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Rethinking and comprehensive planning of the floating city concept

Carlo Ruzzo, Maria Luisa Cacurri, and Felice Arena*

Abstract

Sea level rise, coastal erosion and climate change are major stressors for coastal communities, whose expansion may be also limited by land scarcity and environmental issues. Floating cities may represent an interesting solution, but require further conceptual development, both in terms of technological means and architectural vision. Furthermore, their feasibility and sustainability still need to be explored more in depth. In view of these gaps, here we propose an innovative floating city vision, based on a comprehensive approach, including qualitative and quantitative analyses and ranging between all the above-mentioned topics. The concept is built around three pillars: resilience, sustainability, and urban welfare, corresponding to the three elements of water, nature, and man, respectively. A preliminary quantitative analysis about space, food and energy requirements confirms the feasibility of the floating city and provides a benchmark for future investigation on similar concepts.

Keywords:

Floating city; sustainability; resiliency; urban welfare

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1. Introduction

The concept of floating city may respond to very urgent challenges imposed by urban development and climate change. The current trends indicate that the world population will grow significantly in the next decades and will tend to concentrate in cities. The United Nations [1] predict that it will surpass 9.77 billion in 2050, with a percentage of urban population of 68.4% (~7.80 billion and 56.2 % in 2020). The urban growth, however, must deal with the obstacles and limitations imposed by land scarcity, environmental constraints, and climate change. Such challenges impact particularly the coastal areas [2], hosting about 40% of the world population [3] and about 70% of the world megacities [4], and the islands. The coastal hazards ascribable to climate change [5] encompass particularly sea level rise, coastal erosion, and land flooding. Quantitative estimations from independent literature studies [6] indicate with medium confidence that the global mean sea level rise with respect to 1995-2014 will be between 0.19 m (0.16-0.25) m and 0.23 (0.20-0.30) m in 2050, and between 0.44 (0.32-0.62) m and 0.81 (0.63-1.01) m in 2100, depending on the climate change scenario and the projection method chosen. In conjunction with the increasing probability of extreme weather-related events [7] and with land subsidence of inhabited areas, this may exacerbate the vulnerability of the coastal cities and limit their growth potential. The quantification of these risks and the determination of the required mitigation and adaptation strategies are highly site-dependent, and numerous studies are available in literature for specific sites [8–10]. At a global level [11], a uniform sea level rise of 1 m would increase the land areas below +2 m up to 1,464,000 km^2, involving 410 million people (1,046,000 km^2 and 267 million people in 2020). Based on the sea level rise projections, 360 (310-420) and 480 (380-630) million people would be threatened by annual flood events in 2100, under moderate and severe future scenarios, respectively [12]. Available adaptation strategies, encompassing the relocation of people, assets and activities in safe areas, the restoration or creation of natural buffer areas, the implementation of hard-engineered coastal defenses, and the limitation of human-induced subsidence, have case-dependent risk mitigation efficiency [13], answering only partially to the mentioned challenges.

The floating cities may arise as a promising alternative for future urban development in coastal and offshore areas[14]. They would not suffer from spatial constraints, sea level rise, and earthquakes and would provide the unique opportunity to rethink and revolutionize the city structure and organization, its environmental sustainability and the urban welfare. Recently, Wang [15] identified six architectural paradigms of floating cities and structures, based on the motivation driving their design scheme, namely: traditional settlements, marine utopias, leisure colonies, sovereign

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territories, industrial infrastructures, and climate-resilient urbanism. These archetypes reflect the evolution of the practical, literature, and commercial interests on the topic, and provide a basis for the contextualization of the concept proposed in this work.

Historically, the first examples of floating villages dates back centuries [14,16]. Nowadays, small floating villages or neighborhoods may be found all over the world, with very different characteristics between each other [17,18]. However, up to now, the concept of floating cities has been mostly subject of utopian thinking [19], raising interest particularly since the second half of the 20th century [20], in a context of population and economic growth after World War II (1950-1970). Japanese Metabolists, like Kikutake, Kenzo Tange, and Kurokawa, were protagonists of the first generation of floating city concepts, inspired by the concepts of biological models and megastructures [21]. Another influential concept was Triton City, proposed by Buckminister Fuller [22] for the Tokyo Bay in 1960s and further developed later for potential application in the city of Baltimore (US). These concepts were driven by the technological optimism of those years and answered the need for expansion of the industrial and port areas of Japanese coastal cities, as an alternative or a complement to land reclamation. As such, they may be regarded as "utopian romances", following Fishman's classification of urban utopias [23], and do not contribute to social vision renovation sensibly. In the following years, the economic crisis and the growing awareness about urban sprawl, resource depletion, and environmental degradation caused a reduction of interest in the floating city concept [24]. The most notable step forward was the construction of the first floating city prototype [25], designed by Kikutake for the Okinawa International Ocean Exhibition (Japan, 1975) and dismissed in 2000. The reasons for the missing development of the floating city concepts may be ascribed to a combination of technological, economic, political and regulatory issues [26,27]. However, the recent years have experienced an outstanding development of the offshore technologies from one side, and a strong awareness of the mentioned challenges imposed by the climate change on the other, motivating a renewed interest in floating cities. This is witnessed by the insurgence of several new concepts and ongoing projects worldwide (a comprehensive list up to 2024 is available in Ref. [24]), some of which are already in the construction phase. Among them, Oceanix Busan (South Korea) and Maldives Floating City (Maldives) are the most mature projects, expected to be completed within 2025 and 2027, respectively. Oceanix City [28] will be made up of six hexagonal modules attached to Busan coastal area, covering a surface of ~7.5e5 m^2 and housing ~10,000 residents. Maldives Floating City [29] will be a complex of several thousand floating housing units, with a layout inspired by the brain coral. It will be installed over a protected lagoon close to the capital Malé, on a surface of ~2.0e6 m^2 and housing ~20,000 residents.

Despite the existence of several floating city concepts and ongoing projects, a critical analysis of the literature reveals that the available information are scarce, often not adequately justified, and sometimes contradictory. This is because the most mature concepts are proprietary, while few peer-reviewed research articles on the topic are available. Furthermore, most of the floating city concepts proposed up to now are conceived as nearby attachments to existing coastal cities or islands. Although reasonable in light of the preliminary concept stage, we believe that this limits the potentialities of urban conception and citizen lifestyle renovation that a satellite floating city [14], situated off the cost and independent from existing urban agglomerates, could promulgate. Therefore, this research is driven by three objectives and four specific research questions, formulated in the following:

- Objective 1: To propose and characterize in detail a satellite floating city concept, self-standing from technical, urban, and identity points of view.
- Objective 2: To develop a preliminary, yet comprehensive, urban planning of such a floating city.
- Objective 3: To identify and discuss the main limitations of the adopted methodologies and the open challenges attaining the multidisciplinary research on floating cities.
- Research question 1: What are the structural and functional elements necessary for a floating city functioning?
- Research question 2: What should be the main directories of its urban planning? What are expected to be their implications on the city design?
- Research question 3: What are the quantitative space requirements of the floating city in function of the number of residents? How should these spaces be distributed?
- Research question 4: What are the quantitative energy requirements of a floating city in function of the number of residents? Is it feasible to produce such energy locally by renewable sources?

The main contribution of this research is to fill the identified literature gaps, providing a benchmark and a guidance for future qualitative and quantitative studies on floating cities. Furthermore, the concept proposed represents a step forward in the tradition of utopian floating city models, in which urban space and urban life mutually interact [19]. This approach has elements in common with Fishman's concept of "ideal cities" [23], and is in line with the emerging new urban utopianism [30], pursuing the objective of environmentally sustainable and culturally inclusive cities.

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To pursue the chosen objectives and answer the formulated research questions, we propose an innovative floating city vision based on a comprehensive approach, including both qualitative and quantitative analyses and built around three pillars: resilience, sustainability, and urban welfare, corresponding to the three elements of water, nature, and man, respectively. The resulting concept presents strong identity aspects, ultimately leading to a substantial lifestyle renovation proposal based on sociality and contact with nature. The preliminary estimates carried out indicate the technological and energy-wise feasibility of the concept, under reasonable assumptions. The city layout, dimensions, and resource consumptions are estimated with reference to a case study of a 50,000-inhabitants floating city. These quantitative results can be extrapolated to any city size, being the concept fully scalable thanks to the application of layered modularization principles. Thus, they can serve as a benchmark for future analyses on similar or alternative floating city concepts.

2. Results

The concept proposed in this work can be classified as a satellite floating city [14], situated off the coast and independent from existing coastal urban agglomerates. In line with the work objectives, it is general in scope, and adaptable to a wide range of locations, water depths, and environmental conditions. The ideal installation site would be a limited-fetch sea area in the exclusive economic zones (EEZ) of a coastal/island state, e.g. in proximity of a gulf, a strait, or an archipelago, to draw on moderate wave action and water depth, and facilitate the connection with the mainland.

The floating city is made up of two main modular components: the external protection barrier, and the inner urban conglomerate. A representative layout of the city is shown in Figure 1, while Figure 2 presents a schematic prospectus of the barrier and inner city elements. A further conceptual insight into the main floating city elements is proposed in Supplementary Figure A1.

The floating protection barrier is a modular π-type concrete breakwater. The front wall of the breakwater embodies a U-shaped oscillating water column (U-OWC) [31] wave energy converter (WEC). At its top, the concrete wall is extended by a perforated steel insert. The city-side deck of the barrier is not accessible in adverse sea conditions, and serves as a functional space for floodplain-like temporary crops, city embellishment through sea-resistant elements (natural or artificial), and/or walking area. The barrier mooring system is realized by high-strength steel tension legs (tendons). In plant, the modular caissons are flexibly interconnected, constituting a continuous protection barrier, with an opening oriented towards the less-energetic wave sector for city entrance.

The inner city modules are compliantly-moored, semi-submersible floaters, with the deck raised above the sea level by interconnected slenderer floating elements (columns). In plant, a layered modularization is proposed, distinguishing elementary structural, architectural, and functional modules (Figure 3). The functional modules are square, with ~300 m-long sides, and host all the services ordinarily required for the city life, including residences, health services, education, commercial activities, recreation, etc. Each functional module is made up of two right-triangular architectural modules, juxtaposed at a certain distance (~30 m) and flexibly connected between each other. In turn, each architectural module is made up of a certain number of rigidly-connected structural modules, representing the most elementary floating city components. The size and number of the structural modules composing the architectural module can be adapted, based on the quayside characteristics. A perimeter walkway and other special (customized) modules are attached at the city boundaries, serving for specific functionalities, including the city port.

The residential areas in the functional modules are made up of two building categories, inspired by co-housing principles. Each triangular architectural module contains two five-storey courtyard blocks and three linear six-storey buildings (slats), hosting 240-250 and 340-350 people, respectively, for a total of ~1,500 inhabitants. Graphical inserts about the residential buildings are provided in Supplementary Information, with insights on their layout within each module (Supplementary Figure 2) and on their architecture (Supplementary Figures 3 and 4, respectively). Other buildings, distributed throughout each functional module, are devoted to all the other necessary services, including offices, shops, education, health, religion, and entertainment. A graphical insert on their layout is provided in Supplementary Figure 5.

Table 1 reports the main module and city dimensions. The green areas are placed at the deck level and in elevation, above the roofs of the service buildings and of the slats. The latter may serve also as distributed voluntary crops for local food production. A graphical insert on the green areas layout is provided in Supplementary Figure 6. The blue areas serve for water transport and recreational activities and include the natural pools in each architectural module and the channels between them. A graphical insert on the blue area layout is provided in Supplementary Figure 7. A further graphical insert provided in Supplementary Figure 8 concerns the floating city mobility plan, which

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includes water transport at the still water level, pedestrian, cycling, and electric vehicle paths at the deck level, and a panoramic pedestrian path above the slats.

The 50,000-inhabitants sample city is made up of sixteen square functional modules, and six peripheral special modules, devoted to special activities, such as port, desalination, food production, and waste treatment. The total floating city footprint is estimated considering exemplificative barrier distance and size. Exemplificative render views of the floating city are provided in Supplementary Figures 9-11.

The estimated total floating city final energy consumption under conservative hypotheses is ~470.3 GWh/yr. Food production is the most energy-intensive activity (~47.5%), followed by domestic (~22.2%) and service (~17.6%) consumptions. The required energy is produced locally by renewable energy sources, integrated with storage systems. The solar/photovoltaic panels are sparse throughout the modules, in roofs, canopies or solar trees. The corresponding layout is shown in Supplementary Figure 6, along with the green areas. The wind turbines are concentrated in a floating wind farm, placed outside the barrier. The wave converters are integrated within the floating breakwater. Other energy sources utilizable include waste valorization, current, and thermal and salinity gradients. Considering three reference sites in the North Sea, the Aegean Sea, and Hong Kong, we estimated that the total solar energy power installed in the city rates 68.0 MW and produces ~3.6-5.4 GWh/yr (~16.3-24.5%), while each 10MW floating wind turbine produces ~16-47 GWh/yr (~3.4-10.0%). Details about the estimated energy consumption and production are reported in Supplementary Tables 1-3.

3. Discussion

In order to present and justify the floating city master plan, this Section discusses the principles driving the main design choices, the resulting individual functional elements identified, and their integration within the comprehensive planning, declined through the key directories of resilience, urban welfare, and sustainability.

3.1. Resilience

The term “resilience” is increasingly applied in variegate academic disciplines and focus areas, although with variable and sometimes inconsistent meanings [32]. In the context of urban resilience, a comprehensive definition may be borrowed from Meerow et al. [33], resulting from the synthesis of 25 different definitions from 172 academic studies: “*Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*”. As such, the urban resilience must interest all the dimensions of the city, namely social and institutional, physical, economic, and natural [34]. Thus, it has been chosen as the first key directory for the floating city urban planning, and it has been associated with the element of water, which drives the main floating city stressors (e.g. sea level rise, waves, currents, etc.) and provides the most important resources (buoyancy, space, food, energy, etc.) for its functioning and adaptive capacity. In the following, the urban resilience of the floating city concept proposed is discussed, with reference to the eleven main attributes illustrated by Ribeiro and Pena Jardim Gonçalves [34], namely: robustness, adaptation, resources, redundancy, diversity, integration, inclusion, connectivity, independence, efficiency, and innovation. A schematic counterpart may be found in Supplementary Figure 12. It should be noted that the social and institutional, economic, and natural urban resilience dimensions partially overlaps with the other two key directories of the floating city urban planning, namely urban welfare and sustainability. Therefore, the discussion in this section focuses specifically on how the urban planning interacts with eleven main attributes identified, and thus to urban resilience.

The most straightforward class of disturbances against which a floating city must exhibit resilience is that of the physical stressors, including the natural disasters and hazards induced by the climate change. The floating city is inherently resilient with respect to the sea level rise, because it modifies its vertical equilibrium position, following the mean water level. The robustness against the environmental loads is evaluated as its ability to withstand the design ultimate, service, and fatigue limit states.

Ultimate and fatigue performance requirements are conceptually analogue to those of other floating offshore structures, as structural safety must be guaranteed. These requirements are usually deemed fulfilled for floating city concepts mostly by assuming them to be placed in a protected coastal environment. Previous studies [35] have stated the feasibility of achieving these requirements also in open sea areas, by using floating breakwaters. In this work, we propose π-type breakwaters [36], as they provide enhanced reflection capabilities with respect to box-shaped ones, thanks to the inferior vertical plates. Being the characterization of the wave transmission behind a floating breakwater a complex and partly unresolved task, we have implemented a simplified literature formula [37], assessing the breakwater wave mitigation coefficient as a function of variable parameters and wave conditions. Some results

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are presented in Figure 4. The mitigation performances improve with the breakwater size, and are optimal when the breakwater heave natural period T_h is close to the wave peak period T_p (heave resonance). Instead, they degrade for increasing T_h, up to a maximum around $1.38T_p$, possibly corresponding even to wave amplifications. Thus, relatively small breakwater heave natural periods are required. This is the main reason for proposing a tension leg mooring system, along with the substantial reduction of the maximum barrier horizontal motions. Furthermore, the tendons induce the setdown [38]: a negative vertical motion caused by the horizontal loads, such as wind, current and wave drift. It has a positive effect on the wave mitigation performances, since the barrier adapts to severe wave conditions by augmenting its draft and thus its reflection capabilities. Based on the preliminary quantitative results obtained, however, it is observed that floating breakwaters may not be sufficient to adequately mitigate the longer waves typically occurring in exposed sea areas, due to local storms or long-transmitting swells. Thus, oscillating water column (OWC) wave energy converters (WECs) are embodied in the breakwaters, being suitable for wave energy absorption, especially at relatively long periods. Whilst enhancing the wave mitigation potential, they contribute to the redundancy and diversity of the renewable energy production systems. Among the available concepts [39], floating U-OWC (REWEC3) [31] has been considered, being the first one demonstrated at full scale in a fixed breakwater [40] and at large scale in a multi-purpose floating platform [41]. Finally, wavy-profiled, perforated steel inserts are added on the top of the breakwater, to reduce the wave overtopping and for aesthetical purposes. Seen from afar, they would look like mountains, giving the city a pleasing skyline, well integrated in the architectural context.

The choice of semi-submersible floaters for the inner city modules is intended to provide better hydrodynamic response with respect to the pontoon-type ones, in terms of robustness, mitigation of the oscillations, and excess of available buoyancy. Resiliency-driven considerations are also key in assessing the city layout. The proposed layered modularization offers redundancy and diversity of the buildings and services, while reducing the production costs of the modules, thanks to the economy of scale, and conferring flexibility and adaptability to the floating city shape and size. During the construction and installation phases, the modules may be assembled at quayside and towed to the installation site, without the need for expensive lift vessels and minimizing the operations at sea. Similarly, they may be easily and rapidly added, moved, and/or replaced in case of necessity (e.g., city expansion or maintenance). From an engineering point of view, the architectural modules are sufficiently small to be regarded as rigid bodies. Based on the existing scientific literature, the elastic deformation effects are expected to play a non-negligible role in a floating structure dynamics if at least one of its sides is longer than approximately 1 km [25,42,43]. The representation of the hydro-elastic dynamic behavior of such Very Large Floating Structures (VLFSs) is a complex and partially open challenge. This is not the case of the proposed architectural modules, which are protected from excessive loads by the flexible joints, where the deformations are concentrated. This also facilitates the hydrodynamic modeling necessary for further development of the proposed concept.

The mooring system of the internal modules is conceived as redundant and compliant, made up of shared catenary and/or taut lines. This solution is more resilient and less expensive than a tension leg mooring system, allowing for larger modules' displacements in response to the incoming environmental forces. Furthermore, it implies smaller mooring loads, vertical motions, and horizontal motion natural frequencies. However, relatively large horizontal motion amplitudes are expected. Thus, the spacing between the architectural modules, and between the city and the floating barrier, must be sufficient to avoid contacts. In view of the complexity of the floating city dynamics and to improve resiliency, we also envisage the potential need for propellers for active horizontal motion control in each module. These elements are conceived to support the module handling, towing, installation, and maintenance, and as back-up positioning systems in case of damaged moorings and/or occasional extreme displacements, to avoid contacts between modules and overloading in their connections.

Based on previous literature [42,44,45], high-quality reinforced concrete is envisaged as the core material for all the modules, with steel inserts when necessary. With respect to steel, reinforced concrete is cheaper, facilitates local construction, and offers better resistance to corrosion, while maintaining good robustness. However, other innovative materials may be also adopted, such as bio-rock [28,46], based on techno-economic and environmental analyses.

The service limit states are intrinsically related to the city specific functionalities, and especially to the inhabitant comfort. Although some quantitative comfort requirements have already been identified for civil buildings [47] and manned offshore structures [48,49], we believe that the topic is worth specific investigations, aimed to qualify the resiliency expected from the floating citizens themselves, in terms of adaptation to the floaters' oscillations, and to quantify the impacts on the city service requirements. In the proposed concept, to facilitate the achievement of the comfort requirements, the residential modules are placed internally, being further protected by the special ones, where larger motions and accelerations are tolerated.

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The floating city resilience is not limited to the physical dimension. The urban model proposed encourages the generation of a resilient community in several ways. The adoption of a co-housing approach, the diverse offer of residential units, and the abundancy of common spaces and shared activities are aimed to favor the generation of an inclusive, strong, and interconnected community, which is expected to be actively involved in the city life and management. In turn, the sense of community stimulates the mutual collaboration between citizens, favoring inclusion, connectivity, and integration. The transport, energy, food, and water production systems of the floating city are characterized by diversity and redundancy, and confer it autonomy, in conjunction with the local waste and wastewater treatment systems. Water may be obtained by desalination, rain purification, and wastewater treatment and reutilization, while food by the combination of several sources among which: agriculture, aeroponic, and hydroponic systems, aquaculture, fishing, and/or farming. The abundancy of food sources discourage any intensive farming, enhancing sustainability as well as food quality. A closed-loop system [28] is envisaged for waste treatment, involving reuse and valorization for producing energy, recycled materials, and organic sub-products. The urban planning contributes to optimize these processes, by offering special peripheral modules and areas for the required plants, including aquaculture, waste treatment and wind farm, as well as distributed food and energy production and possibly wastewater/rainwater treatment systems, host in the functional modules. Attaining the energy production, our simplified analysis shows that an average-size floating wind park (100-300 MW) is capable of sustaining the 50,000-inhabitants floating city consumption. However, the envisaged implementation of variegate sources contributes to reduce risks, flatten the production curve, and relax the storage requirements. An interesting outcome of our work is the relatively small solar energy production. This differs from previous literature [28], and is motivated by the scarce solar energy density, resulting in large panel areas required for substantial production. We deem this undesired, since it would reduce the open city spaces and increase the overall sunlight blockage. This point is open for multi-disciplinary research involving technic, economic, and environmental impact assessments, as well as architectural considerations.

The governance model of the floating city and the legislative framework in which it is defined are other key resilience-related aspects, which are not directly addressed in this work, due to their complexity. In this regard, a brief discussion is included in the Methods section to support further research on these topics

Finally, the floating city resilience also has a natural dimension. The floating city is strongly connected with nature and this relationship may lead to mutual advantages. The shelter and the diverse of environments offered by the city, including green (terrestrial), aerial, intertidal and submerged areas, may indeed favor the generation of complex local ecosystems, enhancing the biodiversity. The city may also play an important role in the protection of such ecosystems, by implementing passive and active strategies, commented in more detail in the following sections.

3.2. Urban welfare

Among the greatest opportunities provided by the floating city concept, there is the renovation of the urban lifestyle and of the perceived citizen identity, made possible by the introduction of the sea element, and the opportunity to rethink the urban planning from its most basic elements, which is unfeasible for existing terrestrial cities. Thus, we have chosen urban welfare as the second key directory for the floating city urban planning, and we have associated it with the element of man, with the intention of placing the floating citizens at the center of our proposal.

In literature, the description and quantification of the urban welfare is usually addressed by variegate sets of indicators, encompassing the main dimensions of the urban experience of the citizens [50–52]. The values associated to each indicator depend on quantitative data, e.g., from demographic analyses, or to qualitative observations. Despite the large variability in the definition and quantification of the indicators, we may identify some recurrent dimensions including: 1) Building heritage and living standards; 2) Social stability/development and eradication of poverty; 3) Health care and Instruction; 4) Access to public and private services; 5) Mobility and infrastructures; 6) Environment and effects of climate change; 7) Governance. An exemplificative evaluation framework, considering recurrent urban welfare indicators in pertinent literature, is proposed in Supplementary Table 4. In addition to this framework, we have identified some major drawbacks in modern society and urban lifestyle, especially impacting developed countries. Inevitably, this analysis is somewhat subjective, and may differ from part of the extremely vast literature in this regard. Among the criticalities identified, we believe that individualism plays a major role, pervading all the aspects of the society and breaking the mutual cooperation between people and their sense of community. Concerning the urban lifestyle, we highlight a combination of factors, such as: detachment from nature, fast pace, excessive use of technologies, pollution, and alienation. Based on this perspective, we propose sociality and contact with nature as pillars of the floating city lifestyle, resulting in a preliminary, yet detailed masterplan, illustrated in the following and complemented by the graphical inserts proposed in Supplementary Figures 1-8.

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The building architecture is freely inspired by an existing concept [53], utilizing a cruciform structure to modularize the living spaces. The traditional urbanistic and housing standards are reconsidered, reducing the private dwelling sizes in favor of larger common and outdoor spaces, in the context of a co-housing approach, aimed to boost sociality, sense of community, and efficiency in the use of resources. The two residential buildings categories, namely courtyard blocks and slats, are intended to serve different user needs. The courtyard blocks are dedicated to students, workers, and more generally adults, living alone or together. The private areas are reduced within adequate living standards, and common spaces, including balconies, fitness areas, laundries, and kitchens, are placed at each floor to encourage sociality. All the apartments offer sea view and receive illumination from the perimeter and the courtyard, which serves also as a shared green space at the deck level. The slats are instead intended to host families with children. Thus, they present larger apartments, with common spaces concentrated at the deck and roof levels. The illumination is provided from the perimeter and several light wells, serving each apartment. Detailed insights into the courtyard block and the slat architectures are provided in Supplementary Figures 3 and 4, respectively, including quantitative indications about the apartment size in function of the number of residents. Overall, the residential offer is variegate but substantially egalitarian, and guarantees the access of the whole population to good-quality residences, sanitary services, clean water, electricity, communication networks, and the other necessary services. The scalability of the city and the stability of the population density prevent overcrowding. The marine context and the abundancy of green spaces and parks, either at deck level or elevated (Table 1, Supplementary Figures 6-7), provide openness of space and favor the direct contact with nature. The combination of these factors encourage physical activity and healthy use of the outdoor spaces [54]. The service buildings are interspersed throughout the modules. The smaller ones (e.g., offices, shops) are integrated with the slats, constituting a pedestrian path at the deck level, shared between contiguous architectural modules. The others (e.g., education, health centers) are concentrated in the opposite sides of each module and have larger appliances, including wide open and green areas.

The mentioned architectural choices concur to the objective of supporting the development of a strong and united community [55]. This is a key aspect of the floating city, and has important implications on several aspects, such as the reduction of urban crime and violence, the mutual collaboration between citizens, the associationism, the community engagement in the city life.

The entry and living cost of the floating city is influenced by the construction and maintenance cost of the modules, and of the other systems. A simplified cost assessment framework, limited to floatation and energy systems, is proposed in the following section, with remarks about the cost reduction strategies implemented in the concept proposed. It should be noted that quantitative floating city cost estimations sensibly depend on its size and installation site, while the impact of such costs on the cost of life depends on the economic and governance models of the floating city, which are not addressed in the present work.

The functional modularization of the city reduces the commuting distances and encourages healthy activities, such as walking or cycling. The mobility plan is multimodal and multilayered (Supplementary Figure 8). The first layer is made up of wet routes between the modules at the still water level (quote z = 0.00 m). It is mainly devoted to inter-module transport, by means of electrical or rowing boats, shorter than 3-4 m to pass below module interconnection bridges. Each functional module is equipped with a small marina to host the boats. This transport system has the potential to become a characteristic element of the floating city, recalling the fascinating Venice's channels and gondolas. The second layer is made up of intra- and inter-module dry routes at the deck level (z = 2.00 m), including the city perimeter walkway. Some of these routes are reserved for pedestrian and/or bike paths, including the common spaces at the ground floor of slats and service buildings, while others are open for the use of electrical vehicles. The module interconnection bridges are flexibly jointed, to allow for differential displacements between modules, and inclined up to 10°, to provide the necessary elevation for safe boat passing. The last layer is made up of an elevated pedestrian path (z = 20.00 m), connecting the top of the buildings and their green areas, and offering a beautiful panoramic view of the city skyline and of the surrounding sea. Although potentially feasible, submerged paths and rail transports are not envisaged at this stage, mainly due to technical challenges related to the relative module displacements. For the city size considered, it is assumed that the potential benefices of such modes would not justify the corresponding costs. The water area between the inner city and the barrier is used for internal transports, allowing the transit of taller boats. Furthermore, it may serve as a safe area for aquatic sports and recreational activities. The connections with the outside of the city mainly occur by sea, through the city port. In addition, heliports are envisaged in the peripheral structural models.

Another key identity aspect of the floating city is the relation with the sea. Each triangular architectural module is equipped with a natural swimming pool, partially covered by a slat, close to its geometrical center. Furthermore, each square functional module has a stairways leading directly into the sea, in the internal side opposite to the boat

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path. These elements have high practical and symbolic value, physically representing the return to the nature and to the sea promulgated by the floating city, and offering further areas for healthy recreational and sport activities.

3.3. Sustainability

The urban sustainability concept encompasses dimensions in common with the urban welfare, namely environmental, economic, social, and governance [56]. Several frameworks and strategies have been proposed in literature for the urban sustainability assessment of traditional onshore cities, often based on diverse sets of indicators [57]. As already discussed, the proposed floating concept addresses the majority of such indicators. For example, it addresses at least 23 (B1, B2, B3, B4, E1, E2, E3, F1, F2, G1, G2, M2, M3, M4, UP1, UP2, Up4, W1, W2, Wa1, Wa2, Wa4, Wa5) out of the 28 strategies identified by Petit-Boix et al. [58], and tackles all the 8 issues identified, namely buildings, energy, food, green spaces and landscape, mobility, urban planning, waste and water. In this regard, Supplementary Table 5 schematically reports the strategies adopted within the urban floating city planning in relation to each of these indicators.

In addition, the floating city stands out with respect to the traditional ones for the greater importance of the environmental dimension and the peculiar aspects that it involves. Therefore, we have chosen sustainability as the third key directory for the floating city urban planning, and we have associated it with the element of nature, focusing specifically on the minimization of the environmental impact of the city. The specific aspects of the environmental impact assessment (EIA) of a floating city are not yet adequately investigated in literature. In particular, a scarcity of sources, especially peer-reviewed, is detected attaining the comprehensive environmental impact assessment of a floating city. Thus, in this work we briefly discuss the main beneficial aspects of the proposed floating city concept, with reference to the framework [59] proposed within the Floating Island Project [60]. It identifies nine relevant environmental indicators of a floating city, divided in three classes. The physical indicators include underwater light, water temperature, and suspended matter and turbidity. The chemical indicators include dissolved oxygen, nutrients, seawater alkalinity, and toxic substances. The biological indicators include community aspects and animal behavior. The following discussion focuses on how the peculiarities of the proposed concept may specifically enhance the environmental balance of the floating city. The corresponding strategies adopted within the urban floating city planning in relation to the mentioned indicators are also summarized in Supplementary Table 5.

The mere physical presence of the city introduces a discontinuity in the water-air interface, impacting underwater sunlight, temperature, and dissolved oxygen. Furthermore, the concrete carbonation and leaching may alter the seawater alkalinity and introduce pollutants. The proposed city concept mitigates these effects by reducing the relative vertical and horizontal floating city footprints, being installed on relatively deep waters and thanks to the wide internal free water spaces.

Another class of impacts is related to the human activities. In the proposed concept, the absence of heavy industries and the use of renewable energy sources reduce the production and dispersion in the sea of toxic substances and pollutants. Thermal and noise pollution [61,62] are reduced by the sparsity of the buildings, the adoption of high-quality isolating materials, and the use of electrical engines for all the terrestrial and marine vehicles, in place of combustion ones. Attaining light pollution, warm lighting is recommended, since it rapidly attenuates with water depth, while having a welcome relaxing effect on the population.

From a biological point of view, the floating city may have positive impacts [63]. In particular, floating structures attract variegate sessile and mobile organisms, including fish and megafauna, and provide them habitat and vertical and horizontal connectivity [64]. In the case of the floating city, the interested areas are larger and more closely connected with respect to the structures currently used for offshore installations, including oil and gas (O&G) and offshore wind platforms. Furthermore, the floating city provides variegate interconnected environments, further enhancing biodiversity. The continuous relative vertical motions between the structure and the sea level generates an intertidal environment, distributed among the semi-submersible module columns and protected from direct human contact. The abundance of green spaces on board provides terrestrial and aerial environments as well. Finally, the interaction between the built environment and the resulting ecosystem may not be limited to the minimization of the detrimental effects, but also include active participation, e.g., by establishing sustainable aquaculture plants able to positively impact water quality and/or nutrient disposal [65].

Sedimentation and erosion phenomena are not of concern, being the city installed offshore, on relatively deep waters.

A crucial, and often underrated, role for the minimization of the environmental impact is played by the population awareness and engagement. This is facilitated in the context of the comprehensive approach proposed,

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offering the citizens a radical revision of lifestyle and perspective, and involving them directly in the construction of a new urban model.

4. Methods

The logical framework of this research, outlined throughout the Introduction and Discussion sections, is schematically presented in Figure 5. This section also provides further clarifications about the breakwater performance, the environmental impact, and the energy-wise feasibility assessments, and some recommendations for future research studies on the floating city concept.

4.1. Floating breakwater simplified performance assessment

The simplified formula assumed for the calculation of the wave transmission coefficient k_t behind a π-type breakwater [37] is:

$$k_{\mathrm{t}} = \frac{\lambda \cosh\left(\frac{2\pi}{\lambda}(d-D)\right)}{\sqrt{\lambda^2 \cosh^2\left(\frac{2\pi}{\lambda}(d-D)\right)+\pi^2 W^2 \sinh^2\left(\frac{2\pi d}{\lambda}\right)}} \frac{1}{1+\left(\frac{\chi-\chi_0}{\sigma}\right)\exp\left[-\left(\frac{\chi-\chi_0}{\sigma}\right)^2\right]} \quad (1)$$

$$\chi = \frac{T}{T_{\mathrm{h}}};\ \chi_0 = 0.7919; \sigma = 0.1922 \quad (2)$$

k_t represents the ratio between the transmitted and incident reference wave heights. In the context of our paper, irregular waves are considered. Thus, these reference wave heights are the significant wave heights H_s of the sea state.

λ is the reference wavelength. In the context of our paper, it is assumed to be calculated on deep waters, based on a period $T = T_p/1.1$ [37], being T_p the peak period of the sea state.

d is the water depth. In the context of our paper, the floating city is assumed to be in relatively deep waters. Thus, it is assumed equal to 200 m.

D and W are the draft and the width of the breakwater cross section, respectively.

T_h is the heave natural period of the breakwater. Note that in the context of our paper we ignore the approximation proposed in [37], which is only valid for a compliant mooring system. Thus, T_h is treated as a variable independent from D and W. χ_0 and σ are empirical constants, obtained by fitting experimental data in the range $\chi \in [0.5; 1.5]$.

The preliminary results shown in Figure 4 are obtained by implementing the formula in MATLAB for 48 combinations of W, D, and H_s, and breakwater heave natural period smoothly variable between 1-35 s. For each sample sea state considered, T_p is calculated by considering a mean JONSWAP wave spectrum [66], representative of design conditions.

4.2. Energy-wise feasibility assessment

The quantitative analysis about energy-wise floating city sustainability is based on the estimation and comparison of the expected floating city energy consumption and production. These analyses are carried out assuming that electricity is the only final energetic source. Direct use of primary renewable energy, e.g., by solar panels or water thermal gradient, may further improve the city sustainability, and is neglected in this study for sake of simplicity and conservativeness.

The overall final energy consumption is estimated by splitting it in several components and dealing with them separately, as detailed in Supplementary Table 1. Domestic and service components are estimated based on historical data, surveyed worldwide from International Energy Agency and World Bank databases (2022). The historical data used are reported in Supplementary Table 2, including also transport, industry and other consumptions, gross domestic product (GDP), total population, and urban population. Countries with GDP per capita between 20k$ and 40k$ are selected as the most representative of the floating city, and their median final energy consumptions are considered in the analysis, corrected to take into account the peculiarities of the floating city. The domestic consumptions are highly correlated to the GDP per capita and to the latitude, due to the importance of heating/cooling component. Since the selected countries are all distributed among intermediate latitudes, no correction is applied in this regard. Instead, energy consumption reductions are envisaged due to the application of co-housing principles and to the greater energy efficiency of the new, highly-isolated floating city domestic and service buildings with respect to the existing, mostly out-of-date building stock. The corresponding reduction

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coefficients are estimated based on the available literature. Transport consumptions of the floating city were limited to intra-city travels. Thus, historical data could not be used, since they include all intra-country travels. Furthermore, historical data of existing cities could be misleading, due to the core differences in city dimensions and transport modes. To achieve a simplified and conservative estimation, two transport contributions are estimated separately. The first refers to "private" travels. Based on the city dimensions, a reference daily distance traveled by each citizen individually is estimated and transformed to an annual energy consumption using an average electrical vehicle consumption per km. This estimate is conservative, taking into account that the urban planning minimizes the need for inter-module travels, incentives pedestrian and bike movements, and includes bike and car sharing services. The second contribution refers to the "public" transport, assumed to be made up of electric bus and boat vectors, with frequency sufficient to ensure that a given amount of people is served hourly in each module. The industry consumptions are neglected. Further energy consumption contributions are instead added to account for the required city autonomy, namely clean water and food production. The final energy consumption for water production is estimated assuming the entire household requirements to be satisfied by the desalination plant. The household clean water need is estimated based on historical data, which are expected to be conservative in light of the greater hydraulic efficiency and user awareness of the floating city. An additional water need for hydroponic systems is considered, based on literature estimations. Further water needs for food production are assumed to be satisfied by rainwater harvesting. The final energy consumption for food production is complex to be estimated, due to the variety of the floating city food sources, including at least distributed crops, aeroponic and aquaponics plants, small-size farming, fishing, and aquaculture. Thus, a simplifying and conservative estimate is obtained considering reference values for hydroponic, fish, and mussel farms only, based on the available literature, and cumulating to address the 75% of the entire floating city food demand (vegetables and protein). The remaining food needs are assumed to be addressed by the natural resources.

The overall final energy production is estimated by summing the components corresponding to solar and wind devices, as detailed in Supplementary Table 3. The cumulative solar panel peak power installed is derived from the horizontal area available, assuming an average solar panel power capability equal to 0.2 kW/m2. The annual energy production is estimated for each location using the PVGIS tool v5.3 [67], provided online by the European Commission. The solar radiation database PVGIS-ERA5 is chosen, as it is the only one available for all the locations. The other parameters are assumed as follows: grid-connected installation, crystalline silicon PV technology, default system loss (14%), roof added / building integrated mounting position, optimal slope, 0° azimuth, calculated horizon. The annual wind energy production is estimated for each location as:

$$E_{wind} = \Delta t \int_{v_{in}}^{v_{out}} P_{PC} f(v) dv \eta,$$

being: Δt = 8766 hours = 1 year; v_{in}, v_{out}, and P_{PC} the wind turbine cut-in velocity, cut-off velocity, and power curve; v the wind velocity; f its probability density function; and η an efficiency coefficient taking into account the energy losses due to mechanical issues and wave interaction between the different turbines of the park. Attaining the wind turbine properties, DTU 10MW reference wind turbine [68] has been considered in all the locations, since it represents a well-established benchmark for up-to-date scientific research on offshore wind energy. The wind velocity v is assumed to be distributed as a Weibull variable, i.e., to have the following probability density function:

$$f(v) = \frac{k v^{k-1}}{c^k} \exp\left[-\left(\frac{v}{c}\right)^k\right],$$

being $c > 0$ and $k > 0$ the site-dependent Weibull scale and shape parameters, respectively. These parameters have been extracted from the microscale layers of the NEWA wind atlas [69] for the first two sites in the North Sea and in the Aegean Sea, at a height of 100 m above the still water level. The Weibull parameters for the third site are instead reported from literature [70], based on the 2005-2010 wind data from the Waglan Island (WGL) meteorological station in Hong Kong, at 82.7 m above the still water level. The energy losses due to wake effects have been simplified by the coefficient η = 0.873, obtained from literature. In particular, considering a case study [71] of a park with 25 DTU 10 MW wind turbines, arranged in a square layout (5x5), with spacing of 5 rotor diameters both in stream-wise and transverse direction, η is obtained as the ratio between the park total energy productions with and without taking into account the wake effects.

4.3. Cost assessment framework

The cost assessment of a floating city is a complex task, and is heavily case-dependent. To the authors' knowledge the only available source in this regard is a report from the "Floating city project"[72], which provides limited justification for each cost estimation and is not peer-reviewed. Instead, wider literature is available for the cost assessment of other floating systems, like floating breakwaters [73] or floating offshore wind farms [74,75]. In the

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following, we propose a simplified framework for the preliminary cost assessment of the floating city, limited to floatation and energy systems. A schematic visualization of this framework is also proposed in Supplementary Figure 13.

The city location and size govern the total cost. The installation site defines the environmental loads the city must withstand, as well as the availability of local resources. The city size, corresponding to the target population, defines the number of modules required and the expected energy consumption. For example, this work provides such estimates for a case study of 50,000 inhabitants. Furthermore, the applicability and impact of economy of scale principles for any floating city component depends on the city size.

The construction cost of the modules is the sum of the material and the manufacturing costs. In the case of reinforced concrete, the total material cost is mainly dependent on the solid volume of the hull, including the ballast, being the steel bars cost generally smaller. Thus, a preliminary hydrodynamic and structural design may be sufficient to draw a first-approximation material cost estimation. Such a design depends on the met-ocean conditions of the installation site, and requires the implementation of coupled hydrodynamic, structural, and wave transmission models. A relevant advantage of the proposed concept is that it facilitates the local fabrication, with locally sourced materials. In this regard, quantifying the local availability and cost of material, facilities, and labor is crucial for the cost assessment. In particular, labor cost is site-dependent and has generally a similar order of magnitude with respect to the material cost (30-60% of the total cost) [73,76]. The size of the available facilities governs the width of the barrier modules and the number and size of the structural internal modules, as well as the joining procedures to obtain the architectural modules.

The mooring system cost depends mainly on the bathymetry of the installation site and on the seabed properties. In general, larger water depths imply longer mooring lines and deeper anchors, with subsequent nonlinear cost increases for material and installation. It should be considered that the mooring systems of the internal modules and of the barrier require different components (mooring lines, anchors, connectors) and support vessels. The tension leg system is expected to be overall more expensive than the compliant one, particularly due to the anchors [74]. Several strategies may be implemented for the cost reduction of the mooring system, including design optimization and line/anchor sharing between different modules.

The installation cost of the modules depends mostly on the distance between the construction facilities and the installation site, and on the availability of the required support vessels. In this regard, semi-submersible modules can be towed and connected/disconnected to the mooring lines without the support of expensive lifting vessels. Furthermore, the tension leg caissons of the barrier are self-stable, thus facilitating the installation and not requiring temporary stability modules.

The maintenance cost of the modules depends on their design and on the materials used. The adoption of reinforced concrete provides advantages with respect to steel, as the concrete does not require particular maintenance procedures. However, the steel bars are subject to chloride-induced corrosion, which may compromise the structural safety and require expensive repairs during the life cycle of the structure [76]. Potential strategies to address this issue are the adoption of special high-performance concrete, the increase of the concrete cover, or the adoption of stainless steel bars, at least in the external layers. The choice of the optimal strategy is case-dependent and derives from the life cycle analysis of each structure [76]. Taking into account the importance of the structural safety for the structures composing the floating city and the current absence of dedicated standards and recommendations in the regulatory framework, we recommend to consider adequately long service life (i.e., ≥ 100 years), as well as the adoption of stainless steel bars close to the cover.

The cost of the energy systems depends on the size of each plant, which can be dimensioned as discussed in this work. The cost assessment framework may be derived from the wide literature available for each technology, complemented with the specific observations resulting from the floating city peculiarities. In general, the ad-hoc implementation of the floating city grid allows the adoption of innovative smart grid concepts and technologies, suitable for the optimal integration of renewable energy systems. Among the various sources available in the floating city, solar, wave, and wind have been considered as baseline systems and discussed within this work. The solar panels are distributed throughout the city and their total surface area can be derived directly from the city size. The wave generators are integrated within the barrier. Thus, their costs are limited to the turbines and the other electrical components. The wind farm is close to the city. This may involve a reduction of the energy transmission costs, as well as further mooring line and/or anchor sharing between the internal modules and the wind turbines.

4.4. Recommended analyses for future floating city concept investigation

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In line with the paper scope and methodology, we propose some key research areas for future development of floating city concepts, arisen by the literature review and the critical evaluation of the main simplifications and assumptions made in this study.

From a hydrodynamic point of view, the coupled numerical modeling of the module dynamics, including mooring loads, and of the wave propagation inside the city must be investigated. State-of-art commercial software tools based on potential theory are capable of implementing linear frequency-domain models, also taking into account hydrodynamic interactions between modules and simplified structural connections. These tools can be used for preliminary module motion and load assessment and city layout optimization. However, they neglect or simplify the nonlinear forces, and thus cannot represent accurately some key aspects, including connection behavior under large displacements, wave and structural nonlinear damping, and U-shaped oscillating water column wave energy converter dynamics. These effects may affect the quantitative estimations sensibly, particularly attaining the wave propagation and the wave energy production. Thus, further numerical and experimental research is recommended to develop and validate more complex models in frequency and/or time domains.

Future engineering analyses should also focus on the structural analysis, construction and maintenance of the flexible joints between the barrier modules, and on the overall hydro-elastic analysis of the barrier as a whole. Unlike the other elements of the floating city, the barrier is substantially different from offshore structures in use in the current engineering practice, due to the combination of aspects such as the flexible joints, the integration of the U-shaped oscillating water column (U-OWC) wave energy converters (WECs), and the tension leg moorings. Relevant previous literature analyses on similar structures, ranging from the historical mobile offshore base (MOB) landing unit [42] to long floating breakwaters [77], proved some potential advantages of the concept, but numerical and experimental analyses are required to specifically assess its feasibility and its performances. In this regard, given the sensible extreme and fatigue loads transmitted to the joints, the implementation of internal dissipative systems and of planned maintenance protocols is recommended.

In parallel to the engineering analyses, hybrid techno-social studies should be carried out to assess the floating city safety and comfort requirements, and support the regulatory and certification institutes to fill the existing gaps in this regard.

The environmental impact assessment framework of the floating city should be developed in more detail and particularized for realistic case studies. In particular, innovative integrated architectures for water and food supply, and waste and wastewater treatment should be investigated and characterized, quantifying the potential capabilities, requirements (space, resources, and specific location characteristics), and environmental impacts. Similarly, smart grid architecture, storage requirements, and comprehensive renewable energy potential and feasibility should be assessed for specific case studies, to extend and complement the preliminary calculations carried out in this work, attaining energy autonomy. In particular, the potential impact of sea-related renewable energy sources, including waves, currents, and thermal and salinity gradients, should be assessed and quantified.

Finally, legislative, governance, and social aspects play a fundamental role for the feasibility assessment of floating cities. The review of the current state of art and of the main open challenges may be found in literature [14,78]. Legislative gaps represent a primary barrier for the development of floating cities. Among them, some relevant examples concern the property rights, often based on terrestrial land only [14,78], and the mooring rights and obligations [79].Despite the growing attention on the topic, the last decades have not seen substantial progresses in legislation [80]. It is likely that the future floating city projects will be developed by national or regional institutions, rather than private or supranational ones. This is in line with the first ongoing floating city projects [28,29]. While the national legislations fully apply in the territorial waters, i.e., within 12 nautical miles out of the coast, they apply only partially in the exclusive economic zones (EEZ), which extend up to 200 nautical miles from the coastline and are the most straightforward collocation of a satellite floating city. Therefore, there is a need for the assessment of clear legislative and policy frameworks, especially within these areas, including spatial plans, urban form design guidelines, and governance models specifically oriented towards floating cities [55,78,79]. The feasible governance models depend on the city owner and on the mentioned regulations. The present work recommends a strong community engagement in the city life and in the decision-making process, generally corresponding to a certain degree of political autonomy. This is in line with the outcomes of the survey carried out within the “Floating City Project” [72], which is, to the authors’ knowledge, the sole extensive investigation (1235 interviewees) of the general public perception about floating cities carried out up to now. In this context, we recommend from one side theoretical analyses of innovative governance models, suitable for application in the floating cities and compatible with the mentioned objectives, and from the other further field investigations of general public, decision makers, potential investors, and other stakeholder perspective, to inform the research on these topics.

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Data availability statement

The energy consumption data reported in Supplementary Table 2 are obtained from the freely accessible online IEA data services (license: CC BY 4.0, website: https://www.iea.org/countries).
The population data reported in Supplementary Table 2 are obtained from the freely accessible online World Bank Open Data (license: CC BY 4.0, website: https://data.worldbank.org/indicator/).
The annual solar energy production data in the three sample sites (North Sea, Aegean Sea, Hong Kong) are generated using the freely accessible online PVGIS tool v5.3, provided by the European Commission (license: CC BY 4.0, website: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).
The wind Weibull parameter data in two out of the three sample sites (North Sea, Aegean Sea) are obtained from the New European Wind Atlas, a free, web-based application developed, owned and operated by the NEWA Consortium (license: CC BY 4.0, website: https://map.neweuropeanwindatlas.eu/).

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- **Contributions**

F.A. led the paper conceptualization, methodology, funding acquisition and supervision. C.R. led the multi-disciplinary analyses of the floating city, including barrier characterization and energy consumption and production quantification. M.L.C led the architectural conceptualization, the masterplan and the graphical project, with contributions and coordination from C.R. C.R. led the resilience, urban welfare, sustainability, and cost assessment frameworks, with contributions from M.L.C. C.R. led the writing. M.L.C. and F.A. contributed to the review and editing.

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Ethics declaration

The authors declare no competing interests.

Supplementary Information

Tables reporting the detailed energy consumption and production estimates; graphical inserts providing details about the floating city masterplan and rendering; tables and figures summarizing the framework of resilience, urban welfare, sustainability, and cost evaluations.

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Figure captions

Figure 1. Proposed layout for a floating city of 50,000 inhabitants.

Figure 2. Schematic prospectus of the barrier and inner city modules in the equilibrium position (solid lines) and under a horizontal displacement (dashed lines).

Figure 3. Multi-layered modularization of the floating elements. Elementary functional module: square; elementary architectural module: triangles; elementary structural modules: colored boxes.

Figure 4. Wave attenuation coefficient as a function of the breakwater heave natural period for variable wave and breakwater parameters: each plot refers to a different breakwater geometry, defined by the draft D and the width W, and each line to a different incoming sea state, defined by the significant wave height H_s and the peak period T_p.

Figure 5. Logical framework of the research.

Tables

Table 1. Main module and city dimensions. The green and blue areas include also the covered spaces.

Parameter	Functional module	Floating city (50,000 inhabitants)	Units
Side length	0.34	2.42	[km]
City footprint	9.13e4	2.19e6	[m^2]
Total footprint (including barrier)	-	5.87e6	[m^2]
Buildings (residential, services)	3.17e4	6.03e5	[m^2]
Green area (deck level)	2.01e4	4.24e5	[m^2]
Green area (elevated)	1.82e4	2.91e5	[m^2]
Blue area	2.75e4	3.73e6	[m^2]
Area covered by photovoltaic panels	1.53e4	3.40e5	[m^2]

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Editorial summary:

A design focus on resilience, sustainability, and urban welfare can help the concept of floating cities to reach its potential for relieving land scarcity as well as demands on coastlines, suggests an analysis of space, food and energy requirements.

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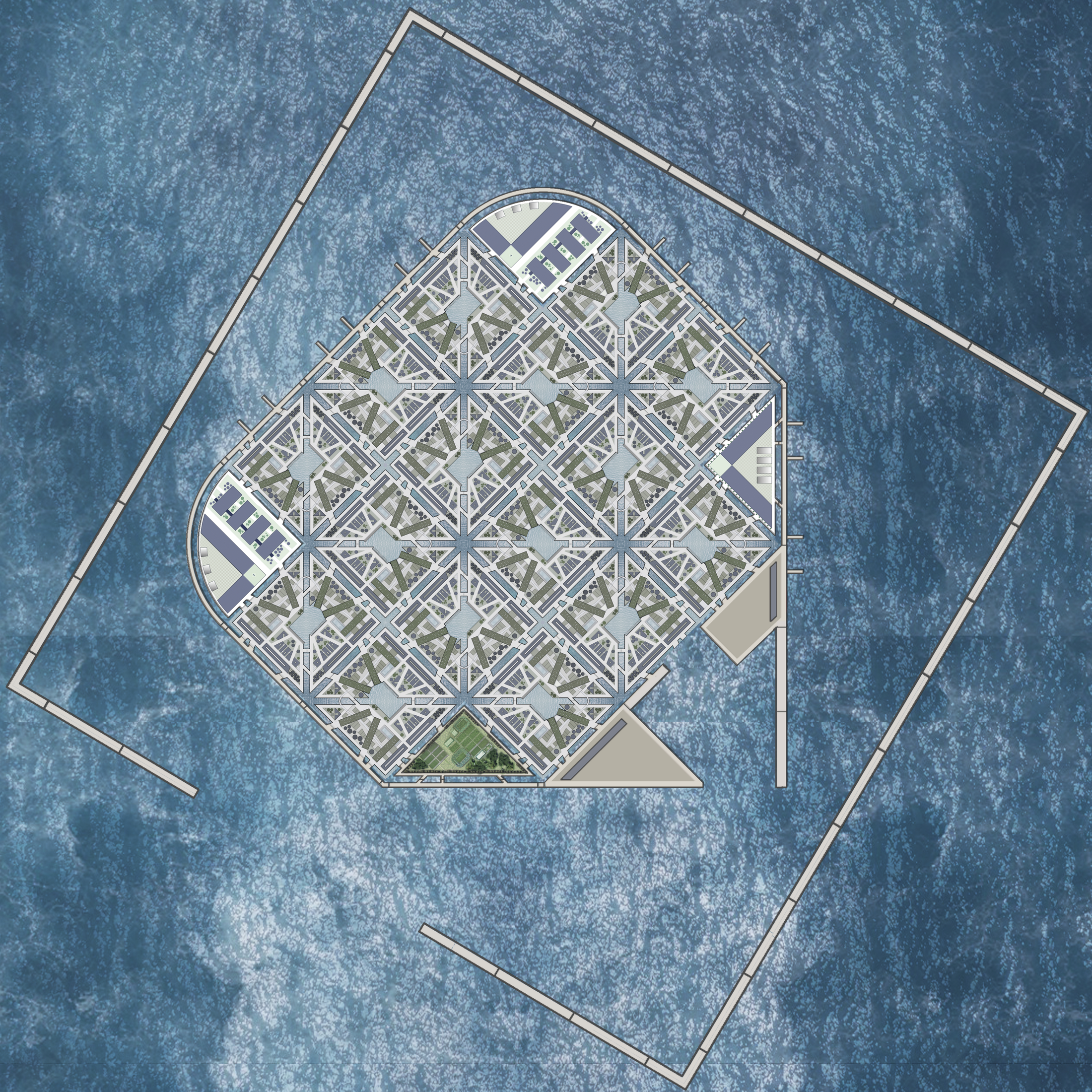
Communications Earth and Environment thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editor: Nandita Basu. [A peer review file is available.]



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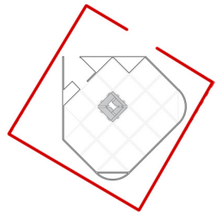
BARRIER



PERFORATED STEEL INSERT

WAVE ENERGY CONVERTER

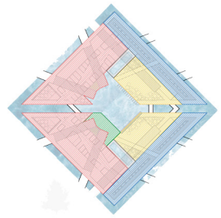
CONCRETE BREAKWATER

UNDERWATER BULKHEAD

TENDONS

ANCHORS

INNER CITY



DECK

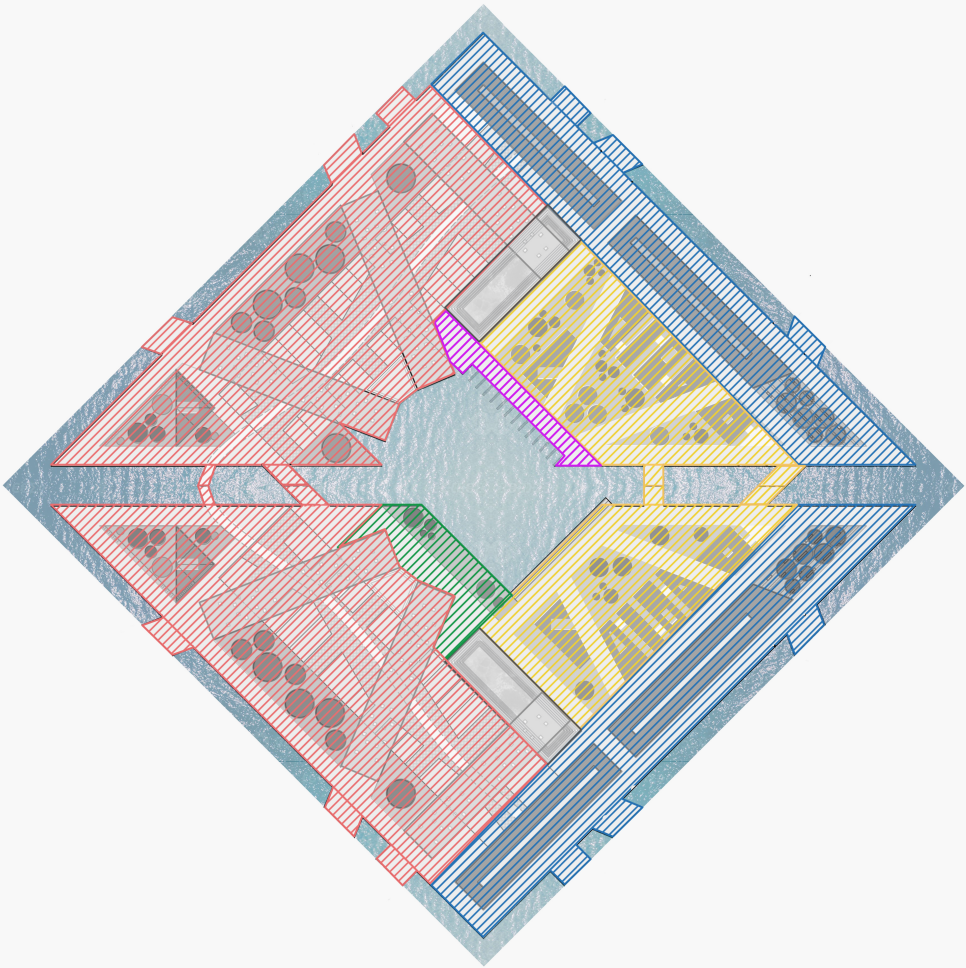
FLOATING COLUMNS

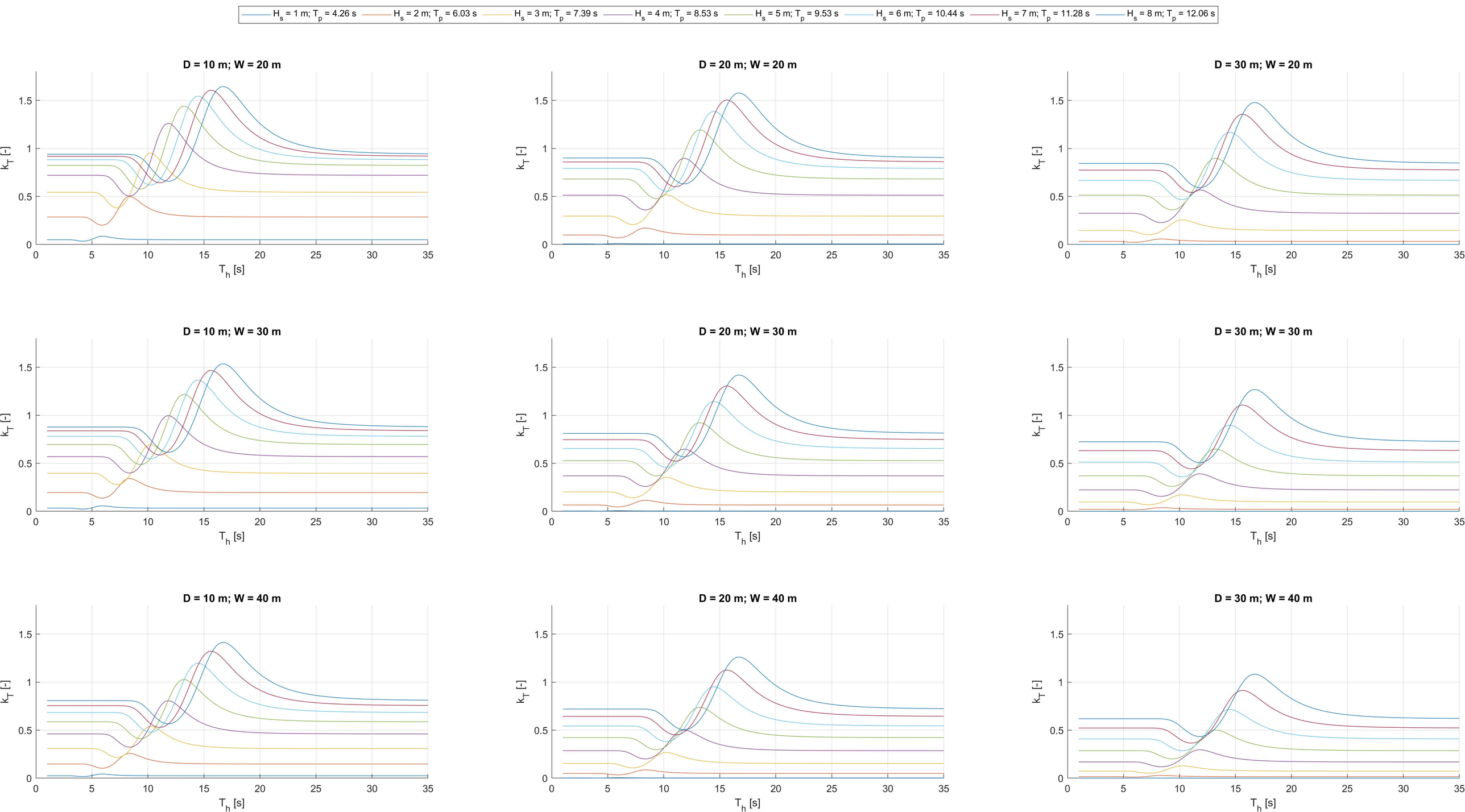
LOWER HULL

PROPELLERS FOR ACTIVE MOTION CONTROL

TAUT AND/OR CATENARY MOORING LINES

ANCHORS




H_s = 1 m; T_p = 4.26 s
H_s = 2 m; T_p = 6.03 s
H_s = 3 m; T_p = 7.39 s
H_s = 4 m; T_p = 8.53 s
H_s = 5 m; T_p = 9.53 s
H_s = 6 m; T_p = 10.44 s
H_s = 7 m; T_p = 11.28 s
H_s = 8 m; T_p = 12.06 s
D = 10 m; W = 20 m
D = 20 m; W = 20 m
D = 30 m; W = 20 m
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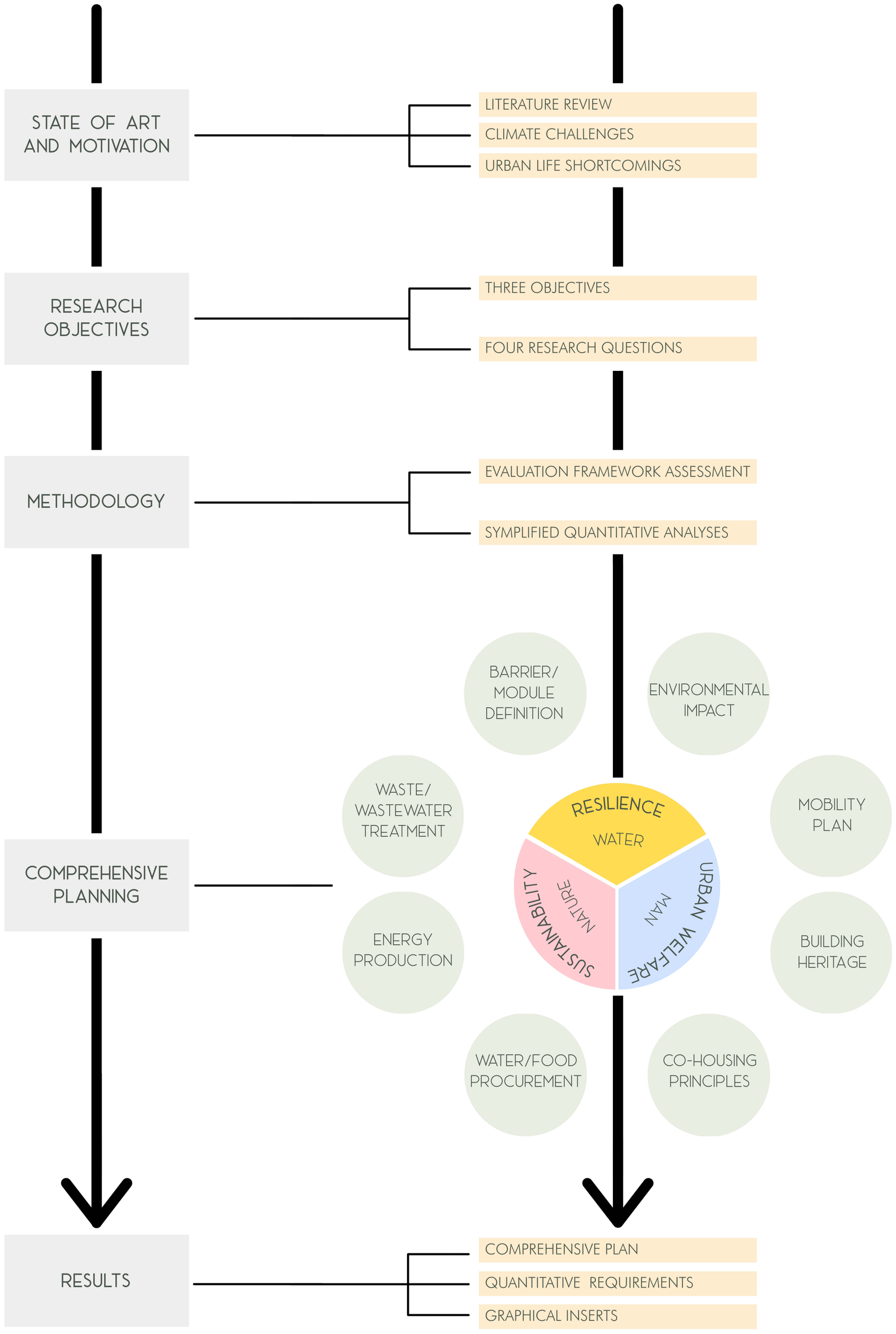
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LITERATURE REVIEW
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BUILDING HERITAGE
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CO-HOUSING PRINCIPLES
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COMPREHENSIVE PLAN
QUANTITATIVE REQUIREMENTS
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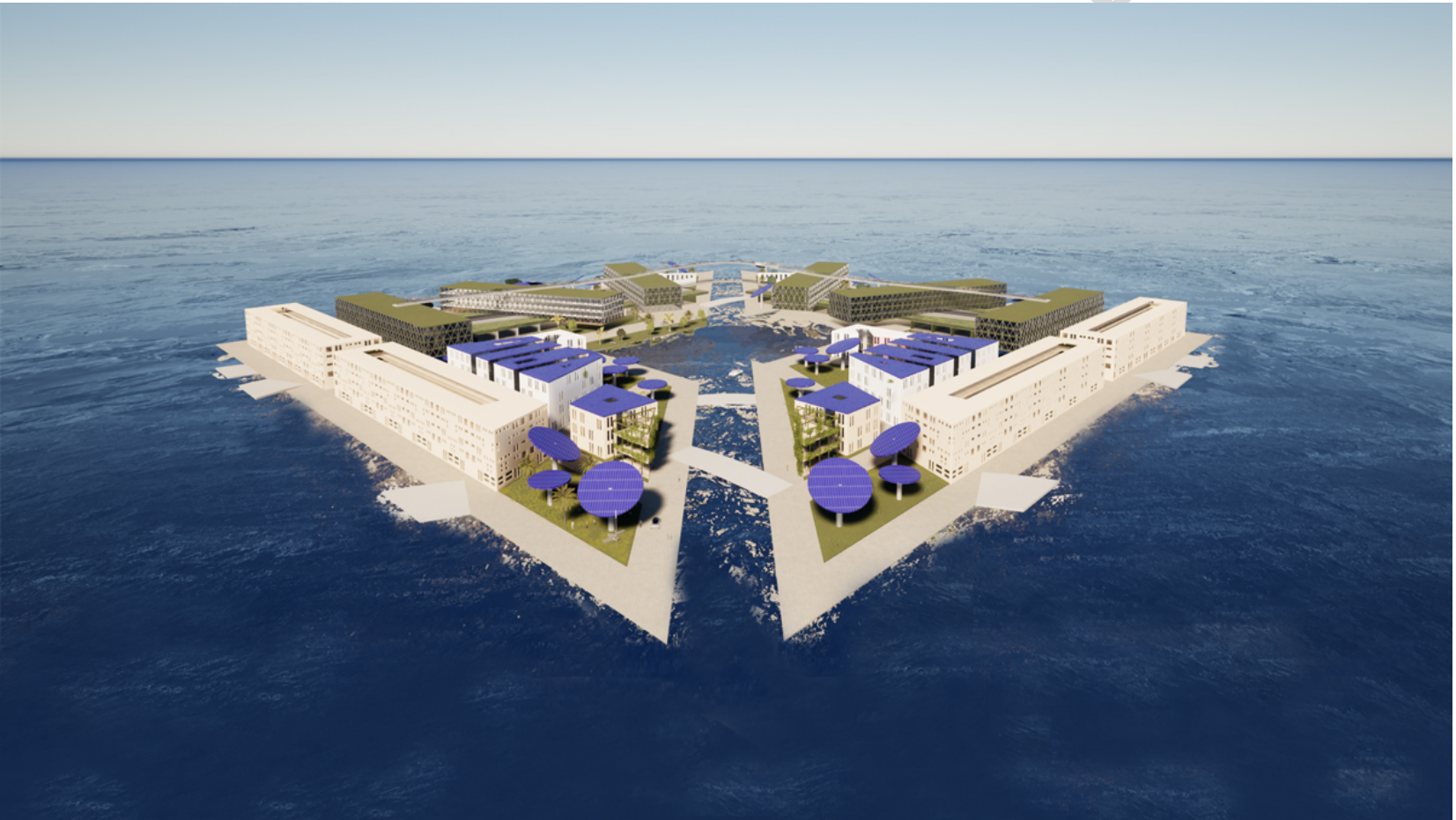
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