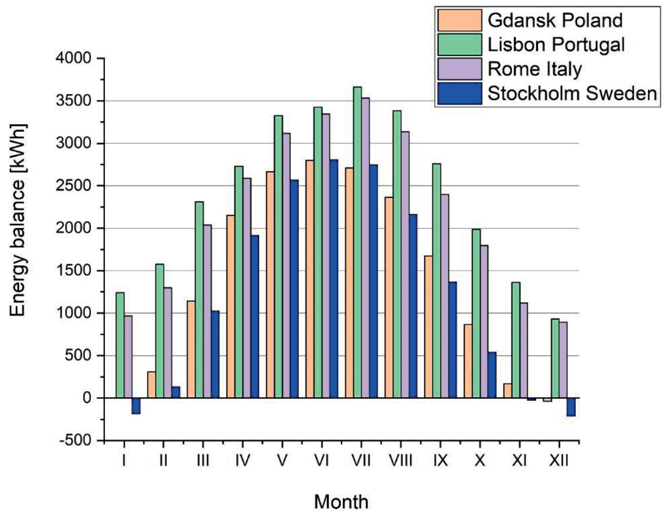


*Fig. 15. Average monthly energy balance [kWh]*

## 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.

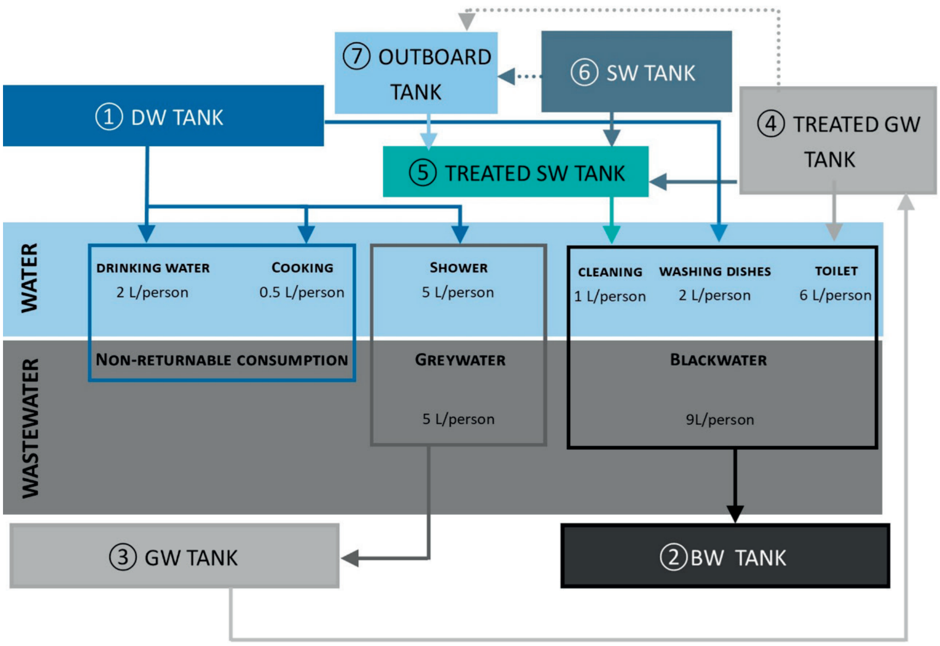


*Fig. 16. Diagram showing the water supply and wastewater system together with the assessment of water demand and analysis of wastewater production (solid line - constant water/sewage flow, dotted line - emergency discharge of wastewater, DW - drinking water, BW - blackwater, GW - greywater, SW - stormwater)*

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.

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 the deck, where the excess is passed to the outboard tank for treatment with the FTW (20 L reserve for treatment processes).

*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 |
|---|---|---|
| Freshwater species:<br>*Carex sp.,* Cyperus sp., *Ipomonea aquatica, Iris pseudacorus, Juncus sp., Phragmites australis, Typha sp., Vetiveria zizanoides* | 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] |
| Saltwater species:<br>*Baumea juncea, Chrysopogon zizanioides, Iris pseudacorus, Isolepis Nodosa, Phragmites australis, Sarcocornia quinqueflora* | 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: $a_n=5+(n-1)*3$ (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.

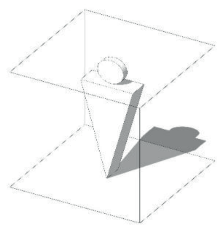

*Fig. 17. A cube-shaped floating model module*

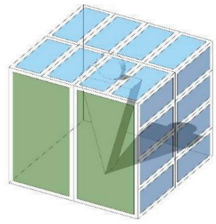

*Fig. 18. Diagram showing PV panels and water treatment system*

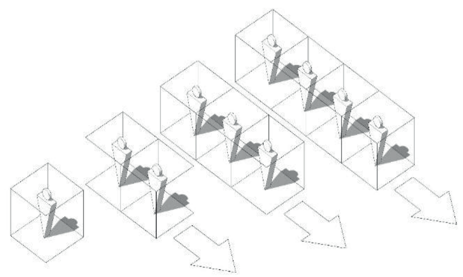

*Fig. 19. Direction of possible addition of user modules*

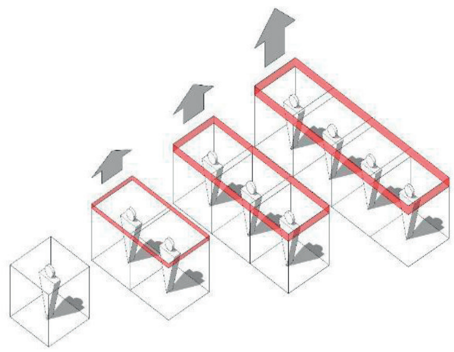

*Fig. 20. Direction of possible expansion for the vessel*

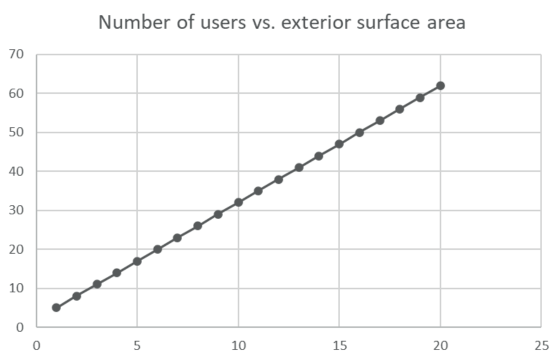


*Fig. 21. Number of users vs. exterior surface area. x – number of users, y – number of parts*

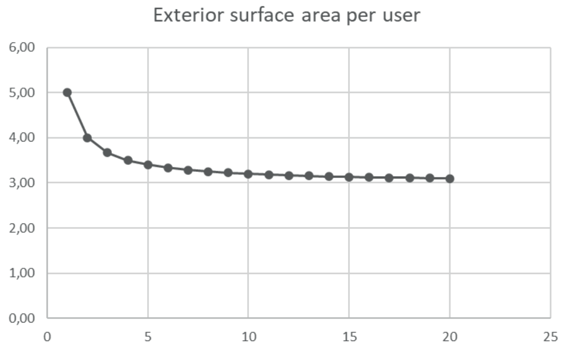


*Fig. 22. Exterior surface area per user. x – number of users, y – number of parts per user*

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.

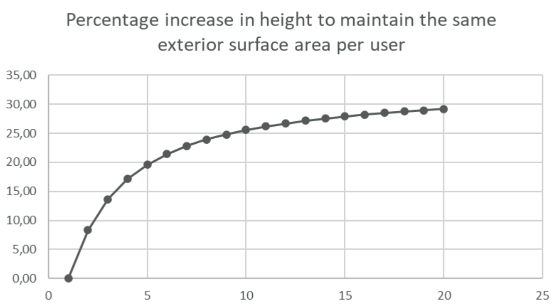


*Fig. 23. Percentage increase in height to maintain the same exterior surface area per user. x – number of users, y – percentage increase of height*

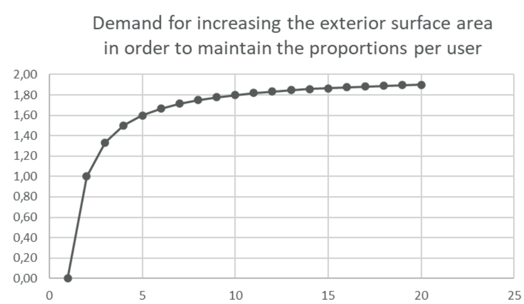


*Fig. 24. Demand for increasing the exterior surface area in order to maintain the proportions per user. x – number of users, y - demand for increasing the external area*

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.

### ACKNOWLEDGEMENTS

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## REFERENCES

1. Mikulčić H, Baleta J, Klemeš JJ, Wang X. Energy transition and the role of system integration of the energy, water and environmental systems. Journal of Cleaner Production 2021, 292, 126027. doi.org/10.1016/j.jclepro.2021.126027
2. Medved P. A contribution to the structural model of autonomous sustainable neighbourhoods: New socio-economical basis for sustainable urban planning. Journal of Cleaner Production 2016, 120, 21–30. doi.org/10.1016/j.jclepro.2016.01.091
3. Goldsworthy MJ, Sethuvenkatraman S. The off-grid PV-battery powered home revisited: The effects of high efficiency air-conditioning and load shifting. Sol. Energy 2018, 172, 69–77, Sep. 2018, doi: 10.1016/j.solener.2018.02.051.
4. Rothrock H. Sustainable housing: Emergy evaluation of an off-grid residence. Energy and Buildings 2014, 85, 287–292. https://doi.org/10.1016/j.enbuild.2014.08.002.
5. Solarek K, Kubasińska M. Local spatial plans as determinants of household investment in renewable energy: Case studies from selected Polish and European communes. Energies 2021, 15, 126.
6. Skiba M, Mrówczyńska M, Sztubecka M, Bazan-Krzywoszańska A, Kazak JK, Leśniak A, Janowiec F. Probability estimation of the city's energy efficiency improvement as a result of using the phase change materials in heating networks. Energy 2021, 228, 120549.
7. Thompson S, Duggirala B. The feasibility of renewable energies at an off-grid community in Canada. Renew. Sustain. Energy Rev. 2009, 13(9), 2740–2745 .
8. Burda IM, Nyka L. Providing public space continuities in post-industrial areas through remodelling land/water connections. IOP Conference Series: Materials Science and Engineering 2017, 245(8), 082037.
9. Matos Silva M, Costa JP. Urban floods and climate change adaptation: The potential of public space design when accommodating natural processes. Water 2018, 10(2), 180. https://doi.org/10.3390/w10020180
10. Bradecki T, Konsek P. Examples and concepts of floating architecture in the face of climate change–The example of Szczecin. 5th World Multidisciplinary Civil

Engineering-Architecture-Urban Planning Symposium (WMCAUS) 2020, 960.

11. English EC, Chen M, Zarins R, Patange P, Wiser JC. Building resilience through flood risk reduction: The benefits of amphibious foundation retrofits to heritage structures. International Journal of Architectural Heritage 2021, 15(7), 976–984. doi: 10.1080/15583058.2019.1695154)

12. Burda IM, Nyka L. Innovative urban blue space design in a changing climate: Transition models in the Baltic sea region. Water 2023, 15, 2826. https://doi.org/10.3390/w15152826

13. Nyka L, Burda IM. Scenario-planning solutions for waterfront flood-prone areas. Global Journal of Engineering Education 2020, 22(3), 149–154.

14. Varkey MV, Philip PM. Flood risk mitigation through self-floating amphibious houses - Modelling, analysis, and design. Mater. Today Proc. 2022, 65, 442–447. doi: 10.1016/j.matpr.2022.02.547

15. Ronzatti G, Lovric P. Floating infrastructure large scale public spaces on water. In Wang CM et al. (eds.), WCFS2019, Lecture Notes in Civil Engineering 41, Springer Nature Singapore Pte Ltd. 2020. https://doi.org/10.1007/978-981-13-8743-2_3

16. Olthuis K, Keuning D. Float! Building on water to combat urban congestion and climate change. Amsterdam: Frame Publishers; 2010.

17. Yang Y, Zhao S, Kim C. Analysis of floating city design solutions in the context of carbon neutrality-focus on Busan Oceanix City. Energy Reports 2022, 8, 153–162. doi: 10.1016/j.egyr.2022.10.310.

18. Penning-Rowsell E. Floating architecture in the landscape: Climate change adaptation ideas, opportunities and challenges. Landscape Research 2020, 45(4), 395–411. doi: 10.1080/01426397.2019.1694881

19. Piątek Ł. Architecture of floating buildings: conditions and directions of development in Poland after 2000. Warsaw University of Technology; 2018.

20. Pal R. The houseboats of Srinagar: A sinking piece of Indian heritage. CNN 19th November 2021. Retrieved from https://edition.cnn.com/travel/article/srinagar-houseboats-india-cmd/index.html.

21. Guerello A, Page S, Holburn G, Balzarova M. Energy for off-grid homes: Reducing costs through joint hybrid system and energy efficiency optimization. Energy Build. 2020, 207, 109478. doi: 10.1016/j.enbuild.2019.109478.

22. García-Vázquez CA, Espinoza-Ortega H, Llorens-Iborra F, Fernández-Ramírez LM. Feasibility analysis of a hybrid renewable energy system with vehicle-to-home operations for a house in off-grid and grid-connected applications. Sustain. Cities Soc. 2022, 86, 104124. doi: 10.1016/j.scs.2022.104124

23. Elazab R, Saif O, Metwally AMAA, Daowd M, Mixed integer smart off-grid home energy management system. Energy Reports 2021, 7, 9094–9107. doi: 10.1016/j.egyr.2021.11.227

24. Tostado-Véliz M, Bayat M, Ghadimi AA, Jurado F. Home energy management in off-grid dwellings: Exploiting flexibility of thermostatically controlled appliances. J. Clean. Prod. 2021, 310, 127507. doi: 10.1016/j.jclepro.2021.127507

25. Kristiansen AB, Zhao BY, Ma T, Wang RZ. The viability of solar photovoltaic powered off-grid Zero Energy Buildings based on a container home. J. Clean. Prod. 2021, 286, 125312. doi: 10.1016/j.jclepro.2020.125312

26. Cho D, Valenzuela J. A scenario-based optimization model for determining the capacity of a residential off-grid PV-battery system. Sol. Energy 2022, 233, 478–488. doi: 10.1016/j.solener.2022.01.058

27. Khajeh H, Laaksonen H, Simões MG. A fuzzy logic control of a smart home with energy storage providing active and reactive power flexibility services. Electr. Power Syst. Res. 2023, 216, 109067. doi: 10.1016/j.epsr.2022.109067

28. Loois G, van der Weiden TCJ, Hoekstra KJ. Technical set-up and use of PV diesel systems for houseboats and barges. Sol. Energy Mater. Sol. Cells 1994, 35(C), 487–496. doi: 10.1016/0927-0248(94)90177-5

29. Inal OB, Charpentier JF, Deniz C. Hybrid power and propulsion systems for ships: Current status and future challenges. Renewable and Sustainable Energy Reviews 2022, 156, 111965. doi: 10.1016/j.rser.2021.111965

30. Gełesz P, Karczewski A, Kozak J, Litwin W, Piątek Ł. Design methodology for small passenger ships on the example of the ferryboat Motława 2 driven by hybrid propulsion system. Polish Marit. Res. 2017, 24(s1), 67–73. doi: 10.1515/pomr-2017-0023

31. Kunicka M, Litwin W. Energy efficient small inland passenger shuttle ferry with hybrid propulsion—Concept design, calculations and model tests. Polish Marit. Res. 2019, 26(102), 85–92. doi: 10.2478/pomr-2019-0028

32. Tillig F. et al. Analysis of uncertainties in the prediction of ships' fuel consumption—From early design to operation conditions. Ships and Offshore Structures 2018, 5302, 13–24. doi: 10.1080/17445302.2018.1425519

33. USTAWA z dnia 7 lipca 1994 r. Prawo budowlane.

34. Ustawa z dnia 20 lipca 2017 r. – Prawo wodne (Dz. U. z 2021 r. poz. 2233, z późn. zm.)

35. Polish Register of Shipping. Rules for the classification and construction of stationary floating objects. Gdansk, PR:2020. Retrieved from https://prs.pl/wp-content/uploads/2024/03/sop_en.pdf.

36. Polish Register of Shipping. Rules for the classification and construction of houseboats (HSB). 2020. Retrieved from https://prs.pl/wp-content/uploads/2024/03/hsb_en.pdf.

37. Jaysawal RK, Chakraborty S, Elangovan D, Padmanaban S. Concept of net zero energy buildings (NZEB)—A literature review. Cleaner Engineering and Technology 2022, 11, 100582.

38. Karstens S, Langer M, Nyunoya H, Caraite I, Stybel N, Razinkovas-Baziukas A, Bochert R. Constructed floating wetlands made of natural materials as habitats in eutrophicated coastal lagoons in the Southern Baltic Sea. Journal of Coastal Conservation 2021, 24(Article 44).

39. Tanner CC, Headley TR. Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. Ecological Engineering 2011, 37, 474–486.

40. Shen S, Li X, Lu X. Recent developments and applications of floating treatment wetlands for treating different source waters: A review. Environmental Science and Pollution Research 2021, 28, 62061–62084.

41. Pavlineri N, Skoulikidis NT, Tsihrintzis VA. Constructed floating wetlands: A review of research, design, operation and management aspects, and data meta-analysis. Chemical Engineering Journal 2017, 308, 1020–1132.

42. Wang CY, Sample DJ. Assessment of the nutrient removal effectiveness of floating treatment wetlands applied to urban retention ponds. Journal of Environmental Management 2014, 137, 23–35 http://dx.doi.org/10.1016/j.jenvman.2014.02.008

43. Polish Register of Shipping. Retrieved from https://www.prs.pl/home.

44. Yuan-Ho L, Yung Chih L, Han-Shih T. Design and functions of floating architecture—A review. Marine Georesources & Geotechnology 2019, 37:7, 880–889. doi: 10.1080/1064119X.2018.1503761

45. Vasquez NG, Amorim CND, Matusiak B, Kanno J, Sokol N, Martyniuk-Peczek J, Sibilio S, Scorpio M, Koga Y. Lighting conditions in home office and occupant's perception: Exploring drivers of satisfaction. Energy and Buildings 2022, 261, 111977. https://doi.org/10.1016/j.enbuild.2022.111977

46. Montana SLF, Sanseverino ER. A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. Sustain. Cities Soc. 2018, 45, 87-104. doi: 10.1016/j.scs.2018.11.027

47. D'Agostino D, Parker D. A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. Energy 2018, 149, 814–829.

48. Karczewski A. Towards an understanding of the stability assessment of floating buildings. Lect. Notes Civ. Eng. 2022, 158, 297–308. doi: 10.1007/978-981-16-2256-4_18

49. Karczewski A, Piatek Ł. The influence of the cuboid float's parameters on the stability of a floating building. Polish Marit. Res. 2020, 27(3), 16–21. doi: 10.2478/pomr-2020-0042

50. Nakajima T, Saito Y, Umeyama M. A study on stability of floating architecture and its design methodology. Lect. Notes Civ. Eng. 2022, 158, 273–296. doi: 10.1007/978-981-16-2256-4_17

51. Westhof L, Köster S, Reich M. Occurrence of micropollutants in the wastewater streams of cruise ships. Emerging Contaminants 2016, 2(4), 178–184. https://doi.org/10.1016/j.emcon.2016.10.001

52. Cai Y, Sun P, Luo Y, Long X, Shi Y. An integrated full-scale system for the treatment of real ship domestic wastewater: Shore-test experiments. Journal of Water Process Engineering 2023, 53, 103786. https://doi.org/10.1016/j.jwpe.2023.103786

53. Prodanovic V, McCarthy D, Hatt B, Deletic A. Designing green walls for greywater treatment: The role of plants and operational factors on nutrient removal. Ecological Engineering 2019, 130, 184–195. https://doi.org/10.1016/j.ecoleng.2019.02.019

54. Nawrot N, Matej-Łukowicz K, Wojciechowska E. Change in heavy metals concentrations in sediments deposited in retention tanks in a stream after a flood. Polish Journal Of Environmental Studies 2019, 28(1), 1–6. https://doi.org/10.15244/pjoes/81699

55. Matej-Łukowicz K, Wojciechowska E, Nawrot N, Dzierzbicka-Głowacka L. Seasonal contributions of nutrients from small urban and agricultural watersheds in northern Poland. PeerJ 2020, 8, 1–22. https://doi.org/10.7717/peerj.8381

56. Lucke T, Sanicola O, Stewart M, Tondera K, Walker C. Assessing the growth of different plant species in constructed floating wetlands in saline environments. IWA SWWS2018 Conference on Small Water & Wastewater Systems and Resources Oriented Sanitation, 2018.

57. Du J, Li Q, Zhao R, Yang J, Zhou S, Chen C, Zhang M, Zhao D, An S. Effect of influent salinity on the selection of macrophyte species in floating constructed wetlands. Journal of Environmental Management 2021, 282, 111947.

58. Gabor M. Houseboats. Living on the water around the world. New York, Ballantine Books; 1979.

59. Cerro C. Floating architecture in the developing world. Sustainable City XI Book Series: WIT Transactions on Ecology and the Environment 2016, 204, 663–669. doi: 10.2495/SC160551

60. Wang X, Xu S, Leung M, Liang Q. A value-based multi-criteria decision-making approach towards floating house development: A case study in Hong Kong.Journal of Civil Engineering and Management 2023, 29(3), 223–237. https://doi.org/10.3846/jcem.2023.17571

61. Piątek Ł, Wycisk A, Parzych D, Modrzejewska K. Floating buildings in the hotel, catering and water tourism industry in Poland—Business environment survey. Journal of Water and Land Development 2020, 45 (IV–VI), 100–106. doi:10.24425/jwld.2020.133051

62. Moon C. Three dimensions of sustainability and floating architecture. International Journal of Sustainable Building Technology and Urban Development 2014, 5(2), 123–127. https://doi.org/10.1080/2093761X.2014.908809

63. Mees, H., Driessen, P., & Runhaar, H. Legitimate adaptive flood risk governance beyond the dikes: The cases of Hamburg, Helsinki and Rotterdam. Regional Environmental Change 2013, 14, 671-682. doi: 10.1007/s10113-013-0527-2

64. Miszewska E, Niedostatkiewicz M, Wiśniewski R. Sustainable development of water housing using the example of Poland: An analysis of scenarios. Sustainability 2023, 15, 11368. https://doi.org/10.3390/su151411368

65. Stopp H, Strangfeld P. Floating houses—Chances and problems. Architecture Civil Engineering Environment 2010, 3(4).

66. Habibi S. Floating building opportunities for future sustainable development and energy efficiency gains. J Archit Eng Tech 2015, 4, 142. doi:10.4172/2168-9717.1000142

67. Ostrowska-Wawryniuk K, Piątek Ł. Lightweight prefabricated floating buildings for shallow inland waters. Design and construction of the floating hotel apartment in Poland. Journal of Water and Land Development 2020, 44(I-III), 118–125. https://doi.org/10.24425/jwld.2019.127052

68. Chen XC, Huang XC, He SB, Yu XJ, Sun MJ, Wang XD, Kong HN. Pilot-scale study on preserving eutrophic landscape pond water with a combined recycling purification system. Ecological Engineering 2013, 61, 383–389.

69. Sędzicki D, Cudzik J, Nyka L. Computer-aided greenery design—Prototype green structure improving human health in urban ecosystem. Inter. J. of Environ. Research and Public Health 2023, 20(2), 1198.

70. Solar (photovoltaic) panel prices vs. cumulative capacity. 2023. Retrieved from OurWorldInData.org.

71. Miszewska E, Niedostatkiewicz M, Wiśniewski R. The selection of anchoring system for floating houses by means of AHP method. Buildings 2020, 10, 75. https://doi.org/10.3390/buildings10040075

72. Perkol-Finkel S, Hadarya T, Rella A, Shirazi R, Sella I. Seascape architecture—Incorporating ecological considerations in design of coastal and marine infrastructure. Ecological Engineering 2018, 120, 645–654.

73. Patrizzi NS, Dobrovolski R. Integrating climate change and human impacts into marine spatial planning: A case study of threatened starfish species in Brazil. Ocean. Coast. Manag. 2018, 161, 177–188.

74. Qin S, Zhong M, Lin B, Zhang Q. Roles of floating islands in aqueous environment remediation: Water purification and urban aesthetics. Water 2023, 15, 1134. https://doi.org/10.3390/w15061134

75. Marcus A, Ikeda M, Jones I, Metcalf T. Buoyant ecologies float lab: Optimized upside-down benthos for sea level rise adaptation. Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Mexico City, Mexico, 18–20 October 2018, pp. 414–423.

76. Yu Z, Gou Z, Qian F, Fu J, Tao Y. Towards an optimized zero energy solar house: A critical analysis of passive and active design strategies used in Solar Decathlon Europe in Madrid. Journal of Cleaner Production 2019, 236, 117646. doi.org/10.1016/j.jclepro.2019.117646