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Floating Solutions for Challenges Facing Humanity

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Abstract. This paper presents a variety of floating solutions that aim to address a diverse set of global challenges and the UN Sustainable Development Goals. The challenges include energy insecurity, water and food shortages, and environmental threats to fragile coastal environments from rising sea levels, extreme storms and pollution. Floating solutions offer a new approach to coastal urban development to support the blue economy while reducing the impact of coastal land pressures, increase connections between communities through connecting infrastructure over deep waters and soft seabed conditions, and address large tidal variations in harbours to allow the expansion of port terminals in deep waters. A vision of *hybrid floating cities* and satellite floating cities in international waters will also be presented.

Keywords: blue economy, floating solutions, ecological engineering, clean renewable energy, aquaculture, floating cities, UN sustainable development goals

Introduction

In 2003, Nobel Laureate Richard Smalley presented a list of top ten 'global concerns' that humanity had to contend with over the next half a century (Smalley, 2003). These global concerns are (as set out in descending order of priority): energy insecurity and the need for alternative sources to fossil fuel; water shortages; food scarcity; environmental threats from climate change and pollution; poverty; terrorism and war; disease, the education gap, the development of democracy, and over-population (Smalley, 2005).

Twelve years later, the United Nations General Assembly adopted resolution 70/1 that set out 17 Sustainable Development Goals (SDGs) (Rahimifard and Trollman, 2018). These goals provided a framework that allowed countries (both developed and developing nations) to align their efforts to, in essence, solve a similar set of problems to Smalley's list of global concerns.

The authors suggest that how we choose to deploy infrastructure and build our cities will have a significant impact on the way we are able to respond to the global concerns and meet the SDGs. While the challenge of adopting cheap and abundant renewable energy sources is given pre-eminent position on the list of global concerns, this article considers that any infrastructure solution addressing the challenge of abundant clean energy production (or any of the remaining global concerns) must also contend with the environmental threat of rising sea levels, particularly in light of coastal urbanisation. Accordingly, this article positions the environmental threat of rising sea levels and extreme storm events on the same level of pre-eminence on the list of global concerns (Michener et al., 1997).

However, rather than armouring our coastlines against the increasing threat of rising sea levels, there is a need to consider the ocean as a means of providing succour to our emerging needs. Ocean exploration has fuelled advancement in drugs, food and energy; vastly improving the quality of life on earth. In fact, twenty percent of the protein we consume comes from seafood and half of the oxygen we breathe comes from the oxygen produced by phytoplankton photosynthesis in the sea (Roach, 2004). This has given rise to a constellation of different economic and socio-political activities seeking to sustainably leverage the resources of the ocean while broadly preserving and enhancing ocean ecosystems. These activities fall under the broad umbrella of the 'Blue Economy' which is defined by the World Bank as the 'sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health (The World Bank, 2017).

In this paper, we present floating solutions in four parts to address the challenges of energy insecurity, clean water and food shortages, environmental concerns, and to support resilient communities in addressing social issues of poverty and population pressures on urban development. The authors note that the floating solutions set out in this article allows us to support the Blue Economy and meet the following SDGs:

> (*SDG 7*) *affordable and clean energy*—through the use of floating wind turbines, floating solar farms, wave energy converters and the exploitation of ocean thermal energy conversion;
>
> (*SDG 6*) *clean water and sanitation*—through the use of floating desalination plants that can be towed and deployed in crucial situations;
>
> (*SDG 9*) *industry, innovation, and infrastructure*—through the use of floating structures to avail offshore fish farming and floating vegetable and dairy farms. Floating structures can also be used to support the blue economy through installations for tourism and cultural spaces;
>
> (*SDG 13*) *climate action*—through the use of floating structures to

access the ocean’s potential to provide abundant and clean energy, reducing dependency on fossil fuels and biomass for energy generation;

(*SDG 14*) *life below water*—through the use of floating structures and ecological engineering to reduce the impact of hard marine infrastructure on fragmentation of coastal environments and disruption to wave patterns and a move away from the traditional land reclamation approach that destroys the marine ecology beneath the project footprint;

(*SDG 15*) *life on land*— through the potential for floating structures to enable cities to alleviate land pressures due to coastal urbanisation; and

(*SDG 11*) *sustainable cities and communities*—through *hybrid floating cities,* where cities expand over adjacent water bodies in an environmentally sensitive way while exploiting the ocean as a clean and abundant source of energy and site for food and clean water production.

Part 1: Floating Solutions for Harvesting Energy from Oceans

Smalley (2005) notes that access to energy is the single most important factor that impacts the prosperity of any society. Cheap and abundant clean energy allows us to deploy technology to help us desalinate water, increase food production, reduce our impact on the environment from the use of fossil fuels and take steps to reduce our environmental footprint.

While we have met our energy demands by expanding into the oceans to exploit offshore oil and gas deposits, the oil crises of the 1970s sparked international research into offshore wind energy in the 1980s (Leary and Esteban, 2009). As the offshore renewable energy industry matures in certain jurisdictions and public desire for solutions to reduce carbon and greenhouse gas emissions become more urgent, a range of clean energy sources such as solar energy, wind energy, wave energy and tidal current energy are coming to the fore.

Presented in this section are floating solutions for harvesting different forms of energy from our oceans or siting sensitive energy infrastructure in the ocean to address energy insecurity and provide a means of obtaining clean and abundant energy without the use of fossil fuels and biomass.

1.1 Floating wind turbines

The ocean offers a source of cheap and abundant renewable energy. There is more wind in the oceans than on land with ‘estimates regarding global potential of wind energy capacity alone exceeding the IEA’s 2010 estimate of average global electricity generation’ (Pelc and Fujita, 2002). Systematic Ocean Energy Resource assessment shows that offshore wind amount to more than 192,000 TWh/year. (Narasimalu, 2019).

This vast amount of wind energy from the ocean may be harvested using floating offshore wind turbines and is readily available to coastal populations. A significant advantage of offshore applications of wind turbines are that the actual components that make up the turbines do not have the same transportation constraints as their land-based alternatives, which allows floating wind turbines to be made at a significantly larger scale. Currently, onshore wind turbines range from 2.1-5.8 MW whereas offshore wind turbines range from 6.0-10.0 MW (Siemens Gamesa). In a recent demonstration project in Goto Island, Japan, a 2 MW spar floating wind turbine was designed and installed. It has a hybrid precast concrete and steel spar of 76m in length that carries a 56m tower with a rotor diameter of 80m (see Fig. 1a). With the success of this project, plans are also underway to build another 8 larger floating wind turbines to supply electricity for the entire Goto Island. Similarly, Saitec is building concrete pontoon type floating wind turbines in Spain (see Fig. 1b) (Maslin, 2017).

Fig. 1a Floating spar wind turbine, Goto Island

Fig. 1b Saitec wind turbine on concrete pontoon off the coast of Spain

1.2 Wave energy converters

It is estimated that wave energy amounts to 80,000 TWh/year (Narasimalu, 2019). However, the technology extant is not at a level of maturity that readily allows the exploitation of wave energy at scale. At the heart of the operational challenges to harvesting wave energy is that the components of the converters tend to break down after a period of time due to the continual movement of their parts under enormous forces.

Pelamis was one of the first companies to commercialise ocean surface wave energy conversion. It began in 2004 with a prototype at the European Marine Energy Centre in Scotland that was followed by the Enersis Aguacadoura Wave Farm in Portugal. Unfortunately, the Portuguese installation proved to be short-lived, operating for less than half a year. Following a number of small-scale wave farms around Europe, Pelamis went into administration in November 2014 (BBC News, 2014).

However, new technologies aimed at harvesting wave energy are still being tested. One such emerging technology is offered by Eco Wave Power[4] where floaters that rest on the water surface are attached to an existing marine structure, such as a wharf, pier or breakwater. The technology utilises incoming surface waves through the use of floaters that pump hydraulic pistons, which in turn generates pressure that drives a hydraulic motor to create energy. The deployment of the technology along coastal installations increases accessibility and ease of maintenance. The technology has been successfully deployed in Gibraltar and in the Jaffa Port in Israel (see Fig. 2a).

Similarly, the Guangzhou Institute of Energy Conversion has developed a new form of wave energy converter based on energy absorbers mounted on a semi-submersible floating structure called the *Sharp Eagle* (see Fig. 2b).[5] The energy production system was integrated into the grid at Dawanshan Island in 2015, and claims to have the highest average wave-to-wire efficiency recorded of 24%.

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[4] Eco Wave Power https://www.ecowavepower.com/.

[5] Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences <http://english.giec.cas.cn/ns/tn/201707/t20170725_181220.html>

Fig. 2a Eco Wave Power installation at Jaffa Port, Israel

Fig. 2b Sharp Eagle developed by Guangzhou Institute of Energy Conversion

1.3 Floating solar farms

Floating solar farms are installations of photovoltaic (PV) systems on floating structures. This form of siting PV arrays in the ocean is a fast-growing deployment option with over 100 installations worldwide (Liu at al., 2019). One of the key advantages of the deployment strategy is that these floating solar farms can be located close to urban environments without the problem of overshadowing by adjacent buildings. Reservoirs, lakes, seas and oceans offer abundant space to site these floating solar farms. When deployed on reservoirs, floating solar farms help to reduce water loss via evaporation and prevent the growth of algae.

An example of such an installation is the Kagoshima Nantsujima mega solar power plant, a 70 MW floating solar plant in Kagoshima Prefecture of Southern Japan (see Fig. 3a) which started operation in 2013. The floating solar farm is presently the largest solar power plant in Japan with a capacity to generate enough electricity for 22,000 average households. Other examples include the floating solar farm at Yamakura dam, which houses 50,000 solar PV panels over 180,000 square metres of the surface of a reservoir (Vaughn, 2016). In Huainan, China, a large floating solar farm, which started operation in 2017 (see Fig. 3b), has been deployed in a flooded area that was once a coal mine. The farm has the capacity to generate 40 MW of electricity to power 15,000 households. In Europe, London has also installed a 23,000 floating solar PV farm on a man-made reservoir near Heathrow airport (Harvey, 2016). Singapore has contributed significantly to the research in floating solar application on fresh water reservoirs by building the world’s largest 1 MW floating solar testbed on the Tengeh Reservoir (Liu et al., 2019).

Fig. 3a Floating solar plant in Kagoshima

Fig. 3b Floating solar farm in Huainan, China, which has been deployed over a flooded area that was once a coal mine.

1.4 Ocean thermal energy conversion (OTEC)

OTEC exploits the temperature differential between the warmer part of an ocean surface and the cooler waters deeper. Warm surface water with a temperature of around 25°C is utilised to vaporise a working fluid that has a low-boiling point (such as ammonia). The vapour expands and spins a turbine coupled to a generator to produce electricity. By using risers (or vertical pipelines), cold water of about 4°C is drawn from an ocean depth of 1km to cool the ammonia vapour back to its liquid state for the power cycle. OTEC plants have yet to be built but it is envisaged that OTEC will be mankind's solution for its energy needs due to the abundance of solar energy been stored in the surface waters of oceans. Figure 4 shows Dr Alfred Yee's 125 MW OTEC plant.

Fig. 4 Dr Alfred Yee’s 125 MW OTEC plant

1.5 Floating nuclear power plants and oil storage facilities

While not directly exploiting the ocean as a source of abundant and clean energy, the following floating solutions aim at addressing energy insecurity by locating energy infrastructure in close proximity to an urban population so as to reduce the requirement to build expensive electrical transmission infrastructure or to utilise valuable coastal land resources for energy or oil stockpiles. Such floating structures also exploit the natural moat of the surrounding ocean space that allows these sensitive installations to be securely operated despite its proximity to coastal populations.

Russia launched the world’s first floating nuclear power plant in 2018 (see Fig. 5a). The 70 MW vessel christened the *Akademik Lomonosov* was towed away from St Petersburg by two boats. It is presently deployed in the Arctic town of Pevek. A floating nuclear power plant makes economic sense where there is a need to supply power to highly remote locations. The ability to tow such energy infrastructure around is ideal as it reduces the need to construct powerlines and transmission towers to bring power to these remote locations. Currently, Russia and China are collaborating to develop other floating nuclear power plants (see Fig. 5b).

Fig. 5a Russia’s floating nuclear power plant Fig. 5b Floating nuclear power plant

At present, oil tank farms are typically sited on land. For safety, these flammable oil tank farms could be floated out and away from urban population. Japan has shown that oil can be safely stored in the sea. There are large floating oil storage bases in Shirashima and in Kamigoto (Ueda, 2015). In Shirashima oil storage base, there are 8 large steel floating modules (each module measuring 397m x 82m x 25.1m) and they can accommodate 5.6 million kilolitres of crude oil. In the case of the Kamigoto base, there are 5 large steel floating modules (each module measuring 390m x 97m x 27.6m) with a total storage capacity of 4.4 million kilolitres (see Fig. 6). These floating oil storage bases were built over 20 years ago. Similarly, Singapore plans to build a floating hydrocarbon storage and bunker facility within its coastal waters due to lack of appropriate land space for oil tank farms. Figure 7 shows the proposed floating hydrocarbon storage and bunker facility designed by researchers from the National University of Singapore and SINTEF (Ang et al. 2019, Zhang et al. 2019).

Offshore storage facilities for the energy industry are also being considered by Deloitte Tohmatsu with offshore hydrogen storage facilities to be deployed in close proximity to offshore rigs in order to exploit and harvest the hydrogen by-product created in these installations (Kokubun, 2014).

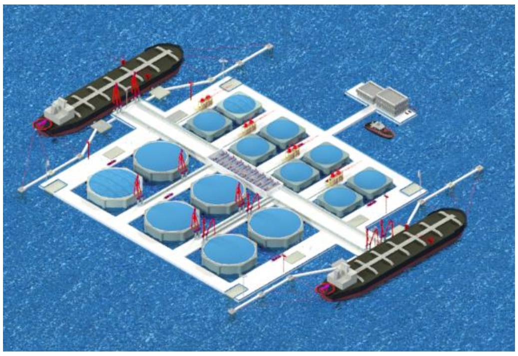

Fig. 6 Kamigoto floating oil storage base Fig. 7 Floating hydrocarbon storage facility

Part 2: Floating Solutions to Address Water Shortages and Food Scarcity

Presented in this section are floating solutions that address water shortages and provide opportunities to increase offshore aquaculture and agricultural applications to meet increasing food demands.

2.1 Floating Desalination Plants

As climate change causes havoc with the world's rainfall distribution, some parts of the world like California, the Eastern Mediterranean, East Africa, South Africa and Australia have all experienced severe and in some cases unprecedented droughts in recent years. The global desalination market has expanded dramatically particularly in North America and the Middle East (Kokubun, 2014).

Kokubun observed that despite Southern California experiencing a continuous drought event that began in the early 1990s and lasting half a decade, it took until 2013 before construction began on a desalination plant at Carlsbad, California. In fact, given concerns of environmental damage caused by drawing from adjacent coastal sources, land-based desalination plants are increasingly required to adopt expensive solutions to draw seawater from further out and at the bottom of the sea to avoid drawing in and killing small marine species in nearby coastal environments. These desalination plants are also expensive to operate with facilities left dormant after the particular drought event passes. In 2012, the Sydney Desalination Plant was left in a ‘water security’ mode after operating for two years, but was recently restarted in January 2019 (although it will take 8 months to restart the desalination facility).

Floating desalination plants offers a means of addressing water shortages in a faster, cheaper and more flexible manner. As these facilities can be floated to the urban centre at need, this flexibility of deployment to meet demand provides significant advantage. These facilities can also be located at sites further from coastal environments to ‘preserve diversification of the shallow sea’ environment (Kokubun, 2014).

Bowarege has developed the world’s first self-contained desalination plants mounted on barges. Each barge has the capacity to produce 25,000 cubic metres a day of desalinated potable water from primary seawater. Barges are fitted with reverse osmosis desalination plants, on-board power generators, laboratories, control rooms and staff accommodation. Since operations began in 2008, the floating desalination plants have provided emergency water supply to several Saudi Arabian cities. First moored at Shuaibah, south of Jeddah, delivering water to Makkah and Jeddah (see Fig. 8). They moved to Shuqaiq in 2009 until the Shuqaiq Independent Water & Power Project came online a year later, and since 2011 they have been at the Yanbu-Madinah desalination plants complex on the Red Sea to serve the industrial city of Yanbu and the city of Madinah. Cyprus and Thailand have similarly deployed floating desalination plants.

Fig. 8 Floating desalination plant at Jeddah

2.2 Floating fish farms

Despite the potential opportunity for using floating desalination plants as a means of clean water production, the existing state of play is that ‘available water resources appear insufficient for agriculture to meet the food demands’ of future populations (Duarte et al., 2009). This water shortage is exacerbated by forecast changes to the composition of diets with a shift to more meat, which consumes 10 times more water to produce per calorie, and a further ten per cent increase in calorie consumption. Coupled with the higher incidence of droughts and floods, the prospect of water shortages translates to greater food insecurity.

Fish is known to be the cheapest protein source that can be farmed to feed billions of people that will be added to the world. Fish has an excellent food conversion ratio of 1.2:1, i.e. we can expect 1.2 kg of protein from the fish by feeding it with 1 kg of protein (Lovell, 1989). The reason for this significant food conversion ratio is the fact that the fish is cold-blooded and the buoyancy force of its environment helps the fish to overcome gravity, allowing its bones to stay relatively small. Given the decline of yield in global fisheries, many countries with coastlines are now farming fish for food and for export, with aquaculture contributing to 39% of food production (Duarte et al., 2009).

Duarte et al. (2009) noted that fish farming in nearshore environment relies on the use of public coastal space. Accordingly, nearshore fish farms end up in direct ‘competition with other societal demands’. This leads to increased community opposition and conflict with other nearshore usages such as shipping, fishing, tourism, recreation and conservation efforts. Further, given the limited space available to nearshore fish farms, the farmed fish tend to be kept in crowded conditions that impact the coastal environment due to pollution caused by uneaten fish feed and fish faeces.

Conservative estimates by Duarte et al. (2009) suggest that an ocean shelf area of 26 million square kilometres could support a distributed offshore fish farms production industry that would yield of 3×10^{10} to 6×10^{10} metric tonnes in fish products. The study, reported in 2009, observed that only 0.04% of shelf area was currently used for offshore fish farming. Accordingly, fish farm operators worldwide are planning to move offshore for more sea space and generally better water quality, which are needed to increase the production of healthy fish (Wang et al., 2019a). Figures 9a and 9b show huge offshore fish cages designed by the Norwegians and by the Chinese, respectively. These fish cages can accommodate more than 1 million salmon, and are 10 times larger than conventional open net cages in nearshore farming.

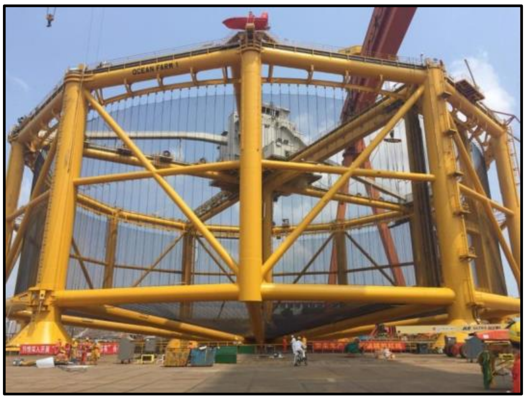

Fig. 9a Norwegian's Ocean Farm 1 Fig. 9b Chinese's Shenlan 1

2.3 Floating vegetable and dairy farms

In order to reduce transportation and energy costs in bringing food to coastal cities or cities with water bodies, floating vegetable and dairy farms have been proposed. The Barcelona-based Forward Thinking Architecture proposed a 2-tier floating farm with the first tier devoted to fish farming, the second tier for hydroponics vegetables and the roof covered with PV panels for power as shown in Fig. 10.

The first floating dairy farm in the world has been built in Rotterdam (see Fig. 11). The cows on this dairy farm produce milk which will be processed into various dairy products at the site on the water. Worldwide the idea of a floating farm is accepted as being animal friendly, economically sound and as a sustainable alternative to traditional agriculture. With this scalable and duplicable pilot, Rotterdam is testing the real possibilities for floating farms in cities.

Fig. 10 Floating farm by Barcelona-based Forward Thinking Architecture
< http://smartfloatingfarms.com/>

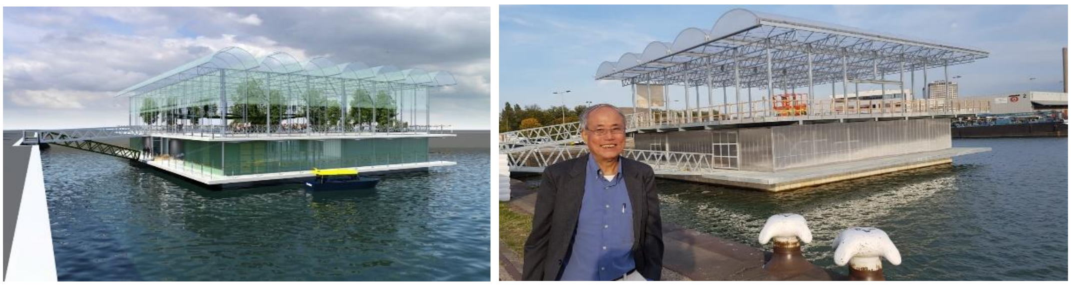

Fig. 11 Floating dairy farm in Rotterdam (photo courtesy of Soon Heng Lim)

Part 3: Floating Solutions to Address Environmental Concerns

3.1 Floating Solutions for Clean and Safer Water Environment

Smith-Godfrey (2016) observed that the 'inherently fluid nature' of the ocean makes it challenging to isolate marine industries and other economic activities from impacting marine ecosystems. Consequently, Burt et al. (2019) note that the primacy of coastal cities in the global economy has led to considerable costs to the environment.

The oceans have been used as rubbish dumpsites. In the Pacific Ocean, there is a garbage patch called the Pacific Trash vortex discovered in 1985. The garbage patch (a soupy mix of plastics and microplastics), now the size of Texas, is trapped by the ocean currents. In 2017, a 22-year old Boyan Slat proposed using a 2000 ft long floating plastic boom, attached to a geotextile skirt that extended about 10 ft beneath the water surface to concentrate the plastic garbage like an artificial coastline (see Fig. 12). The screens capture plastic trash as small as 1 cm and as large as discarded fishing nets. At regular intervals, a ship would transport the trash back to land where it would be recycled. By 2040, Slat promised that he could clear 90% of the trash. The removal of plastic garbage in the oceans is essential as it has been recently discovered that microplastics have been found in the fish that we eat.

Fig. 12 Boyan Slat's long floating screens

Rivers and coastal waters may potentially be cleaned by Vincent Callebaut's proposal of a whale-shaped floating garden that is designed to drift through the water bodies while cleaning the water by using a bio-filtration system (see Fig. 13) (Meinhold, 2014).

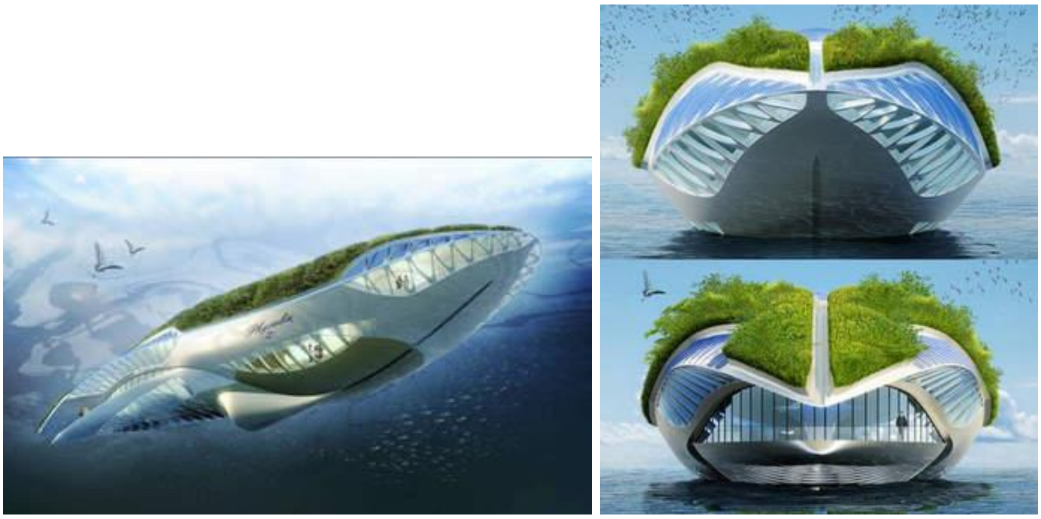

Fig. 13 Vincent Callebaut's whale shaped floating garden

3.2 Floating Solutions for Protecting Fragile Shorelines, Beaches and Ports from Large Waves and Winds

Sustained coastal urbanization patterns have led to the alteration of coastal habitats to accommodate residential and commercial infrastructure. Land reclamation practices cause the complete destruction of the marine ecology below its urban footprint. This is exacerbated by the growing need to protect coastal development from the threat of seal level rises and the intensification and increased incidences of tropical storms. This has led to the prolific use of marine infrastructure such as breakwaters, seawalls, and pilings to protect the coastal urban fabric. However, these marine structures fragment the undersea environment and lead to significant loss of habitat (Bulleri and Chapman, 2010).

Engineering practices in respect of coastal urban development have shifted in response to growing awareness of the need to restore fragile shoreline environments. This has led to the development of 'soft engineering' practices that deploy the 'wave attenuating and flood control properties of natural ecosystems such as marshlands, mangroves, and oyster reefs in order to reverse the impact of hard infrastructure changing coastal hydrodynamics and wave environments, particularly in intertidal and shallow subtidal habitats (Bulleri and Chapman, 2010).

Instead of solid breakwaters breaking up littoral flows, large-scale floating breakwaters now provide a solution to shield all coastal assets from being destroyed by strong waves while ensuring that fragmentation of the undersea habitat is minimised (Dai et al., 2018). By having a windbreak structure on the floating breakwaters, destructive wind speeds may also be reduced to manageable wind speeds. Wang et al. (2019b) in the University of Queensland have developed a floating forest (inspired by mangrove forests) as part of a component of a mega floating breakwater and wind-breaking structure to protect fragile beaches, ports and marinas from extreme storms (see Fig. 14). This continues a new approach towards 'ecological engineering' that aims to integrate 'theoretical and applied ecology…into the design of artificial, engineered structures in order to enhance both the environmental and human-use benefits of constructed habitats' (Burt et al. 2019).

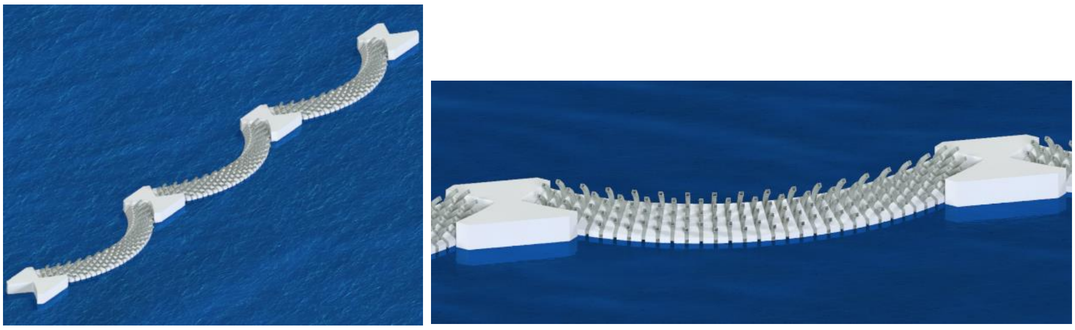

Fig. 14 Floating forest

Part 4: Floating Solutions to Support Resilient Communities

4.1 *Hybrid Floating Cities*: Architecture and Urban Design in support of the Blue Economy

Our crucial relationship with the ocean is highlighted by the significance of coastal cities where '80% of global trade transits through port cities and nearly two-thirds of the petroleum that powers the global growth engine… are transported via maritime networks' (Burt et al. 2019). This attraction to the ocean has driven coastal urbanisation such that close to 50% of global population, and two thirds of mega-cities worldwide are squeezed into the tenth of available global landmass that comprise our coasts (Burt et al. 2019).

Floating structures anchored onto the shoreline of coastal cities allow the creation of *hybrid floating cities,* where cities expand over their adjacent water bodies in an environmentally sensitive way while exploiting the ocean as a clean and abundant source of energy and site of food and clean water production. In such a manner, architecture and urban design can be harnessed to support and grow the Blue Economy.

In his germinal work on 'Making a City', John Montgomery noted two decades ago that the 'sprawl, strip or edge city, more often than not planned around the automobile… is no longer considered sustainable (economically and socially as well as environmentally)'. Despite these observations, the compression of the urban form against shorelines naturally produces linear urban development that characterise strip or edge cities. By expanding over the adjacent water body, linear urban forms can be gradually reshaped to be made denser and more compact.

However, the idea of using floating solutions to shape and supplement coastal urban forms is not novel. The Japanese Metabolists and Archigram and Buckminster Fuller in the West provided sophisticated proposals that aimed to grow our cities into the adjacent ocean space, connecting floating communities back to the mainland via bridges (Wang, 2019).

This section surveys floating solutions, built and unbuilt, that offer key potential solutions for cities to utilise floating structures to create vibrant and new spaces for activity, bringing together disparate parts of the city through new floating infrastructure to permit greater densification of the existing urban environment.

First, given the intimate connection a floating structure offers to the water, there is a clear advantage offered by such installations to the tourism industry and for cultural activities. Montgomery notes the critical ingredient of ‘activity’ (described as ‘natural animation’ or the ‘city transaction base’) to the success of urbanity. Where a city does not possess these spaces to ‘facilitate exchange of information, friendship, material goods, culture, knowledge, insight, skills and also the exchange of emotional, psychological and spiritual support’… the urban form of the city ‘becomes progressively more lifeless, dull and inert’. Consequently, cities have also been using floating structures as a means of programming places for ‘activity’ into the city without subsuming existing parts of the urban fabric, and instead, utilising public ocean space.

In the summer of 2016, artist Christo deployed a three kilometre long floating walkway in Lake Iseo, Italy. Comprising 220,000 high-density polyethylene cubes, the floating walkway was 16 metres wide and was covered in 100,000 square metres of shimmering yellow fabric (Fig. 15). Visitors who were attracted by the installation remarked that the experience had offered them the opportunity to feel like they were walking on water or the back of a whale.

Fig. 15 Christo’s floating walkway on Lake Iseo, Italy

This idea was duplicated as a 500m scenic floating wooden walkway in Shiziguan, Hubei (see Fig. 16), and the world’s longest boardwalk on the Hongshui River in China (see Fig. 17). Both floating solutions assisted in supporting the tourism industry in contributing significantly to the local economies.

Fig. 16 Floating walkway in Hubei

Fig. 17 Floating boardwalk on Hongshui River

But beyond the economic potential offered by such tourism installations, floating solutions can contribute to the vibrancy of the urban fabric of cities, contributing to the well-being of residents. In Singapore, floating wetlands were built to bring vibrancy onto the Punggol Waterway. Each floating wetland comprises hexagonal shaped HDPE modules with a hole in the middle of each module for water plants to be housed (see Fig. 18). But beyond the spaces for play and for activating the city, since the deployment of the wetlands project, the water quality in Punggol Waterway has improved and many pond animals are thriving on the wetlands. Additional floating wetlands were recently constructed in Singapore’s Pulau Ubin to provide additional habitats for herons.

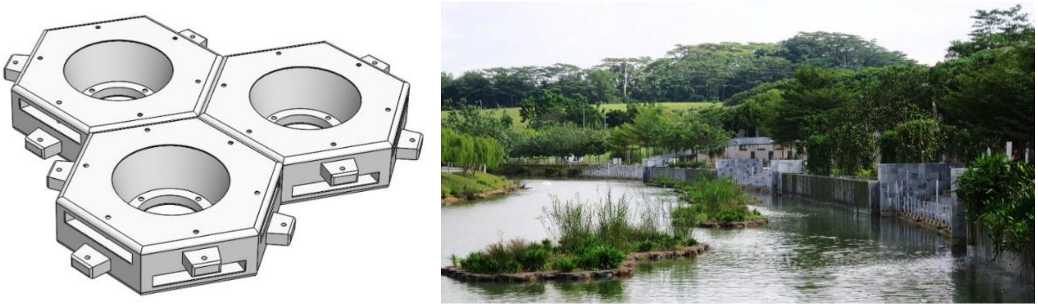

Fig. 18 Floating hexagonal shaped HDPE modules and floating wetlands on Punggol Waterway

In Seoul, three floating islands were constructed to bring vibrancy to the Han River (see Fig. 19). The islands can accommodate 6,200 people. The 20,400 square metre complex houses 3 cultural centres, featuring performances, water sports and aquatic events. Since its opening, millions of people have visited the islands and the site has evolved to become a very popular tourist and local cultural activity spot.

Fig. 19 Seoul Floating Islands

In Europe, Paris has activated its public river spaces by creating a floating community centre (Fig. 20a) and a separate floating urban art centre (Fig. 20b). These floating solutions create new and attractive public space and provide the preconditions for successful urban places (Ronzatti and Lvric 2019; Montgomery 1998).

Similarly, the Dutch have built a floating pavilion in Rijnhaven (see Fig. 21) comprising 3 interlinked spheres, the largest of which has a radius of 12m and the floor space of the pavilion island is 46m x 24m. The floating pavilion currently serves as an exhibition and events venue.

Fig. 20a Floating community center in Paris

Fig. 20b Floating urban art centre in Paris

Fig. 21 Floating pavilion in Rotterdam, The Netherlands

Other projects that may drive activity and place making in the city are oriented on creating novelty – addressing Sherman's (1998) indicator of a successful urban place of a surprising feature in a city 'to keep citizens awake, provide topics of conversation, [and to] prevent ennui'. In Sorenga, Oslo, a floating beach was built next to a hip condominium complex (see Fig. 22). The additional commercial benefit of the novelty was the resultant increase in property prices of the adjacent properties.

Fig. 22 Floating beach in Sorenga, Oslo, Norway (photos courtesy of Tor Ole Olsen)

In the same vein, floating restaurants and floating hotels serve as places of surprise in cities. Their novelty create excitement for customers and city occupants. Examples of such floating solutions are seen in Figure 23, showing the famous Jumbo restaurant in Hong Kong, and Figure 24, showing the Le Off Paris Seine floating hotel.

Fig. 23: Jumbo restaurant in Hong Kong

Fig. 24 Le Off Paris Seine floating hotel

Singapore has the world’s largest floating performance stage which is sited on the Marina Bay (see Fig. 24). It is a steel platform and measures 120m x 83m x 1.2m. A more detailed description of this floating platform is provided by Koh and Lim (2015). The National Day Parade and festival celebrations are held annually on this floating platform.

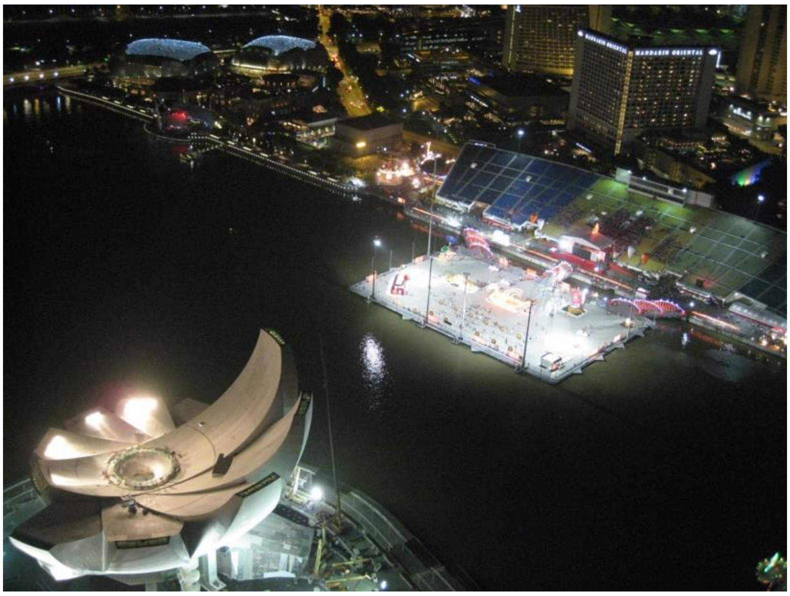

Fig. 24 Floating performance stage at Marina Bay, Singapore

4.2 Floating Solutions for Infrastructure

Urban communities separated by deep rivers, lakes, fjords and straits may be joined by using floating bridges, roads and railways to generate greater economic activities and human interaction. These floating structures can be kilometres long as they exploit the free-of-charge buoyancy force of the water to carry the massive dead loads and traffic loads. Examples of these large floating bridges are the 2020m long Lacey V Murrow Memorial Bridge over Washington Lake (see Fig. 25a), the 2350m Evergreen Point Floating Bridge in Seattle over 61m water depth atop 61m soft silt (see Fig. 25b), the 1246m long Nordhordland bridge at Salhus over a fjord depth of 500m (see Fig. 25c), the 845m long Bergsoysund Bridge near Kristiansund over a fjord depth of 320m (see Fig.25d) and the 410m Yumemai Floating Steel Arch Bridge in Osaka (see Fig. 25e). More ambitious plans are underway to build submerged floating road tunnels with either pontoon or tension-leg supports to cross the wide and deep fjords in Norway along the E-39 highway.

Fig. 25a Lacey V. Murrow Bridge

Fig. 25b Evergreen Point Floating Bridge

Fig. 25c Nordhordland bridge

Fig. 25d Bergsoysund Bridge

Fig. 25e Yumemai Floating Steel Arch Bridge in Osaka

Where a marine site is characterised by a large tidal variation, floating piers have been built so that the required freeboard can be maintained at any time. South Korea has built two very large floating cruise ship piers in the Incheon Golden harbor, where a tidal variation of 10m is experienced (Jung et al. 2019). One floating pier is made of steel whilst the other made from prestressed concrete (see Fig. 26). In Japan's Ujina port, there are a few floating piers which have been in operation for a few decades. Alaska has a floating prestressed concrete terminal dock. It is envisaged that many floating ports will be built in the near future as ships get larger (longer and heavier) and longer wharves and deeper water depth are needed for berthing.

Fig. 26 Floating piers in Incheon Golden harbour (photo courtesy of Kwanghoe Jung)

The Japanese successfully demonstrated the feasibility of a floating airport by carrying out tests on a 1km long floating runway from 1995 to 2000 as part of the investigation into a second runway for Kansai International Airport (see Fig. 27) (Suzuki 2008). The project underscored the urban design strategy of locating sensitive infrastructure (much like the oil storage and hydrogen storage facilities identified above) in the ocean securely away from but still in close proximity to urban centres. Subsequent research in this area has also produced investigations into the feasibility of a super-scale floating airport comprising multiple floating modules (Zhang et al 2019).

Fig. 27 Mega-Float – a 1 km long floating airplane runway test model in Tokyo Bay (photo courtesy of M. Fujikubo)

4.3 Floating Solutions for land scarce coastal mega-cities

The phenomenon of coastal urbanisation has led to significant pressure on land-based resources. Chief among these is the quest for available land space for residential, commercial and recreational activities. While this has led to significant projects to reclaim land from the ocean, land reclamation projects are highly environmentally problematic as they destroy the marine ecosystem below their footprint and require further damage to the environment at the source of where fill materials are extracted. Land reclamation also becomes economically unfeasible where the site has a soft bed or where water depth exceeds 30 metres. However, one of the significant issues of land reclamation is that the created space is still subject to the threat of rising sea levels.

Floating solutions utilising VLFS technology has been embraced by land-scared countries such as Singapore, Monaco, the Netherlands and Japan. The advantages of VLFS over traditional land reclamation include the fast pace in which space for urban development can be created and utilized, lowering the cost of deployment and allowing projects to be delivered more quickly. The flexibility of deployment allows the programmed space on top of these floating structures to be towed to the area of need. Further, as these floating structures are inherently base isolated, they are not affected by seismic action and are, due to their nature, immune to rising sea levels.

Although there is no VLFS suburbs currently under construction, floating houses and villages have long been part of our history. For example, Fig. 28a shows the floating houses in Vancouver, Canada and Fig. 28b shows the floating homes (made from container boxes) in Copenhagen for students. As more examples are built in the future as solutions to tackle coastal urbanisation, the authors suggest that there will be growing familiarity and acceptance of floating structures as simply extensions of the existing urban environment. This in turn may open the way to more visionary satellite applications of floating cities, such as Vincent Callebaut's Floating LilyPad settlements (see Fig. 29a) to accommodate climate refugees and Bjarke Ingels' Oceanix City proposal to house 10,000 people (see Fig. 29b). Joseph Lim from the National University of Singapore recently explored the prospect of repurposing semi-submersible and superbarges into offshore and nearshore settlements to potentially accommodate 1.6 billion people on 6,510 offshore settlements (Lim, 2019).

Fig. 28a Canoe Pass Village in Vancouver

Fig. 28b Floating homes in Copenhagen

Fig. 29a: Floating Lily Pad City

Fig. 29b: Floating city by Bjarke Ingels

Concluding Remarks

Our world faces many challenging problems ahead as a result of climate change and overpopulation. Some of these challenges can be solved by looking towards the vast oceans which take up about 70% of the world's surface. By using our technological advances in ocean engineering, marine and offshore structures and innovative ideas of floating solutions, we can:

- secure abundant offshore renewable energy for the world's energy needs;
- deploy mega-floating aquaculture farms and desalination plants to meet our need for clean water and food production requirements:
- create cleaner marine environments and safer urban spaces by cleaning the oceans and siting hazardous industry at sea away from urban populations;
- increase economic activity and vibrancy through the creation of businesses and jobs associated with the Blue Economy;
- construct infrastructure through the use of floating structures to create new urban corridors by connecting land parcels separated by water bodies. This will allow enhanced economic activities and population distribution through these new connections; and
- build floating villages, towns, cities and even countries to produce hybrid floating city solutions to address population pressures on land-based resources and ameliorate the linear sprawl of urban development along coastlines.

The ocean is clearly the next frontier for the future of cities. It offers itself as a resource that we must sensitively engage with in order to increase our habitable environments for us to live, work and play. It is crucial we understand our role as city builders and exercise stewardship of this resource for future generations and to ensure that we lean on (or float over) the oceans for our urban needs while preserving and celebrating our valuable marine ecosystems.

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