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ADAPTING TOWARDS RESILIENCE: ANALYSIS OF THE CONSTRUCTION FEATURES AND DYNAMIC ENERGY PERFORMANCE OF AMPHIBIOUS AND FLOATING HOUSES

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Highlights

Adaptation to changing climate conditions could support resilience. Amphibious and floating houses can be employed in flood-prone regions. Their peculiar construction characteristics are analyzed. Their energy performance in different climates is assessed. The application in Mediterranean regions needs tailored passive strategies to improve energy performance.

Abstract

In the current scenario where urban areas are exposed to extreme climate phenomena, resilience of cities and buildings becomes fundamental. Thus, not only defensive, traditional actions, but also alternative solutions towards resilience need to be implemented. Amphibious and floating houses, still not investigated in literature, allow the building to adapt to water presence due to their specific construction and technical properties. Here, we consider such buildings' typologies under the construction and thermal-energy performance lenses, by means of yearly dynamic energy simulations.

Keywords

Amphibious Architecture, Construction Elements, Thermal Energy-Performance, Resilience, Flooding Risk.

1. INTRODUCTION

In the current scenario of cities' growth, the United Nations predictions state that in 2050 66.4% of the world's population, about 9.5 billion people, will reside in urban areas [1]. This data assumes greater relevance when compared with contemporary data: today, of the total world population of 7.2 billion people, 54% resides in cities, which corresponds to 3.9 billion citizens living in urban areas nowadays; by 2050 there will be 6.3 billion living in cities.

This means urban areas will be one of the main fields where the challenge for sustainability will be held, by means of social, economic, and environmental sustainability. In addition to the increased population and land use, other challenges regarding decision making and social issues, frequently reported by the scientific community, need solutions to mitigate their negative consequences. Therefore, it is essential to take into account climate change [2–4], which effects include global warming, an increase in extreme climatic phenomena, drought and desertification. The forecasts for these changes are more or less exacerbated according to the achievement of specific objectives, such as the drastic reduction of consumption and therefore of emissions.

Specifically, urban areas are affected by climate change in terms of increased temperature, due to the phenomena known as Urban Heat Island [5, 6], and increased flood risk, caused by extreme rainfall and soil sealing, due to the constantly increasing land consumption [7–9], as well as sea-level rise (Fig. 1).

Both phenomena constitute risks to the safety of the population and a significant economic burden: just considering the last twenty years, flooding has affected 2.3 billion people and caused damage for over 165 billion dollars. The built environment, "responsible" for the sealed soil and for protecting people's safety, has an important role in reducing these critical issues, through strategies that are increasingly aimed at resilience and adaptation, rather than traditional defence.

Fig. 1. *Sea level rise and flooding risk in Ostia Lido, Rome (Italy). 1, scenario in the case of 1°C temperature rise. 2, scenario in the case of 2.5°C temperature rise. Projection from [10].*

Resilience means the ability of a system (for example, the city) to adapt to changes that disturb its balance: in this case, the risk from climate change is mitigated by adapting flexibly to the changing environmental conditions. This approach is seen by the scientific community as more effective or complementary to the traditional defensive approach.

An example of this strategy, applied to the built environment and buildings, is the development of water resilient building typologies [11–14]. In this article, amphibious and floating houses are taken into account, which are designed to increase resilience in urban and non-urban areas vulnerable to floods. The construction features make these buildings suitable to be livable in the presence of water while maintaining safety and well-being requirements.

In this work, a careful analysis of the construction and technical characteristics of the amphibious and floating buildings is carried out and their energy performance is particularly considered, since knowledge of the consumptions is fundamental to reduce emissions, mitigate climate change and Urban Heat Island. While amphibious and floating houses are gaining popularity – especially in flood-prone areas – and the state of the art is advancing, there are still not numerous scientific studies aimed at analyzing their characteristics to better understand the technologies applied, and improve their overall performance [12, 15]. The objective of this contribution is to analyze amphibious and floating houses, highlighting their constructive characteristics and energy performance, hypothesizing improved application particularly suitable for the Mediterranean area.

2. METHODOLOGY

The study is conducted throughout different phases, which are described in greater detail in the following subsections.

In the first phase, the technological and construction characteristics of amphibious and floating houses are presented. The differences between these two building typologies are evidenced and the most suitable applications, depending on the surrounding context, are highlighted. A case study is then selected, and an existing amphibious house in England is modeled in the Mediterranean environment also. The case study is eventually modeled and simulated by means of yearly dynamic energy performance. Results are gathered and discussed in the last sections of the work.

2.1. ANALYSIS OF CONSTRUCTION CHARACTERISTICS

For the analysis of the construction characteristics of amphibious and floating houses, a careful investigation of the state of the art and literature was carried out. Most of the existing examples are located in the Netherlands, but there are some cases of amphibious and floating architecture also in Australia, Canada, England, Bangladesh, and Thailand [12], where the need to be protected and adapt to the presence of water has led to the diffusion of resilient solutions.

In the volume “Aquatecture” [16], the authors, co-founders of the architectural studio BACA, define amphibious houses as “houseboats designed to rise on fixed foundations […] and that rise on guide-posts, floating on the water”, while floating houses “rise on a floating base, designed to rise and fall with the water level”. BACA Architects, London, are the designers of the first amphibious house in the United Kingdom, located on the River Thames [17] (Fig. 2 and Fig. 3).

In the Netherlands, entire neighborhoods are built on water, as in the case of Ijburg in Amsterdam, where Mar-

Fig. 2. *1, Amphibious home, BACA Architects, UK; 2, amphibious home, Morphosis, USA; 3, 4 and 5 Floating homes Ijburg NL, Marlies Rohmer; 6, floating home, Attika, NL.*

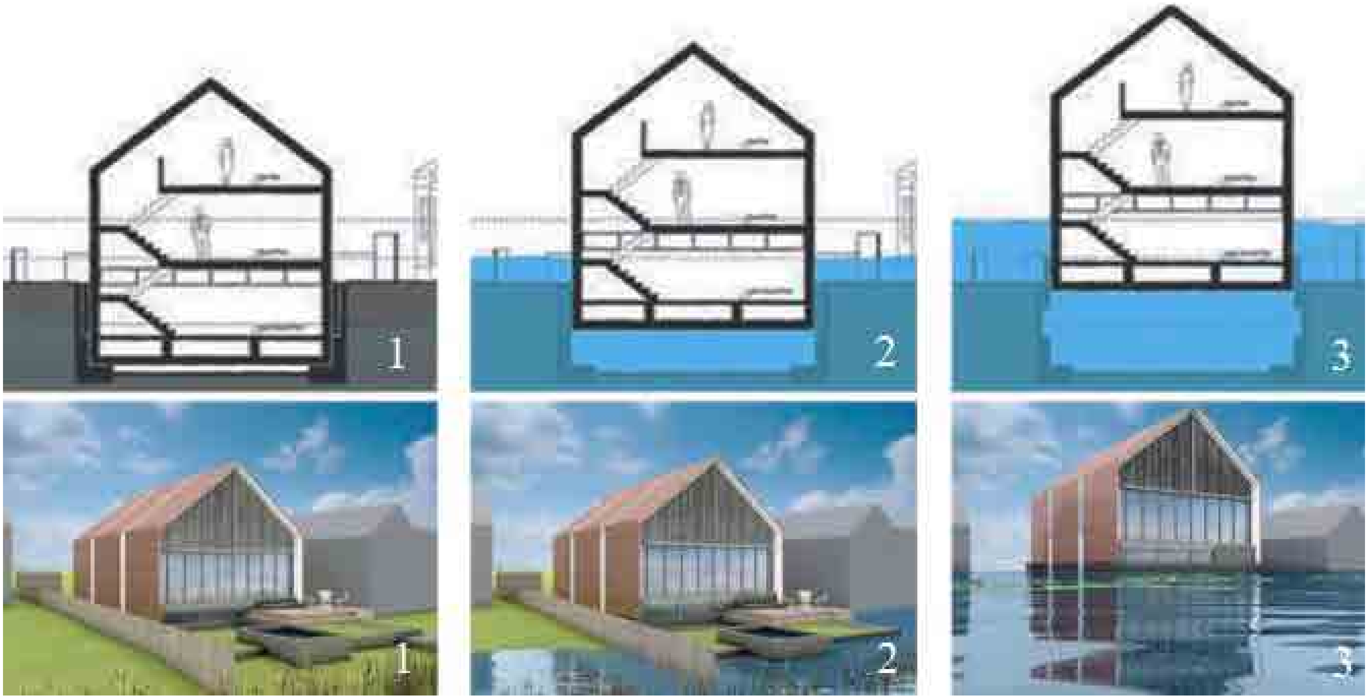

Fig. 3. *The amphibious home by BACA architects in UK: 1, static position; 2 e 3, floating in different flooding stages. Image adapted from [16]*

lies Rohmer Architects and Waterstudio studios [18, 19] designed the floating buildings (Fig. 2). The architecture studio Attika [20] built many houses of these typologies, as well as ABC Arkenbouw and Dura Vermeer, which is a construction firm specialized in floating houses [21, 22] (Fig. 2). Another North-European example of floating architecture is "Urban Rigger", by BIG Architects, which consists in 12 floating studio apartments for students in Copenhagen, and which received multiple awards in 2017 [23] (Fig. 4).

In Canada, MOS Architects built a floating house, a "houseboat" on Lake Huron, while in the United States, following Hurricane Katrina, Morphosis designed LEED-platinum-certified amphibious houses to improve resilience. Images of the above-cited floating houses are visible in Figure 4.

From the analysis of the considered examples, the construction and technical characteristics of the two building types emerge. Buoyancy, which is the main physical basis for the functioning of such typologies, is based on the Archimede's principle, according to which a body immersed in a fluid receives a vertical buoyant force equal to the weight of the fluid that the body displaces. The buoyant force is applied to the center of gravity of the displaced mass. For both amphibious and floating houses, the internal arrangement of partitions and furniture components must be designed with particular attention. Indeed, it is crucial to have a uniform and symmetrical weight distribution to achieve and maintain the equilibrium.

With respect to amphibious houses, they are characterized by two fundamental conditions: (i) the "static" position, in the absence of water, and (ii) the "floating" position, in the presence of water at different heights (flood depths), depending on the intensity of the flood (Fig. 3). The house is partially built inside a hole in the ground, the so-called wet-dock, which is about 2.5-3.0 m deep. The base of the wet-dock is a concrete slab, permeable to water, placed on piles, with Larssen sheet piling retaining walls along the perimeter. In static conditions, the house rests on the stalls and is secured to the wet-dock by two "guide" poles, on which it slides, rising and lowering, in case of flooding. The ground floor of the house (*caisson*) is made of dense and waterproof reinforced concrete, designed to be resistant to impact damage but also for ensuring the buoyancy. Above the caisson, which constitutes the basement, and which can be partially underground, the house has a wooden frame or still employs other light materials for the above-ground parts. The utilities' connections between the building and the ground are made of flexible and well-insulated pipes so that they can move when the house floats. The space between the building and the walls of the wet-dock is reduced as much as possible by a concrete curb, to avoid the access of debris that could prevent the floating mechanism, which works within certain height limits: it is limited to 2.5 -3.0 m elevation compared to the static condition.

The difference between amphibious and floating houses is that the latter is always in the water, i.e., in a floating condition, while the former is in the water only in case of flooding. Floating homes are connected to the mainland by a jetty and are subject to greater variety. They are very similar to amphibious houses; they are anchored through guide-poles, but they differ from each other in the techniques used to guarantee buoyancy. Some floating homes, such as those in Ijburg, are built with a heavy base made of waterproof concrete, just like the above-described amphibious houses, with a light wooden frame structure above to keep the center of gravity low and ensure stability. As already mentioned, unlike amphibious houses, floating houses always remain in floating conditions, and the mooring posts are placed on the two diagonally-opposite corners to avoid overturning. The floating houses are built entirely in the factory and then transported to the site, sometimes directly by water, as shown in Fig. 2.

Other floating homes are simply based on floating foundations of different types, as in the case of MOS Architects building on Lake Huron: in this example, the floating home is a light, wooden house designed with a careful analysis of weight distribution, placed on floating foundations (Fig. 4, images 3 and 4). The latter, as suggested by English and colleagues [12], can be both a

Fig. 4. *1 and 2, Floating home in Boiten-Ohe-Laak, Maasvillas complex [22]; 3 and 4, Lake house Huron, Canada, MOS Architects [24]; 6 and 7, Urban Rigger in Copenhagen, Denmark, BIG [23].*

solution for new buildings and a retrofit solution for existing buildings in critical environments, such as in Florida or Louisiana, which are often hit by extreme flooding events. Furthermore, especially in the case of developing countries, these floating foundations can be made up of recycled elements, such as empty plastic bottles [25].

Both floating and amphibious houses require careful maintenance and annual tests to verify the buoyancy. They have a construction cost that is 20-25% higher than standard houses on the mainland. In addition, amphibious and floating houses cannot withstand high water speed (>2 m/s), therefore they must be located in suitable areas according to flood characteristics.

2.2. CASE STUDY AND DYNAMIC SIMULATION

In consideration of the greater variety of amphibious houses, with their "double identity" of being employed either with or without water, we decided to analyze this typology as a case study. Moreover, the choice is supported by the additional consideration that some floating houses (e.g., Jiburg) also have the same construction characteristics. As evidenced in the previous sections, the main difference in construction characteristics of amphibious houses with respect to floating houses resides in the presence of the wet-dock.

In this work, we aim to test – under the energy perspective – the construction typology of the amphibious home, as it was designed by the British designers, but in a Mediterranean context, so as to investigate its behavior and compare it to the Dutch and British ones. Therefore, Ostia (Roma, Italy) is selected as a location for the case study, also due to the increasingly frequent flooding events [7] in the area and the future projections confirming this trend (Fig. 1). Within the Ostia environment, amphibious homes could be employed to improve resilience in the built environment and safeguard citizens living in more prone-to-flooding areas.

The case study building is residential, and is modeled after the amphibious house designed and built by BACA Architects with respect to the construction characteristics of the wet-dock, the concrete caisson and the envelope (vertical and horizontal) of the floors above the caisson. The building has three levels. One of them is partially underground when the building is in its static position and goes above the ground when the building rises when the wet-dock is inundated.

Each floor has 68.5 m^2 surface area, for a total surface area of 205.5 m^2. The thermal zones are modeled in accordance with each room's function and occupancy (e.g., bedroom, kitchen), with the same schedule described in [26]. The external envelope is composed of a finishing wooden layer (2 cm thick); a waterproofing layer; a prefabricated layer composed by a sandwich panel with 14 cm of thermal insulation and an internal finishing layer. The thermal transmittance of the entire vertical opaque envelope is equal to 0.25 W/m^2K. The energy system is entirely fueled by electricity, both for heating (CoP of 0.83) and for cooling (CoP 1.67) and does not vary among the different simulated cases. The only differences among the simulated cases are location (Ostia, Amsterdam, London) and the position of the building with respect to the ground (amphibious, amphibious in floating position and partially-underground).

The modeled building is then simulated (dynamic annual energy performance) by means of EnergyPlus software, which is widely employed and validated in literature. Different simulations are performed, for different configurations of the amphibious building. In greater detail, simulation is performed (i) in the static position and (ii) in the amphibious-floating condition; moreover, we compare the amphibious typology performance with that of (iii) a building with the same construction characteristics, where the first floor is underground; finally, the static position of the amphibious building is simulated for the climates of (iv) Amsterdam and (v) London for comparison purposes. The results are presented in the next subsection.

3. RESULTS

The results of the simulations are presented below in the Table and Figures below. The results evidence that the semi-underground house is linked to slightly reduced consumptions, 1-2 kWh/m^2 with respect to the amphibious house, and this finding is consistent in all the considered locations. This is an expected result since, in the amphibious house, there are air and water flowing between the ground and the vertical envelope. On the other hand, the semi-underground house is thermally protected by the adjacent ground.

Annual energy consumption [kWh/m^2]			
Location	Ostia	London	Amsterdam
Amphibious house	84.75	98.41	101.85
Semi-underground house	81.63	96.56	99.59

Tab. 1. *Annual energy consumption for the case-studies in the different locations, for the amphibious and the partially-underground cases.*

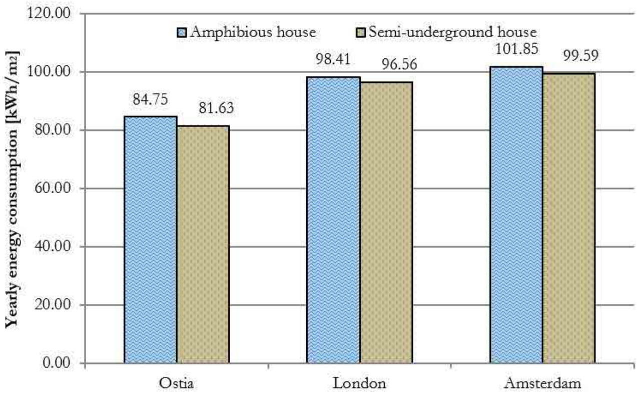

Fig. 5. *Annual energy consumption for the case-studies in the different locations, for the amphibious and the partially-underground cases.*

Such comparison is merely indicative and is conducted due to the similar configuration of the two house typologies in question, since both typologies have one floor below the ground level and the other floors are above the ground. The similarity, as evident from the description of the construction and technological features of the two houses, is merely apparent and derives from the houses' configuration with respect to the ground.

The design and technological features of the amphibious houses are driven by the requirement to withstand inundation, while in this situation the semi-underground house would be absolutely inadequate. However, as demonstrated by the results of the numerical computations, the difference in the energy performance of the two houses is not enormous.

Moreover, the difference in the energy performance of the amphibious house in static and floating position is not significant. Thus, in the tables, only the results of the static position are reported. Significant differences can be noticed when considering the yearly and monthly energy demand in the different locations of the case studies, Ostia, London, and Amsterdam. From the simulations, it is evident that the energy demand related to Ostia is mainly for cooling purposes in the hot season, while that for heating in the cool season is lower. Instead, in London and Amsterdam the opposite happens. This finding is significant for the Mediterranean cities and evidences the differences with respect to the other Mittel-European countries, where, until now, the amphibious house typology is mainly employed and diffused. This difference is due to the local climates in the cases at hand, leading to different air temperatures, direct solar radiation, wind velocity and other variables throughout the year (Fig. 6).

In Ostia, air temperature is higher and wind velocity is lower throughout the entire year, leading to lower energy consumptions, around -15 kWh/m^2 each year, than they are in London and Amsterdam. In greater detail, in Ostia, cooling energy demand is prevalent; this finding is visible in Fig.7 where the highest peak is in summer months. While London and Amsterdam consume around 850 kWh each for cooling throughout the year, Ostia consumptions are three times higher, equal to 3000 kWh. On the contrary, during the cold season, Ostia consumptions for heating, equal to 3000 kWh, are less than 1/3 lower than in London and Amsterdam, where heating energy consumption is 9000-9600 kWh. The same ratio, equal to 1/3, is thus observed between cooling (Ostia 3, London and Amsterdam 1) and heating (Ostia 1, London and Amsterdam 3) energy demand.

The findings of this study evidence two main observations:

– The adaptation capacity towards inundations does not significantly affect energy performance when compared to the "non-adapted" solution (from the comparison between the amphibious house and the semi-underground house).

– In the Mediterranean area, energy-efficient measures for the inundation-resilient house typology – which are mainly designed and implemented in northern European, heating-prevalent countries – should aim at reducing cooling-energy demand.

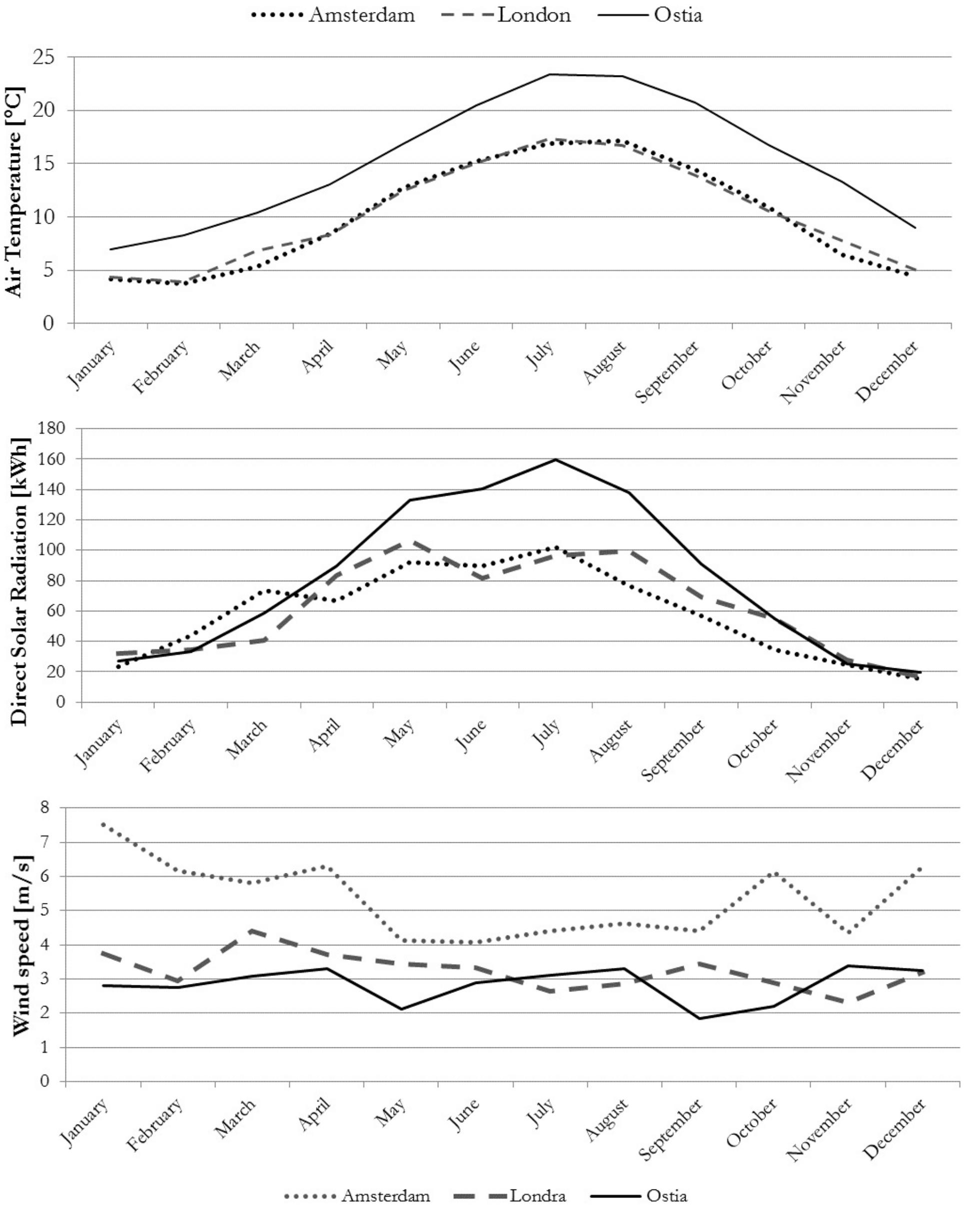

Fig. 6. *Weather variables in the locations in question.*

The possibility of reaching optimal energy performance in amphibious and floating houses could have great potential towards the diffusion of such houses in Mediterranean countries. Indeed, these house typologies could be suitable for those locations, where, due to the changing climate and more frequent extreme rain events, adaptation actions are required towards resilience.

4. CONCLUSIONS

In the work presented here, two peculiar residential building typologies are taken into account, which are designed to adapt urban areas to the growing inundation risk that follows the increase in frequency of extreme rain events. Such inundation risk, according to the United Nations, will be exacerbated in the near future as an effect of climate change.

Amphibious and floating houses are solutions aimed at contributing to resilience and adaptation of urban areas with respect to such climate-related issues, mitigating the risk and safeguarding safety and well-being of the urban population.

These building typologies are mainly used in places such as Northern European countries, whose climates differ from those bordering the Mediterranean. Here,

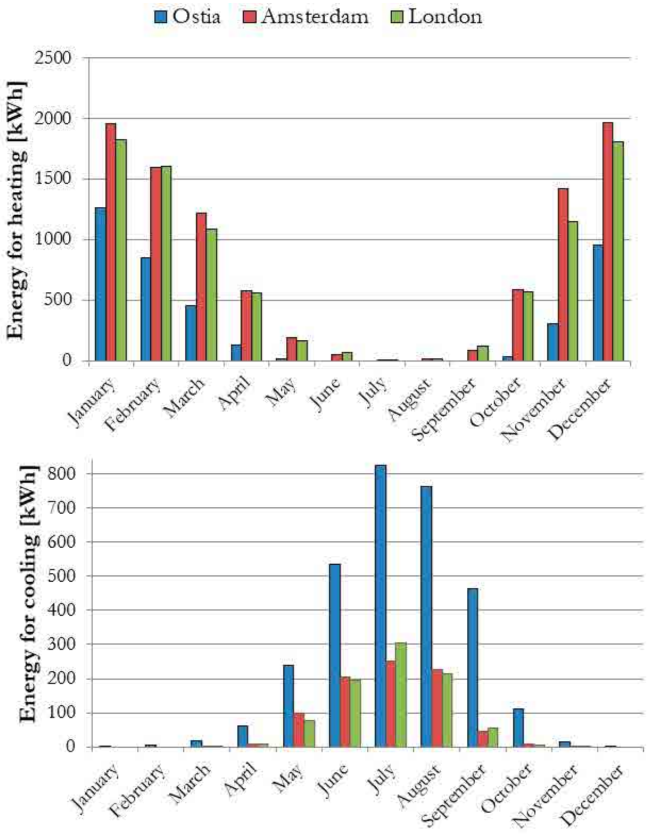

Fig. 7. *Monthly energy consumptions for heating and cooling throughout the year in the locations in question.*

we aim to (i) analyze the construction features of amphibious and floating houses, based on existing examples mainly located in the Netherlands and England, and (ii) consider such typologies in Ostia (Rome), where inundation risk of some areas is high, and where climate conditions are typically Mediterranean, especially with respect to their influence on energy performance. Dynamic simulations to evaluate energy performance are conducted for Ostia, London and Amsterdam and results compared. Findings demonstrate that the typology in question consumes less energy in Ostia than it does in London and Amsterdam, but it can be potentially improved with respect to hot-season performance, in terms of reduction of energy demand for cooling. Moreover, energy performance is not significantly worse, with respect to energy consumptions in all three locations, to that of a traditional semi-underground building with similar ground position.

As a closing remark for this first part of the study on the considered typologies, we can say that amphibious buildings are a promising solution to improve resilience towards inundation in some urban areas with a Mediterranean climate. Future studies should provide a more in-depth focus on the application of passive strategies for reducing energy demand for cooling, thus improving the energy performance of these typologies. Also, their economic, and regulatory feasibility should be addressed, given the scarce diffusion of such buildings in Mediterranean countries.

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