Highly efficient innovative shallow-water based Sea Water Air Conditioning solution for the Channel Area

EUROSWAC

Study of Environmental Constraints

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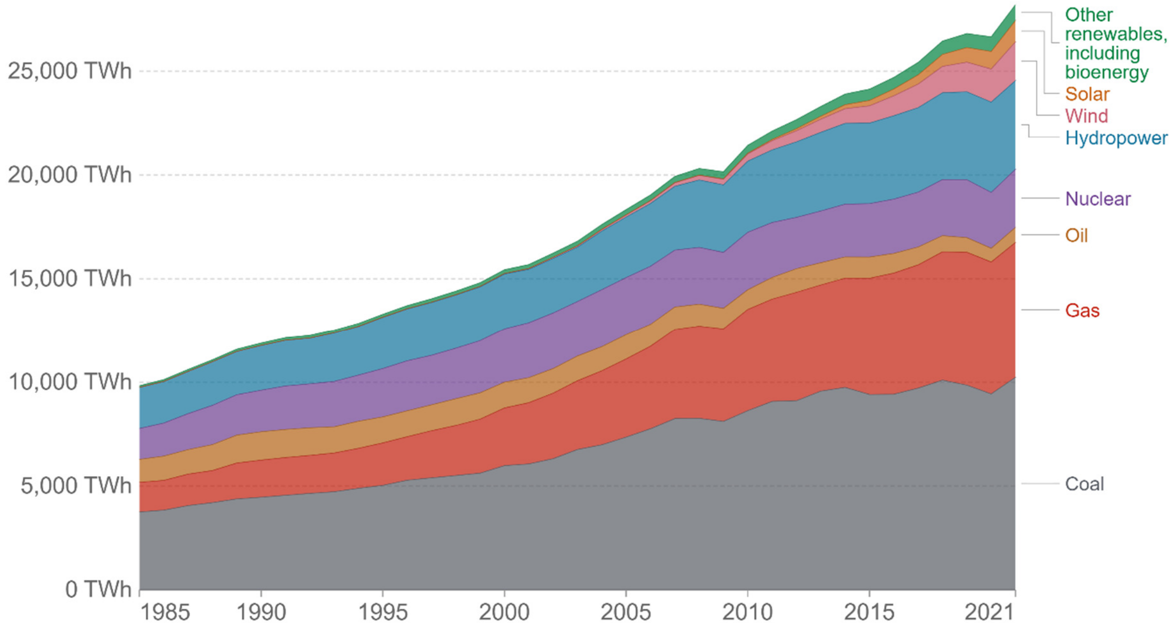
1. Abstract

With increasing cooling demands in large coastal cities at UK-FR levels, cooling produced through chiller systems that rely on electricity generated partially by fossil fuels slows down the ability to meet the Channel Area (CA) energy-climate objectives. The EUROSWAC project, funded by Interreg France (Channel) England programme, aims to propose an innovative, cost-efficient and environmentally friendly solution for cooling production, using English Channel's seawater by designing and validating highly efficient innovative shallow-water based Sea Water Air Conditioning (SWAC) systems. The EUROSWAC project plans to initiate the deployment of 35 SWAC systems by 2030 in the channel area. This may raise concerns regarding the individual or cumulative impacts of the SWAC systems in the CA marine environment. Hence, this report aims to review the reported impacts of the deployed Waterbody Thermal Energy Based Systems (WTEBSs) in the marine environment around the world. Two physical-chemical properties of seawater, biofouling and corrosion, that can potentially damage the equipment and affect the systems efficiency are described and countermeasure methods are discussed. Additionally, water quality measurements are presented based on data that were gathered in Tor Bay using two buoys provided by NKE Instrumentation.

2. Introduction

Anthropogenic global warming is a direct consequence of activities such as burning of fossil fuels (coal, oil and gas), which causes emission of large amounts of greenhouse gases (GHG) to the atmosphere [1,2]. Renewable energy technologies that exploit energy from sources such as solar, wind, wave, and ocean thermal energy, have been deployed to protect the environment from the impacts of carbon-based fuels GHG [3, 4]. The ever-rising oil costs and increase in the efficiency of renewable energy technologies due to learning curves and increased installation capacity have accelerated the development and competitiveness of renewable energy technologies in the global energy market, as seen in figure 1 [5, 6]. The thermal capacity of waterbodies (e.g. lakes, seas, and oceans) is by comparison an unlimited intact heat sink/source that can help meeting the high energy demands of coastal regions and islands. To illustrate the significant thermal capacity potential of waterbodies, Hunt and Byers [8] provided a comparison between energy potential in seawater with other renewable electricity generation sources for cooling purposes. Based on their approximate calculation, energy potential of 1m^3/s of seawater for cooling purposes with 10°C temperature gradient is equal to a hydropower plant with a generation head of 186m and ten times the flow, or a 488, 000m2 solar power plant, or energy generation by 21 wind turbines. Technologies that harness the thermal energy of oceans or seas, Waterbody Thermal Energy Based Systems (WTEBSs), rely on the temperature of the waterbodies that varies around the globe and depends on depth and regions. In terms of water temperature variation with depth, the oceans are divided into surface and deep water. Surface ocean water is warm water that extends to depths of a few hundred meters, while beneath that is the deep ocean with cold, dense, and nutrient enriched water [9, 10]. The higher density of the cold deep ocean water prevents it from mixing with the surface water with a transition layer called thermocline with approximate depth of 400m to 1, 000m from the water surface [9, 11]. The temperature of deep ocean water is roughly independent of the latitude and between 2 to 5°C, while surface ocean water shows more alteration with latitude change. Figure 2 illustrates the temperature and density variation profiles with depth in different latitudes of the open ocean for tropical, equatorial, and middle latitudes. For seas that are separated from the deep ocean such as the Mediterranean Sea, the Sulu, Visayan, and Bohol Seas in Southwestern Philippines the profiles can be different from the ones in Figure 2 [12, 13]. In the case of lakes, Hattemer and Kavanaugh [14] mentioned that the water temperature below a depth of approximately 18 to 24m may remain relatively constant throughout the year. However, this depends highly on the amount of inflow and/or outflow relative to the surface water body size [15].



Note: 'Other reneables' includes biomass and waste, geothermal, wave and tidal.

Figure 1: Global electricity production

Up to now, WTEBSs can generally be broken down into three main categories (shown in figure 3):

- Seawater Air Conditioning (SWAC) systems: systems that exploit water from waterbodies for heating/cooling demands using heat exchangers without heat pumps or chillers [15]. SWAC systems are onshore-based plants, intake and discharge pipelines with adequate lengths are shore-crossing and deployed at the bottom of the sea or ocean. SWAC replaces the chillers used in conventional air conditioning (CAC) systems and aims to greatly reduce the electricity consumption and cooling costs, as the electricity consumption of a SWAC system is around 80% lower than CAC [11, 17, 18]. A comprehensive list of globally deployed SWAC systems can be found in [8]. SWAC systems can be categorised into shallow and deep seawater systems according to the depth at which seawater is extracted [8].
- Surface water heat pump (SWHP) systems: systems that benefit from heat pumps or chillers to provide heating/cooling with their heat source/sink being surface water [15]. Under circumstances that the direct usage of seawater cannot meet the required cooling/heating demands, SWHP can be introduced as a justified alternative. SWHP systems are onshore-based plants, and have a higher efficiency compared with conventional CAC systems that use ambient air as a heat source/sink [19]. Therefore, with the rise in energy carriers costs,

SWHP has a great potential for operational cost savings [20]. A non-exhaustive list of SWHP around the world can be found in Su, Madani [19].

- Ocean Thermal Energy Conversion (OTEC) systems: systems that generate electricity from the natural thermal gradient between warm surface and cold deep ocean waters [21]. The efficiency of OTEC significantly depends on the ocean thermal gradient. Equatorial latitudes are ideal regions for OTEC systems as they provide the maximum temperature difference between surface and deep ocean water, shown in Figure 2. OTECs have high implementation cost and low actual efficiency of around 3% or 4%, but benefiting from an unlimited source of energy make them an attractive renewable technology [10]. OTEC systems can either be built onshore or on offshore floating platforms [21]. In case of floating platform, the energy can be transported via seafloor cables or stored in the form of chemical energy (e.g. hydrogen, ammonia, or methanol) and be regularly transferred to the shore by tankers [21, 22]. Currently, there are very limited number of OTEC plants that operate worldwide, mostly small scale or pilot systems [10, 23].

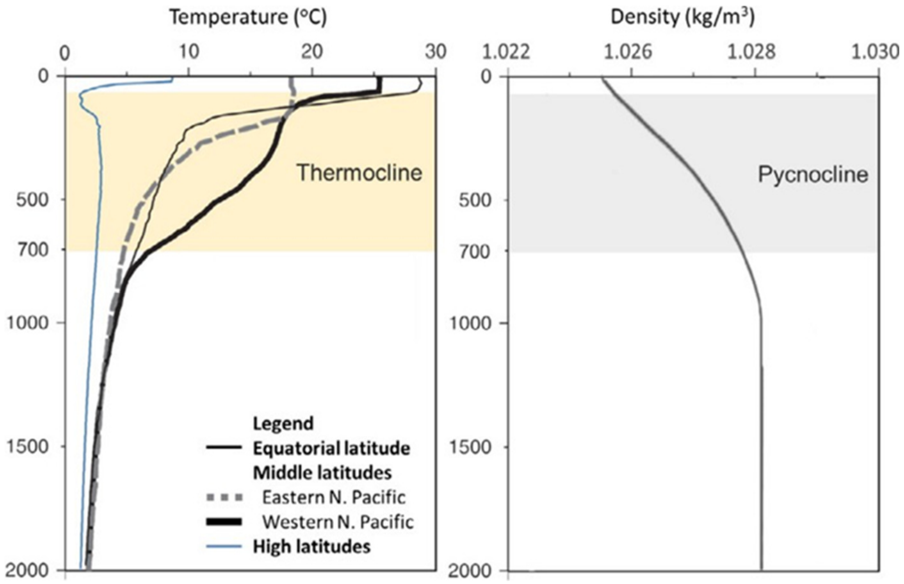


Figure 2: Typical Temperature and density variation with water depth in the open ocean

To maximise energy utilisation efficiencies WTEBSs can be combined. A hybrid SWHP and SWAC system can be a robust configuration that will be able to switch between two modes. The system works as a heat pump to provide cooling and heating, in case it is designed as a reversible heat pump. When the water temperature allows for it, the system can switch to SWAC mode and utilise cold lake water or seawater directly for cooling purposes [15, 24]. Such a system has been successfully deployed in different cities around the world [25, 26]. WTEBSs can also be combined with other technologies. The warmer seawater outlet of SWAC systems, which can be rich in nutrients, can be used for production of algae, fish, and crustaceans [11, 27]. In the open cycle OTEC system, which refer to systems that use seawater as the working fluid, the desalinated water (condensate) is fresh enough for municipal or agricultural use, and the cold nutrient water can be applied to aquaculture [21, 22]. Hunt and Weber [9] propose a combination of SWAC and reverse osmosis (RO) desalination to supply both affordable water and cooling services in a one-way district cooling system which can provide several advantages compared to SWAC and RO individually, such as reducing distribution costs. A combined system to use an offshore wind-driven hydraulic pump to supply high pressure deep seawater to a land base cooling plant (SWAC or SWHP) is proposed in [28–32]. With growth of the marine renewable energy technologies, concerns regarding their impacts on the sustainability of marine environments have been raised [4, 21, 33–35]. To address these concerns, it is critical to investigate the environmental footprint of existing WTEBSs and seek to minimize these impacts in future applications.

In the EUROSWAC project, Environmental studies including hydrological analysis, sea water quality measurements, and sediment and geomorphology analysis will be carried out in two demonstrator sites in the UK. The demonstrator sites are:

2.1. Brixham Laboratory

Brixham Laboratory of the University of Plymouth is one of the two demonstrator sites for the EUROSWAC project, which is based on Brixham harbour, UK. Figure 4 illustrates the location of Brixham laboratory on the map. The Brixham Laboratory was taken from former owner AstraZeneca in May 2014 and has since been transformed into a hub for local, national and international businesses. It is currently more than 90% occupied and is home to over 25 tenant organisations providing more than 200 jobs and attracting investors, innovators and customers from Europe, Asia and America. Its clients include an anchor tenant, Scymaris, which provides ecotoxicology, environmental and analytical chemistry services to the agrochemical, pharmaceutical and chemical industries. Other tenants include a wide variety of small and medium-sized organisations across the marine, photonics, business services and charity sectors, many of whom work closely with the University to create research and employment opportunities [26].

Brixham laboratory has its own shallow-water based SWAC system which has been out of service for quite a few years. Figure 5 shows the top view of the Brixham laboratory site and the current position of the inlet of the intake pipes, the outlet of the discharge pipe, and the pumping station of the SWAC facility. The facility has two inlet pipes called inner and outer intakes. Their names are simply defined based on their distance from the shoreline. The inlet of the inner and outer intake pipes is roughly 45 and 70 m away from the shoreline, respectively. The discharge outlet is located at the shoreline and depending on tide condition can be over the water surface level. The pumping station includes two obstruction pumps positioned around 2.5 m above the mean water level.

The EUROSWAC project aims to reawaken the SWAC system by carrying out offshore and onshore works with respect to the current activities at the site. This may include the installation of a new pumping station, filters, heat exchangers and potentially new pipes [27]. The simplified schematic of the existing seawater piping of the Brixham laboratory can be found in **Error! Reference source not found.**6.

The reawakening of the SWAC system will be followed by environmental studies to evaluate the potential environmental impacts of the future system. For this purpose, seawater property (pH, salinity, O2, total suspended solids) measurements will be conducted in Tor Bay. The outcomes may lead to optimising the design of the filters and anti-biofouling measures. Besides, the SWAC performance will also be evaluated and the findings will be used for future improvement options [27].

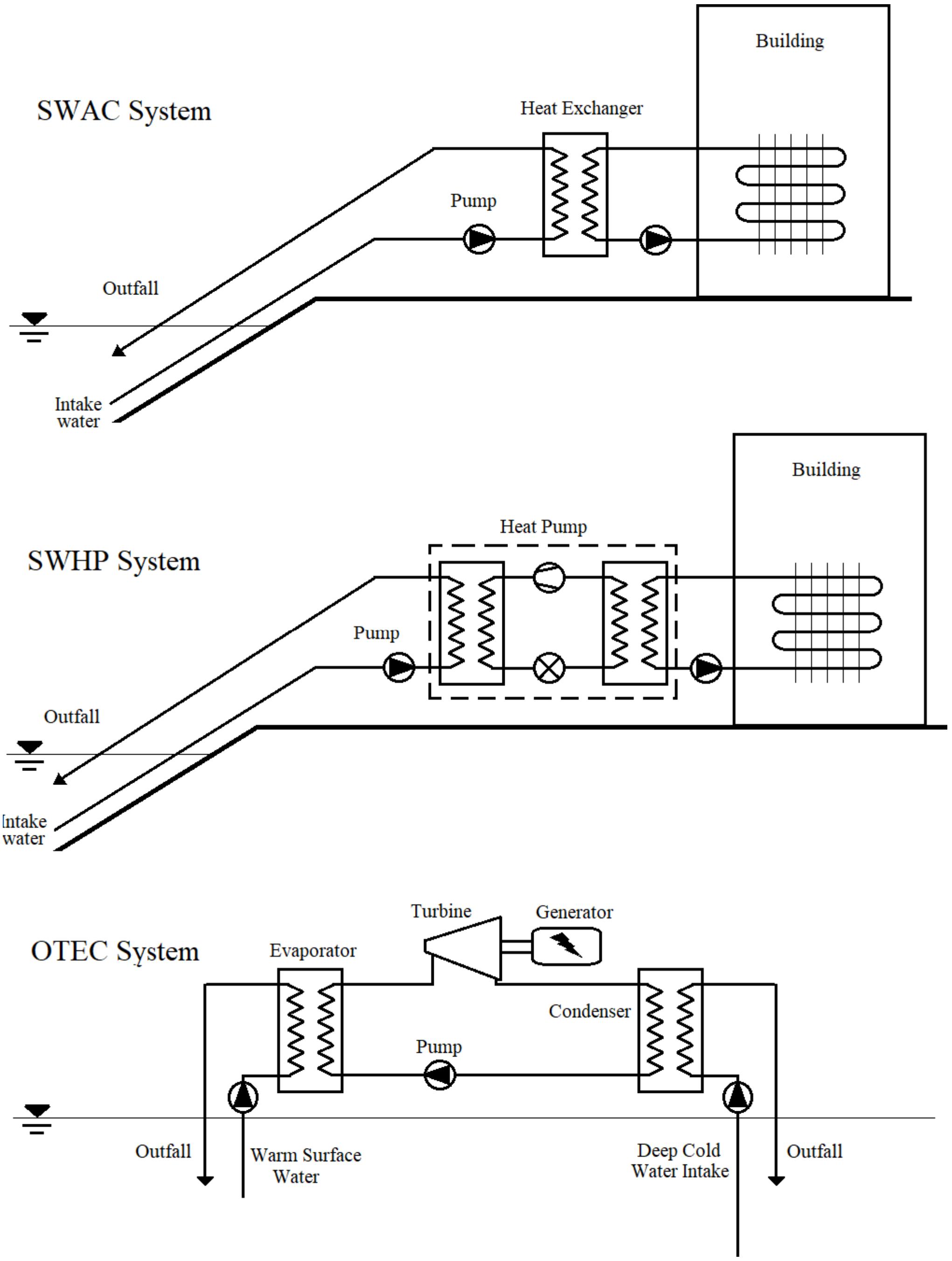


Figure 3: Simplified schematic of different types of WTEBS systems

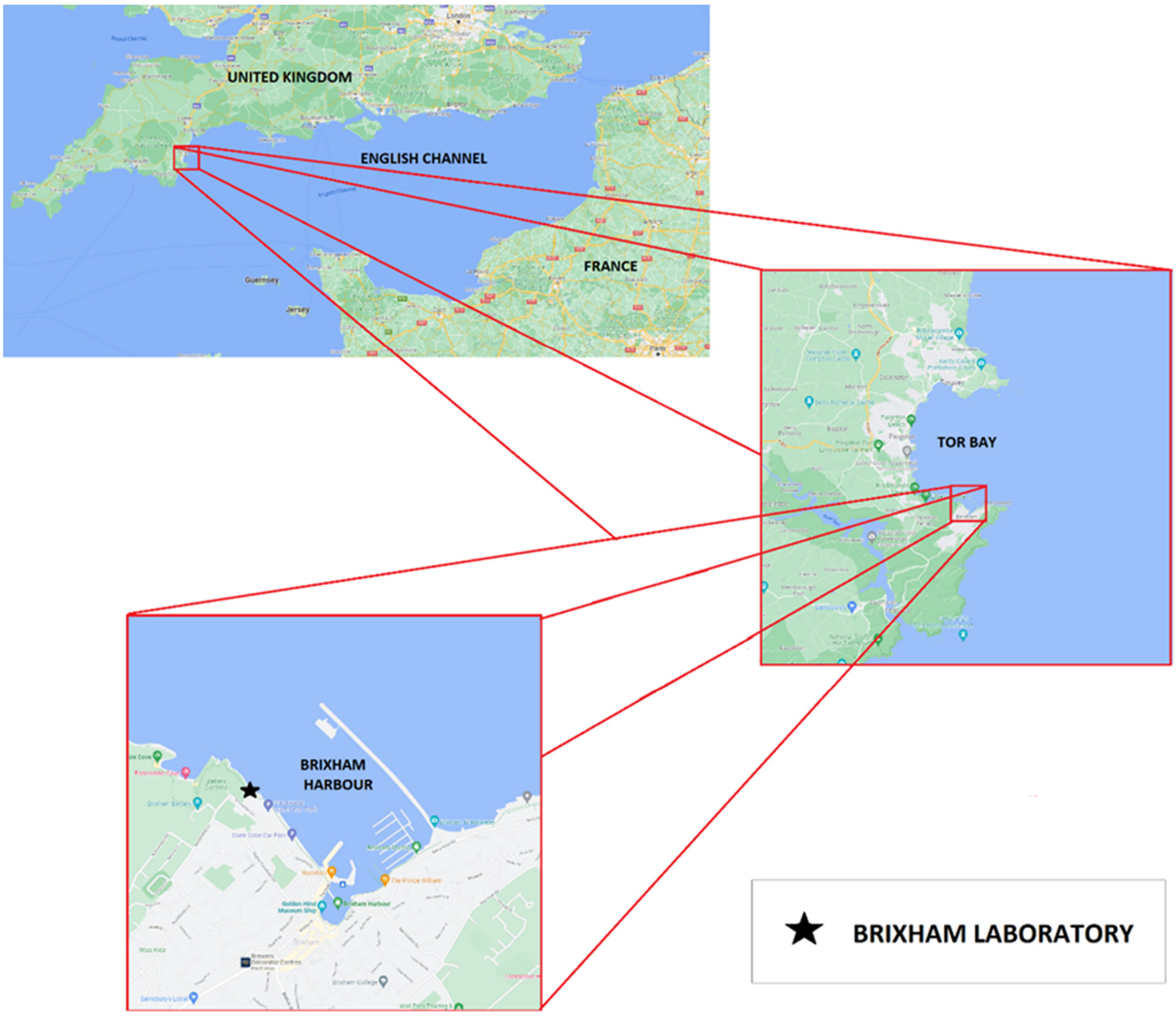


Figure 4: Location of Tor Bay, Brixham harbour, and Brixham Laboratory

GPS positions	Longitude	Latitude
Pump station (●)	50.40174	-3.51732
Discharge (●)	50.40186	-3.51773
Inner intake (●)	50.40212	-3.51743
Outer intake (●)	50.40239	-3.51723

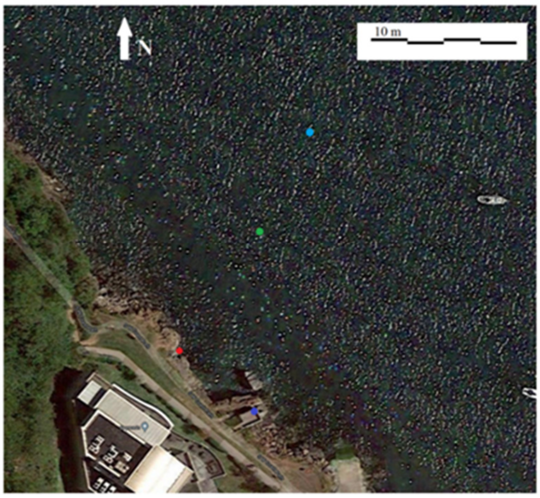


Figure 5: Location of inlet and outlet pipes of the SWAC facility at Brixham Laboratory

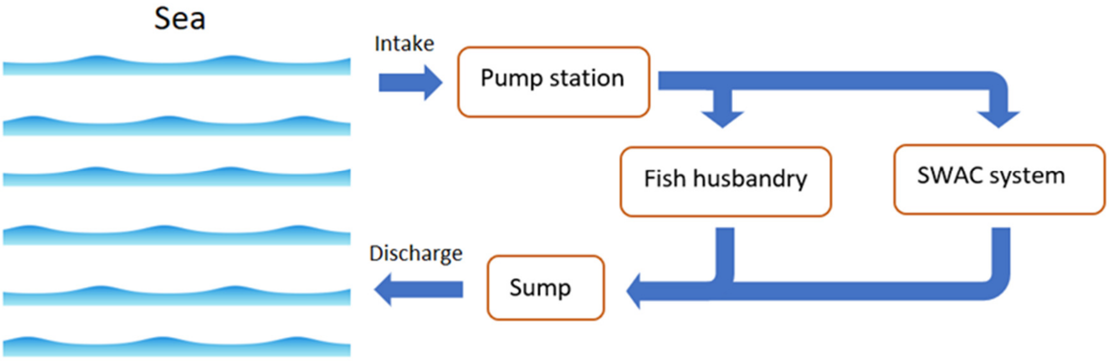


Figure 6: Simplified schematic of seawater piping of Brixham Laboratory

2.2. National Lobster Hatchery (NLH) at Newlyn

The second physical demonstration site for the EUROSWAC project is based in Newlyn harbour, UK operated by The National Lobster Hatchery (NLH). The Newlyn site is home to a lobster hatchery situated inside two shipping containers placed on the harbour wall, also known as The Lobster Module (LM). The LM aquaculture systems, operate as either a Recirculating Aquaculture System (RAS) or a partial Flow Through System (FTS) (explained in Figure 7). These are used to rear European lobsters (*Homarus gammarus*) for the purpose of replenishing fragile stocks within Cornish waters, creating a sustainable fishery. These aquaculture systems, like most, have a high demand for energy. The main consumption comes from the technology used to maintain an optimum temperature in the systems (EUROSWAC - The National Lobster Hatchery, 2021). In the LM, chiller/heater units pass systems water through a heat exchanger heating or cooling the water as needed. Additionally, AC is used in each container to maintain the air temperature inside the LM, helping to sustain the systems water temperature whilst also reducing evaporation from the systems, which in excess can lead to increases in salinity well above the threshold limit for *H. gammarus*. AC uses refrigerant gas inside a closed loop heat exchange system to absorb heat energy from the air inside the LM and expel it to the exterior environment using the cooler air outside with fans to chill the gas before being pumped back into the LM to continue the cycle. With a reliable and consistent supply of seawater adjacent, LM was chosen to assess the potentials of a specially designed SWAC system and its ability to maintain optimum air and water temperatures inside the containers for the cultivation of lobster stock. Plus, to review the possible further uses for SWAC systems within the aquaculture industry. As a marine conservation charity, the potential for more energy efficient and sustainable operations whilst optimising output would be extremely beneficial for the NLH.

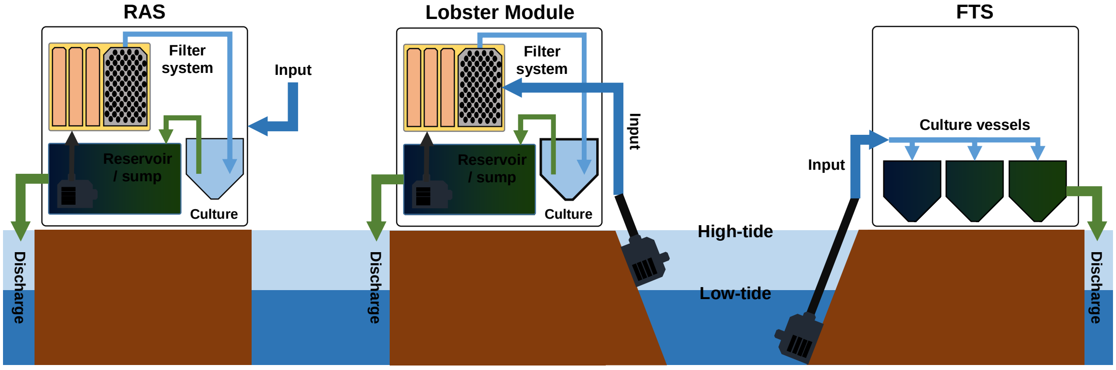


Figure 7: Flow diagrams of recirculating aquaculture systems (RAS), flow through systems (FTS) and the LM. Illustrating how the LM is setup to run as a RAS or a FTS dependant on the users' needs

3. WTEBS Environmental Impacts

Anthropogenic activities are the main reasons for major changes to marine wildlife [35, 36]. Activities such as a variety of terrestrial land uses and near-shore activities, dredging, overfishing, oil and gas operations, illegal dumping of solid wastes, and other industrial processes have been dramatically implicated in the perturbation of the marine environment [35–42]. Recently, Halpern, and Frazier [43] investigated the cumulative impact of 14 stressors related to human activities on 21 different marine ecosystems globally during an 11 year period from 2003–2013. In result, they realised that most of the ocean (59%) is experiencing significantly increasing cumulative impact, in particular due to climate change but also from fishing, land-based pollution, and shipping. The growth in deployment of offshore renewable energy technologies also adds to the concerns regarding interactions with the marine environment. A list of newly emerging renewable energy technologies with special concentration on marine energy generation can be found in [44, 45]. The life-cycle (i.e. including construction, installation, operation, decommissioning) environmental impact assessment of tidal and wave energy generation devices has been reviewed and evaluated in [46–52]. Williamson and Fraser [53] used ecological and physical measurements to show the predictability of fish school characteristics (presence, school area, and height above seabed) in a high energy tidal site, and how this changed around a turbine structure. Malinka and Gillespie [54] studied the behaviour and movement of small cetaceans around a tidal turbine. Seyfried and Palko [55] reviewed the potential environmental impacts of a salinity gradient energy (SGE) facility through the construction, operation, and decommission phases. The life-cycle environmental impact assessment of offshore wind turbines has been investigated in [51, 56, 57]. Gill and Degraer [58] studied offshore wind development effects on fish and fisheries. Tougaard and Hermannsen [59] and Madsen and Wahlberg [60] reviewed available measurements of underwater noise from different wind turbines during operation and reported that the underwater noise radiated from individual wind turbines is low compared to the noise radiated from cargo ships. The combined noise level of a large wind farm can cause negative effects on species of fish and marine mammals. Boehlert and Gill [34] noted that devices with subsurface moving parts, such as underwater turbines, are assumed to be the noisiest. An investigation on underwater operational sound of a tidal stream turbine can be found in [61]. The potential impacts of submarine power cables during the installation, operation, and decommissioning phases on the marine environment has been studied in [62–64].

In this section, a review of the relevant concerns and interactions of the development of WTEBSs including different stages of construction, operation, and decommissioning with marine environment is provided in detail. Many of the associated effects of WTEBSs are common with other types of development in the marine environment. Potential uncertainties may arise when their impacts have not been evaluated or anticipated accurately.

3.1. Construction and decommissioning impacts

The construction and decommissioning phases of development of a WTEBS are likely to cause significant positive and negative disturbance to local environmental resources and fundamental changes to the habitat, both above and below the water surface [34, 65]. Their spatial scale may have ecological impacts extending over several square kilometres, while temporal scales are both short- and long-term on marine environments [35, 66]. The magnitude of the impacts is highly depending on the duration and intensity of the disturbance and the stability and resilience of the marine communities [35, 67–69]. The ecological implications associated with WTEBS construction can be similar to the alterations of the benthic habitats that have been subjected to fishing or marine dredging [35, 70, 71]. Based on that, Gill [35] listed a number of effects on costal environment as a result of development (construction, operation, and de- commission) of offshore renewable energy systems including WTEBS. In general, during construction and decommissioning, the seabed will be disturbed by installation of foundations and hard-fixed structures (such as submerged heat exchangers or pump stations), pipelines, scour-protection systems, mooring devices, and seabed mounted power cables. Marine organisms within the footprint of these objects would be smothered or crushed [65]. These artificial structures may have the greatest impact on benthic habitats and ecosystems [34]. They also may alter the local flow which is essential to some aquatic species such as corals [72], lead to entrainment and deposition of sediments, and change the seabed bathymetry [73]. Conversely, the deployment of these objects on the seabed, provides artificial reefs in benthic environments [74, 75]. This may stimulate the benthic ecosystem and lead to a greater biodiversity [75, 76]. The construction and decommissioning phases will disturb the surface and midwater with structures including spars, buoys, pipelines, and cables that may result in modifications on pelagic habitats and ecosystems [34, 77]. These effects are widely studied in oil and gas platform industry where these structures can serve an equivalent function to artificial reefs in benthic environments [74, 75]. The presence of these objects may have positive effects on attraction of some species (e.g., krill, mysids, and fishes) and consequently additional predators in the region. The presence of the structures may modify the local water flow and may take up significant areas of the sea surface which may influence migratory surface dwellers [34].

The construction of sea water pipeline systems for onshore WTEBS is the main interaction with ocean environment. the pipeline system may contain submersible pumps or submerged- coils (heat ex- changers) in seawater/lake heat pump systems [78–81]. The pipelines are mainly made of high-density polyethylene (HDPE) material due to the several advantages it offers compared to alternative materials (e.g. strength, durability, flexibility, insulation, resistance to high pressure, cost effectiveness, and slight negative buoyancy) [11, 82, 83]. For pipelines that are exposed to storms, tsunami, seismic activity, and other environmental concerns, the most challenging aspect of the development of the pipelines is the coastal transition zone (sea/shore interface) aspect [26]. To reduce the risk of damage or incident, in most cases, the pipelines are either trenched or tunnelled under the shoreline, from a point before the shoreline to a point in the seabed, a few meters deep [26, 65, 84]. Among these two techniques, tunnelling such as micro-tunnelling, and horizontal directional drilling (HDD) is more recommended [26, 65, 85–87], as trenching comes with removal of sediments and direct loss of marine habitats [35]. The removal of sediments also increases the local water turbidity as a result of suspended particles. This may increase the risk of spreading any contaminants from the suspended particles or lead to temporarily reduction of the available oxygen which may smother the neighbouring habitats of sedentary species [35]. The other benefits of trench-less technologies compared to open cut trenching are: minimum impact on existing infrastructure, longer lifetime of the pipeline, minimum efforts to reinstate the site following pipe installation, and independence from weather conditions and waves during the construction phase [88]. Nevertheless, trench-less technologies may also have some environmental impacts. Potential leakages of drilling mud through the sediment into the water column during the micro-tunnelling can be eliminated by grouting the void between the micro-tunnel and the pipes [65]. In development of sea water pipelines using trench-less technologies, the pipeline construction impacts would be mainly related to the excavation of a breaking point, where sediments would be removed and bathymetry temporarily changed at the pit [65]. The breakout point (receiving pit) is where buried pipes and seabed surface mounted pipes are connected. The temporary impacts of the constructions such as elevated levels of suspended sediments in water adjacent to the excavation area can be minimized by installation of sheet piles around the pit to isolate it from the surrounding water [65]. The long-term impacts on ocean current are negligible as the breakout pit would be back-filled and caped with concrete similar to the original bathymetry. The main part of the pipelines is mounted on the seabed surface which is installed in a controlled submergence process. Detailed discussion regarding the installation of the HDPE deep seawater pipelines can be found in [26, 65, 89]. A possible long-term impact would be associated to the scouring and sediment transportation beneath the mounted pipes. This can be minimized with sufficient clearance between the pipes and the seabed [65]. Some recent studies in numerical modelling of scouring can be found in works of Bordbar et al. [90–92]. Nevertheless, close monitoring will be essential and whenever required a scour countermeasure method have to be considered [93].

Offshore WTEBS that include platforms, intakes and outfall pipelines, and mooring systems can affect both benthic and pelagic ecosystems. The main environmental impact in pelagic zones during the installation of the system is likely to be related to the seismic surveys at the start of the project, shipping movements, construction noise, and potential chemical pollution associated with marine vessel operations. Brandt and Diederichs [94] reported that marine mammals temporary avoid an area where construction is taking away. The effect disappears immediately after the cease of noisy activities. Water pipelines of a floating WTEBS can be made of HDPE or Fiber-Reinforced Plastic (FRP). For large scale OTEC floating plants with 4 to 10m diameter intake pipelines, FRP material is proposed as the use of HDPE solution is not available for pipelines with diameters larger than 2.5m [95]. HDPE is not a biodegradable material and at the end of life it should be responsibly recycled, while FRP pipe material is considered as non-corrosive [96, 97]. McHale [98] reported the development process of a cold-water pipeline associated with a 50KW mini-OTEC plant at Kona, Hawaii. In OTEC systems, cold-water pipelines may serve as a combined cold-water pipe and mooring line [98–100]. The impact on the benthic zone is likely related to the installation of mooring systems and power cables. The installation of these devices may locally disturb the ecosystem and temporary increase the turbidity of the water, however biota density is limited in that depth, i.e., infra to 1000m depth [101]. If no anti-fouling is used, the presence of the WTEBS structures will provide settlement habitats for a variety of organisms [102, 103]. As discussed earlier in this section, for a large-scale platform the potential impacts of the local water flow modification and large area of the occupied ocean surface on migratory surface dwellers and pelagic ecosystem need to be considered.

To minimize the environmental impact of pipeline installation for a future SWAC application, DeProfundis and DORIS Engineering has introduced and innovative intake pipe self-burying system. The system limit the impact on the underwater environment and reduce installation cost [104].In simple words, the system includes of injecting water into the sand located under the pipe places on the ground to thin the sand so that the pipe sink in under its own weight [104]. The method benefits from a new concept called “flexible pipe” which will contribute to the cost reduction of conventional SWAC systems by reducing the material and installation cost [105].

The associated impacts of the decommissioning a site are assumed to be similar to those for the site construction [34, 35]. The removal of existing underwater structures will cause a sudden alteration on heterogeneity of the benthic habitant by removing a component of the ecosystem [106]. This may disturb the local food web and also change habitat availability [35].

3.2. Operation Impacts

A WTEBS intakes/discharges large volumes of ocean water. For example, an OTEC plant typically needs around $5m^3s$ of cold deep seawater, and equal intake of warm surface water per $1MW$ capacity, therefore a commercial OTEC system with $100MW$ capacity needs a massive volume of $500m^3s$ of cold and warm intake water for operation [22]. The system mixes the water and discharges it into the ambient environment with different characteristics. Considering the lifetime of a plant (25-30 years), the operation of WTEBS may change the water characteristics in near-, intermediate- and far-field and consequently disturb marine ecosystem [21]. Furthermore, concentrated deployment of large-scale WTEBSs can accumulate and intensify the impacts [33]. While environmental impacts associated with processing seawater is the main focus, impacts from other factors such as power cable electromagnetic fields, acoustic effects of the WTEBS machinery and pipelines and leakage of chemicals from the system can also be of importance during the operation of the system. In the pertinent literature, most of the knowledge regarding the environmental impacts of WTEBS comes from studies that investigated the pre-impact condition at a future WTEBS site. Among them, Comfort and McManus [4], Cardno TEC [65] Ciani [24], and Comfort and Vega [33] studied the coastal area of Hawaii for SWAC and OTEC projects. A review of the features of the marine environment that may change with the operation of a WTEBS, and potential impacts of these changes on marine life are presented in this section.

3.2.1. Impingement and Entrainment of organisms

The inlet pipelines may intake marine organisms, especially those with low mobility and smaller than the mesh of the inlet pipe screen, into the system during operation [22]. These organisms will be impinged to the internal walls of the system and will encounter rapid changes, such as changes in temperature, dissolved oxygen, turbidity, and light levels of the water, which to a great extend reduce their chance of survival [22, 93, 107]. This phenomenon has been studied for coastal nuclear power plants and may be similar for WTEBSs [22, 108, 109]. Due to the higher concentration of marine life in shallow water, this is an important factor in systems that intake surface water, while need to be assessed for systems that intake cold deep seawater depending on existing ecology [33, 93, 110, 111]. The intake pipelines are designed in a way to have as low an approach velocity as possible [107]. Nevertheless, Plankton, small nekton, and most tuna larvae are at high risk for entrainment into the surface water intake [110, 112]. This risk extremely decreases for larger organisms due to their swimming capabilities [33]. In addition, pipeline vibrations during the system operation may create a signal for marine mammals and fish to avoid approaching the pipelines [33]. The discharge outfall can also be an attractive destination for marine organisms as it may be rich in nutrients. This increases the probability of impingement and injury of marine organisms [93]. Using the discharge water for secondary purposes can influence the water discharge quality which need further monitoring and observations.

3.2.2. Chemical Effects

During the normal operation of a system, the potential of leakage from those devices that use a hydraulic fluid needs to be considered. In systems with closed-cycle operation, the working fluid (e.g. ammonia or R-134a) is conserved. Ammonia is classified as a highly toxic substance to fish while concerns regarding the impact of R-134a on marine life are growing [113–115]. A study of a selection of working fluids in terms of toxicity, environmental performance, and flammability can be found in Jung and Hwang [115]. Leakage or spill of a small volume of working fluid into the environment would not endanger the local marine population [93]. However, if ammonia were released into the surface water at a large rate, it could pose a serious health threat to the platform crew, the adjacent population, and the marine life. This could only occur if there were serious malfunctions such as a major breakdown, a collision with an ocean-going vessel, a storm exceeding once in 100 years severity, military or political terrorism, or human errors [22]. It is to be noted that a workflow leakage due to a malfunction of the system should be avoided at all costs [116]. The toxic impact of heavy metal concentrations from heat exchangers needs to be evaluated [117]. Chemicals used for controlling bio-fouling and corrosion, such as chlorine or protective coating materials can accumulate in the tissues of organisms, and be passed up the food chain [22, 93]. Pre-treatment before disposal of chemicals and/or mechanical control of fouling should be implemented [93].

3.2.3. Nutrient Loading

For WTEBS that intake deep cold ocean water, the untreated plume has different physical and chemical properties (e.g. temperature, density, salinity, dissolved gases, nutrient level, and pH level) than the surrounding ocean water where it is discharged [4, 33, 34]. The density difference between the discharge outfall and the ambient water will cause the plume to sink or rise to an equilibrium depth and produce an artificial nutrient enriched zone [33]. If the plume equilibrium occurs in the photic zone, it may induce phytoplankton and algal blooms and subsequently change the pelagic food web ecosystem and habitat [4, 34, 101, 118–120]. In coastal areas, this may disturb human activities such as shore-based businesses, fish industry and recreational tourism [34, 93]. To minimize the environmental impact of WTEBS plume, it is crucial to ensure the nutrient-rich plume does not mix with surface waters and remains beneath the most biologically productive depths (below the 1% light level)[26, 33, 52]. For this purpose, different water depths between 90 to 200*m* have been recommended in the literature [33, 52, 120, 121]. These values depend on more detailed local site conditions, environmental regulations, and diffuser dispersion modelling [122]. Nutrient enhancement for WTEBS that intake water from shallow sea or lakes also need to be investigated, as many lakes and shallow sea areas show vertical stratification of their water during the warm seasons [123, 124]. The rich-nutrient discharge of WTEBS can also serve secondary utilization for energy production, cooling, desalination, aquaculture, and agriculture [26, 125, 126]. Nevertheless, the environmental impact of the effluent from the secondary utilization system into ocean needs to be assessed.

3.2.4. Temperature Concerns

As mentioned above, if the WTEBS discharge water is not returned to isothermal depth, there will be a risk of slight change in water temperature. This thermal effect may have severe consequences on marine life, as the reduction on hatching success of eggs, inhibition of larvae development, and increase in death among corals and fish are reported due to thermal changes [21, 93, 127]. However, Avery and Wu [22] as a result of several theoretical and experimental studies (e.g. Adams, Fry [128]) concluded that climatic alterations due to the operation of an OTEC system is negligible or extremely localized. Over the long term, the large volume of discharge plume has the potential to alter the marine ecosystem in regions near the discharge outlet [34, 118]. The impacts in far-field region may be more noticeable in presence of a very large number of OTEC plants [22].

3.2.5. CO_2 Outgas and pH level

Seawater has many different gases dissolved in it, including nitrogen, oxygen, and carbon dioxide. The intake water to a WTEBS is subjected to change in temperature and pressure which leads to changes in solubility of the dissolved gas in the water. For systems that intake deep sea ocean water, it can result to dissolved CO_2 outgas [93]. While, this amount will depend on the volume of water being pumped, Avery and Wu [22] pointed out that such an amount would be smaller than emissions from a fossil-fuel-fired plant. Conversely, CO_2 and other carbon compounds (e.g. carbonate and bicarbonate) play an important role in the pH level of ocean water [129]. Changes in the concentration of the CO_2 levels in water, may increase concerns regarding the acidification effect of the artificially upwelled water [34, 130, 131]. The change in the pH level of the seawater can disturb the marine ecosystem, biodiversity, and marine food web [131].

3.2.6. Acoustic effects

Acoustics are essential in animal communication, reproduction, orientation, and prey and predator sensing [34]. Anthropogenic underwater noise will likely add to the normal background acoustic environment [34]. The possible impacts of artificial noise in fish, marine mammals, and crab and lobster larvae have been indicated in [73, 132, 133]. The generated noise associated with the operation of WTEBS can be of concern, as the plants operate permanently over the long period of 25-30 years [134]. The operational acoustic noises from onshore WTEBS in marine environment can be mainly due to the vibration from the pipelines, however there is no evidence of such an impact being studied in the literature. For offshore systems, cold water pipelines, water pumps, and noise associated with devices in a typical WTEBS plant, such as pumps associated with the transport of working fluid) can be the main source of noise [134, 135]. Ducatel and Audoly [136] conducted a preliminary study to predict the potential acoustic impact of an OTEC plant due to onboard machinery. They noted potential impacts of the system on marine mammals if they stay permanently at short distances to it [136].

3.2.7. Electromagnetic Effects

Offshore-based OTEC systems require to transmits the produced electricity to shore. This may be carried out using a network of cables that are mounted on the seabed. The transmission of the produced electricity through these cables will emit low-frequency electromagnetic fields (EMF) [34]. A number of marine organisms uses electroreception as a fundamental sensory mode for mate finding, feeding, and navigation [34, 63, 137–139]. Therefore, it is most likely that EMF from power cables affect these animals. Scott and Harsanyi [64] indicated that EMF from sub-sea power cables affect edible crabs both behaviourally and physiologically. Westerberg and Lagenfelt [140] reported a significant change in eels migration swimming speed around the sub-sea power cables. Other growing concerns regarding mounted or buried power cables include an increase in temperature of the adjacent water, sedimentation, and impacts on benthic ecosystems due to electricity transmission [34]. Further investigation is recommended for better understanding of the impact of sub-sea power cables on marine organisms.

4. Modelling of discharge dispersion

Discharge dispersion modelling of WTEBSs can assist addressing concerns regarding their impacts on the sustainability of marine environments and provide opportunities for achieving maximum effluent mixing efficiency and understanding of the mixing behaviour of plume jets.

The application of modelling of discharge dispersion is not confined to WTEBSs as the topic is also of interest to other growing technologies such as aquafarming, desalination plants, and thermal power plants that discharge a considerable amount of wastewater directly back to waterbodies. Desalination brine, a by-product from desalination plants, comprises high concentrations of dissolved substances and suspended solids as well as possible waste heat [141]. Thermal power plants of coastal cities discharge enormous quantities of waste heat into seas and lakes [142], while aquafarming effluent is typically enriched in suspended organic solids, carbon, nitrogen, and phosphorus [143], which may have detrimental impact on many species living around the discharge location.

In general, wastewater discharges from industrial processes are categorized in two major groups based on their density discrepancy with the ambient water bodies [144]. If the effluent has higher density that the ambient water, the plume of outfall discharge tends to sink, which is known as a negatively buoyant jet plume. Conversely, if the effluent has a lower density than the ambient water the effluent jet plume tends to rise, which is termed as a buoyant plume [145]. Nevertheless, the mixing behaviour of the discharged effluents can show a great diversity of flow patterns, depending on the geometric and dynamic characteristics of the environment and the discharge flow [146, 147].

In the pertinent literature, the study of submerged jet flow has been extensively studied. Experimental investigations on the characteristics of the inclined brine dense jets, such as maximum jet height rise and concentration field, into stagnant environment can be found in [148–150]. These studies reported that dense jets with 60° inclined angle produce the longest trajectory for entrainment and thus the highest dilution. [141] and [146] studied the effect of stationary shallow water on the mixing of 30 and 45° inclined dense jets. It was realized that the surface constraint may lengthen jet-spreading distances and reduce surface dilution. They also recommended that the terminal rise related to 60° inclined dense jet is rather high and therefore the angle may be too large for providing efficient mixing in shallow waters. [142] investigated turbulence buoyant jets vertically discharged into a large body of stagnant non-stratified water. The temperature characteristics of a hot rising plume as a function of discharge Froude number and discharge depth were illustrated.[151], [152], and [153] studied the impacts of horizontal buoyant jets discharged into stationary environments and investigated the effect of bed proximity or so-known Coanda effect. Coanda effect occurs when the jet discharge is placed close to the bed boundary, the discharge will then cling to and proceed along the boundary [146]. The Coanda effect can improve the mixing efficiency for buoyant flows while for saline dense jet, it may cause negative effects on benthic community around the impacted area [146]. [154], [144], and [155] carried out numerical modelling of turbulent buoyant jets in stationary ambient water. These studies applied Reynolds-Average Navier-Stokes (RANS) combined with different turbulence closure models. In result, a linear eddy viscosity model, realizable k-e turbulence model, and Reynolds Stress Models, LRR, were found to be the most reliable and accurate in modelling of Coanda effect, buoyant and non-buoyant jet in stagnant environment. [156] conducted a series of experimental tests for negatively buoyant effluents discharged through a protruding surface channel into unstratified stagnant water. The results show that the influence of free-surface on the entrainment and mixing of the flows is small. [157] carried out comprehensive laboratory experiments on multiport diffusers for negatively buoyancy effluents into stationary water. As a result, it is recommended that to prevent reduction in entrainment, it is essential to consider sufficient spacing between the ports in designing. [158] developed a classification chart for thermal-saline inclined single-port jet, as a result of an extensive set of laboratory experiments for thermal-saline effluent with three different discharge angles of 30°, 45°, and 60° in stagnant water environment. [159] carried out numerical and experimental studies of negatively buoyant jet discharged with 45° inclined angle in a stationary water environment. As recommended by [154], [144], and [155], simulations were conducted using RANS model with realizable k-e model and the outcomes showed good consistency with the results of physical modelling. More recently, [160] studied submerged thermal-saline jet discharge into a stagnant environment using the LES turbulence model. The results illustrated that the flow patterns only depend on the density ratio, which is the thermal flux to salinity flux ratio.

Investigations on the characteristics of jets into non-stationary environments have also been widely carried out. [161] conducted a series of experiments on the characteristics of vertical and inclined dense jets with different angles discharged into a uniform crossflow of various velocities and directions. They discovered that inclined jets are generally preferable to vertical jets. When a submerged discharge outlet is located where currents may flow in all directions, then vertical jets may be the preferable choice instead of inclined jets [162]. [163] conducted laboratory experiments for turbulent non-buoyant jets vertically discharged into two different environments, one with stagnant ambient water and a second with regular waves and observed higher entrainment velocity in the case of wave environment. [164] experimentally investigated the behaviour of a horizontal non-buoyant jet located at the mid-depth of a shallow water wave environment. The results revealed that the influence of wave amplitude on jet diffusion is substantial. [165] numerically simulated seawater temperature field to monitor the environmental impacts of hot effluent discharged from a seawater-source heat pump in Dalian, using a two-dimensional convection-diffusion equation model. As a result, the water temperature elevation impacts on the marine ecosystem was found to be negligible. [166] established a two-dimensional hydrodynamic model to predict and optimize the thermal plume from a Rizhao power plant discharge on Rizhao sea. [167] conducted numerical modelling of a buoyant and non-buoyant round jet discharge into wave environments using Large Eddy Simulation (LES). The Buoyancy effect was considered using the Boussinesq assumption. The results were validated against the experimental data by [168]. As an outcome, they realized that under the buoyancy force the wave effect on jet entrainment and mixing is considerably weakened. [169] developed and validated a three- dimensional time-dependent model for predicting biological and physical impacts of OTEC. The model simulated negatively buoyant discharge flows by a dynamically coupled Lagrangian jet-plume entrainment model in the near-field, and by dynamic oceanic circulation and turbulence in the far-field for the water surrounding O’ahu in Hawai’i. The model used to define the effect of nutrient-rich and low-oxygen deep sea water on increased productivity of phytoplankton. [170] developed a primitive three-dimensional model to predict and minimise the mixing behaviour of thermal discharges of an OTEC system in coastal water of Kosrae, Micronesia. They declared that the model was capable of reproducing the plume behaviour. The effect of free-surface waves in temperature distribution in thermal boundary layer region close to the seabed was theoretically modelled in [171]. The study suggested a need for expanding existing models that neglect the effects of a wave field.

There are also some well-known commercial models that have been widely used for predicting the effluent discharges in waterbodies. In this group, [172] implemented a Lagrangian interactive virtual reality model (JETLAG/VISJET) based on the project-area entrainment hypothesis and a heuristic theory to treat the shear to vortex entrainment transition. [173] developed VISUAL PLUMES (VP) model which is a platform for mixing zone modelling. [147] introduced an integral model for turbulent buoyant jets in unbounded stratified flow which was coded into a Fortran program COREJET/CORMIX. [174] carried out a detailed analysis of these commercial models (i.e. JETLAG, COREJET, and VP) and realized insensitivity of these models in predicting the influence of crossflow direction on jet behaviour. Most recently, [175] investigated a non-buoyant vertical round jet in a wave-current coexisting and current-only environment both numerically, using Large Eddy Simulation (LES), and experimentally. They observed the effluent clouds phenomenon in the wave-current coexisting which leads to considerable increment of jet spread and dilution. [176] investigated the impact of regular waves on three dimensional scalar structures of a vertical jet in the wave-following-current environment using numerical modelling of submerged non- buoyant vertical round jets. [177] developed a set of semi-empirical equations to quantify the wave effect on the initial dilution of wastewater discharge based on numerical modelling of non-buoyant jet discharges in wave-following-current environments. [178] conducted several experimental tests about submerged multiport diffuser effluent discharges in a wavy cross-flow environment. It was discovered that the wave-to-current velocity ratio is a very important parameter in describing effluent discharge dilution. [179] implemented an *OpenFOAM* -based solver that can be applied in modelling of thermal discharge into water bodies. The solver was suitable for simulating three fluid phases with different densities and temperatures, i.e., two miscible liquids and air. The model was validated against an experiment of a multiphase dam-break. However, the model did not consider buoyancy effects. [180] implemented an integral model for predicting the characteristic behaviour of a buoyant jet in a wavy crossflow environment. [181] carried out a set of laboratory tests in modelling of submerged negatively buoyant outfall under typical conditions in the Mediterranean Sea. The results revealed that the strongest waves tested in the study tend to decrease dilution, while the weakest waves tend to improve it. [182] reviewed the literature of the jet in the wave environment and identified the various mean and turbulence quantities of the jet in the regular and random waves environment. They concluded that the behaviour of the jet can be predicted based on the ratio of the jet inlet velocity to the wave orbital velocity. As listed above, many numerical and experimental studies have been conducted to study effluent dispersion, however the literature lacks a comprehensive and sophisticated computational fluid dynamics (CFD) model to simulate the hydro-thermal behaviour of discharged effluents into waterbodies under combined wave-current conditions. The recent advances in development of numerical tools in simulation of hydrodynamics of wave and currents with mesh-based (such as, [183] that developed a realistic wave generator and active wave absorber for the Navier-stokes equation and [184] that implemented a new turbulence model capable of predicting accurate pre- and post-breaking surface elevations, as well as turbulence and undertow velocity profiles of surface waves) and mesh-less (such as, [185] and [186] that implemented a numerical wave-current flume based on smoothed particle hydrodynamics (SPH)) approaches provide an opportunity to bridge this knowledge gap.

5. Biofouling and corrosion

Exposed surfaces of systems that use sea water as the main processing fluid can be affected by physical- chemical properties of sea water such as fouling and corrosion [187]. Fouling occurs as a result of deposition of dissolved and particulate matter in the water on surfaces that are in contact with it [188]. The undesired growth and accumulation of foulant on surfaces in contact with water can potentially affect the system's efficiency, while damaging equipment in the process [187]. An uncontrolled growth of fouling can have damaging consequences to WTEBSs [187], marine vessels [189], rigs [190], marine aquaculture [191], and other infrastructure that are submerged in the sea. Crystalline fouling, organic fouling, particle and colloidal fouling, and microbiological fouling are categorised as the most important types of fouling [192, 193]. Among them, controlling the biofouling (microbiological fouling) is the most complicated one [192, 193]. Marine biofouling is the unwanted growth of marine micro- and macro-organisms like bacteria, algae, sponges, barnacles, mussels, Balanus etc. [194]. The growth and accumulation process of biofouling on the exposed surfaces can be found in detail in [187, 192, 193, 195, 196]. Bott [197] classified the parameters that can influence biofouling growth into three main categories of chemical, physical, and biological, as listed in table 1.

Table 1: Chemical, physical, and biological parameters that affect biofouling growth [197]

Chemical	Physical	Biological
Substrate type	Temperature	Microorganism type
Substrate concentration	Fluid shear stress	Culture type
pH	Heat flux	Suspended cell concentration
Inorganic ions	Surface composition	Antagonist organism
Dissolved oxygen	Surface texture	
Microbial inhibitors	Fluid residence time	

Untreated fouling can lead to increases in the thermal resistance as well as the required pumping power [15]. Abidin, Rodhi [187] and Jenkins [198] affirmed that on the design of OTEC systems, biofouling is an inevitable condition that cannot be avoided. They highlighted the impacts of the flow velocity and temperature of the seawater intake as two main parameters on control of the biofouling growth. The relationship between the flow velocity and the biofouling growth is complicated to correlate due to its dual impacts. The rapid velocity of the water can provide a sufficient oxygen and nutrient that favours the growth of macro foulants, but it can also cease the biofouling growth if the water shear rate surpass the shear rate of biofouling settlement [192, 198]. Panchal and Knudsen [199] pointed out that the seawater temperature in the range of 20°C to 50°C is the desired temperature for microorganism's growth which can explain why high temperature surface seawater exposed to continuous sunlight accommodates the growth of biofouling [15]. Conversely, higher potential of biofouling is anticipated in shallow water-based onshore facilities in comparison to offshore facilities owing to the high concentration of organisms in sea water near the shoreline area [22]. Seasonal seawater temperature changes can also influence the potential of biofouling growth as low range of temperature changes, e.g. tropical area, provide a steady condition for biofouling development [200].

One of the most common techniques in industry to kill bacteria in the system is the use of Biocides [201]. There are two types of biocides, oxidizing and nonoxidizing. The oxidizing biocides, such as chlorine, peracetic acid, sodium bromide, attack microorganisms by disrupting nutrients from passing across the microorganisms cell wall [201, 202]. On the other hand, the nonoxidizing biocides, such as 1,2-benzisothiazolin-3-on, 5-chloro-2-methyl-4-isothiazolin-3-on, interfere with reproduction, stop the respiration process, or break the microorganisms cell wall [201, 202]. In open systems due to environmental concerns regarding chemical discharge, only using direct injection of the oxidizing agent sodium hypochlorite (chorine) is allowed [15]. Antifouling coating is another usual practise in marine and maritime industries to prevent biofouling. Until recently, tributyltin (TBT) was an active biocide ingredient in many paints that were very successful in reducing biofouling [203]. However, its use has been prohibited as it was found harmful to marine organisms. It’s replacements include metallic species, such as copper and zinc and many other alternatives [203].

Abidin [187] elaborated on a list of common and potential techniques of biofouling assessment for OTEC systems including microscopic and optical techniques, spectroscopic, physical assessment, electrical techniques, and biological/ chemical detecting techniques. This list can be generalized and adapted for biofouling assessments for all other types of WTEBSs. Makai Ocean Engineering [204] stated as a result of long-term testing of heat exchangers that fouling is not a serious problem with WTEBSs that intake cold deep seawater in the range of 3–8 °C. However, for warm water systems biofouling can be unavoidable. In addition, other system components such as strainers, pumps, holding tanks and pipeline fittings of are among the equipment that are still exposed to potential biofouling [187]. Berger and Berger [205] recommended that injection of chlorine at a concentration of 50 to 70 parts per billion *ppb* for 1 hour per day (24-h average of 2-3 *ppb*) can completely prevent fouling in the systems as a continuous and non-destructive method.

Apart from biofouling, corrosion can also impact WTEBSs performance due to the way that seawater interacts with system components and structures. Corrosion is defined as the process of destruction of a material under the chemical or electrochemical action of the surrounding environment [206]. An essential key to improve the marine structures optimum service life against corrosion is understanding of the type of marine environment, materials, appropriate designing, and corrosion control measures [207].

An important controlling factor in structures made by metals and alloys is the formation of a passive film that reduces ionic transport of reactive species [207]. In seawater, the dissolved oxygen and chloride ion lead the formation and repair or breaking down of the passive films, respectively [207]. Therefore, environment parameters such as atmospheric salt concentration, temperature, oxygen concentration, salinity, and flow-related corrosion parameters (e.g. Erosion-corrosion [208] and cavitation [209]) need to be considered. The presence of a bio-film can also increase the corrosion rate in a structure or operate as a passive deterrent [207, 210]. Proper design, including selection of compatible materials from both corrosion and mechanical aspects, optimizing geometries and joining processes that minimize corrosion, and utilization of corrosion control measures, is the most effective way to reduce corrosion costs [207]. Typically, corrosion can be controlled by using various coatings that act as ionic filters or oxygen diffusion barriers [207] or by cathodic protection [211] that can be very cost-effective and potentially combined with coatings. For WTEBSs that need to have pipelines in large depths it is advised that Polyethylene is an excellent choice of material as the pipelines will not corrode or contaminate the water [212]. In heat exchanger systems, corrosion due to the salty seawater can be eliminated using either titanium or aluminium heat exchangers, while titanium is proposed as a low-risk solution for a condenser especially in cold seawater[126, 213, 214].

6. Water quality measurements

6.1. Water properties to be measured

Here is a list of the parameters that has been agreed with the NKE to be measured at the Brixham harbour region, which is followed by some justification from the pertinent literature to note the necessity of measurements for these parameters.

6.1.1. Temperature

Water temperature is one of the most important physical characteristics of the marine environment. Temperature controls the rate at which chemical reactions and biological processes occur. In addition, most organisms have a distinct range of temperatures in which they thrive. A greater number of species live within the moderate temperature zones, with fewer species tolerant to extremes in temperature. Typically, organisms cannot survive dramatic temperature fluctuations.

6.1.2. Salinity

Salinity refers to the salt content of sea water. For oceanic waters, the salinity is approximately 35 parts of salt per 1,000 parts of sea water. Variations in the salinity of ocean water are linked primarily to climatic conditions. Salinity variations are at their highest at the surface of the water. The salinity of surface water is increased by the removal of water through evaporation. Alternately, salinity decreases through dilution from the addition of fresh water (e.g., rain, runoff from fresh water sources such as streams, etc.). Estuaries represent transition zones from saltwater to fresh water. Seawater salinity has a profound effect on the concentration of salts in the tissues and body fluids of organisms. Slight shifts of salt concentrations in the bodies of animals can have stressful or even fatal consequences. Therefore, animals have either evolved mechanisms to control body salt levels or to tolerate their rise and fall with the salinity of the seawater around them.

6.1.3. Density

Density (mass per unit volume) of seawater is dependent upon its composition and is a function of both temperature and salinity. Dissolved salts and other substances contribute to the higher density of seawater compared to fresh water. As temperature increases, density decreases. Accordingly, water that is denser will sink, while water that is less dense will rise.

6.1.4. pH

The measure of the acidity or alkalinity of a substance, known as the pH, is based on a scale ranging from 1.0 (highly acidic) to 14.0 (highly basic). A pH of 7.0 is considered neutral. Surface seawater often has a pH between 8.1 and 8.3 (slightly basic), but the acidity of deeper ocean water is very stable with a neutral pH. The very high concentration of carbonate ions in seawater gives it a large buffering capacity and resistance to pH changes. Nevertheless, in shallow seas and coastal areas, the pH can be altered by plant and animal activities, pollution, and interaction with fresh water.

6.1.5. Dissolved Gases

Oxygen is not readily soluble in sea water. The amount of oxygen present in seawater will vary with the rate of production by plants, consumption by animals and plants, bacterial decomposition, and by surface interactions with the atmosphere. Most organisms require oxygen for their life processes. When surface water sinks to deeper levels, it retains its store of oxygen until consumed by deeper organisms . Carbon dioxide is a gas required by plants for photosynthetic production of new organic matter. Carbon dioxide is 60 times more concentrated in seawater than it is in the atmosphere.

6.2. Measurement methods

Talley [215] described in detail different methods and instruments that can be applied for measuring the water properties of the ocean. Their measurement methods can be divided into two groups of traditional manned measurement platforms such as ocean research vessels, and autonomous (unmanned) platforms such as floating or moored instruments, or satellites. Traditional deep oceanographic measurements have been made from research ships with auxiliary measurements from merchant ships (ocean temperature and salinity, weather) and from coastal stations (tide gauges, wave staffs, lighthouse temperature and salinity observations, etc.). Nowadays, the research vessel continues to be essential for oceanographic research, but rapid improvements in technology, including satellite communications and long-lived mooring capabilities, have introduced new options.

For the EUROSWAC project, the measurement of the water quality will be carried out using two buoys provided by NKE. One of the Buoys is supposed to be fixed in the area near the inlet pipelines, while the other one is supposed to be available to be moved in different locations.

6.3. Bathymetry data

Based on the available map from the Tor Bay harbour website, a 3D geometry of the Brixham harbour was created that can illustrate the morphology of the Brixham harbour bed. The datum point for the measurements on the map was based on the average of the low-tide water surface. Figure 8 presents the bathymetry data for the area of interest near the Brixham laboratory site.

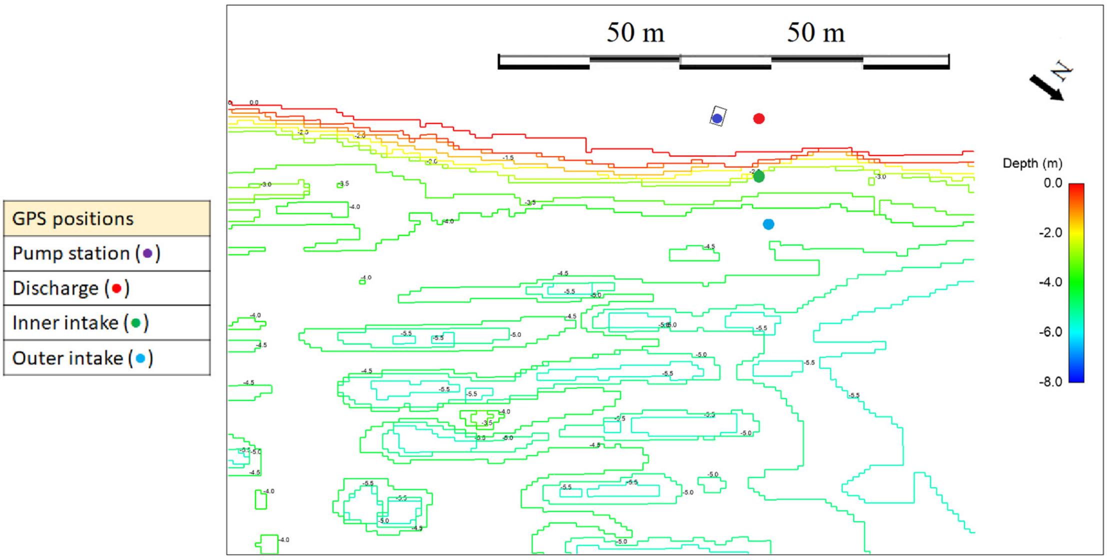


Figure 8: Bathymetry data close to the intake and discharge from the SWAC system, at the Brixham harbour.

6.4. Additional data to help the installation of the buoys at Tor Bay

The ocean physics analysis and forecast for the North-West European Shelf [6] was utilised to gather data for the Tor Bay area. For this analysis and forecast, the ocean model NEMO (Nucleus for European Modelling of the Ocean) is used to assimilate observations such as surface temperature, vertical profiles of temperature and salinity, and satellite sea level anomaly data. The model is forced by lateral boundary conditions from the UK Met Office North Atlantic Ocean forecast model and by the CMEMS Baltic forecast product. A more detailed explanation of the model, along with all available data and results can be found on the Copernicus website (available here).

Figure 9 below shows the daily mean northward and eastward current velocities during 2021 for Tor-Bay, as obtained by the ocean model NEMO.

The geoid is a surface of constant geopotential with which mean sea level would coincide if the ocean were at rest. The parameter "sea surface height" is the difference between the actual sea surface height at any given time and place, and that which it would have if the ocean were at rest. The hourly-instantaneous data presented in Figure 10 below are obtained from the ocean model NEMO.

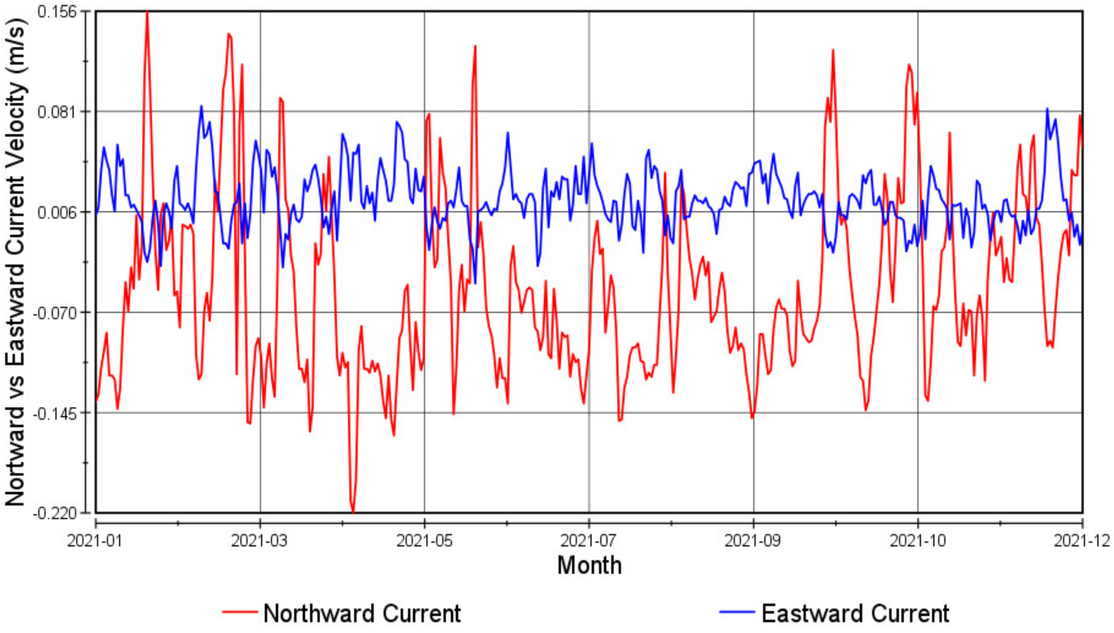


Figure 9: Current speeds at the site during 2021 (daily mean data)

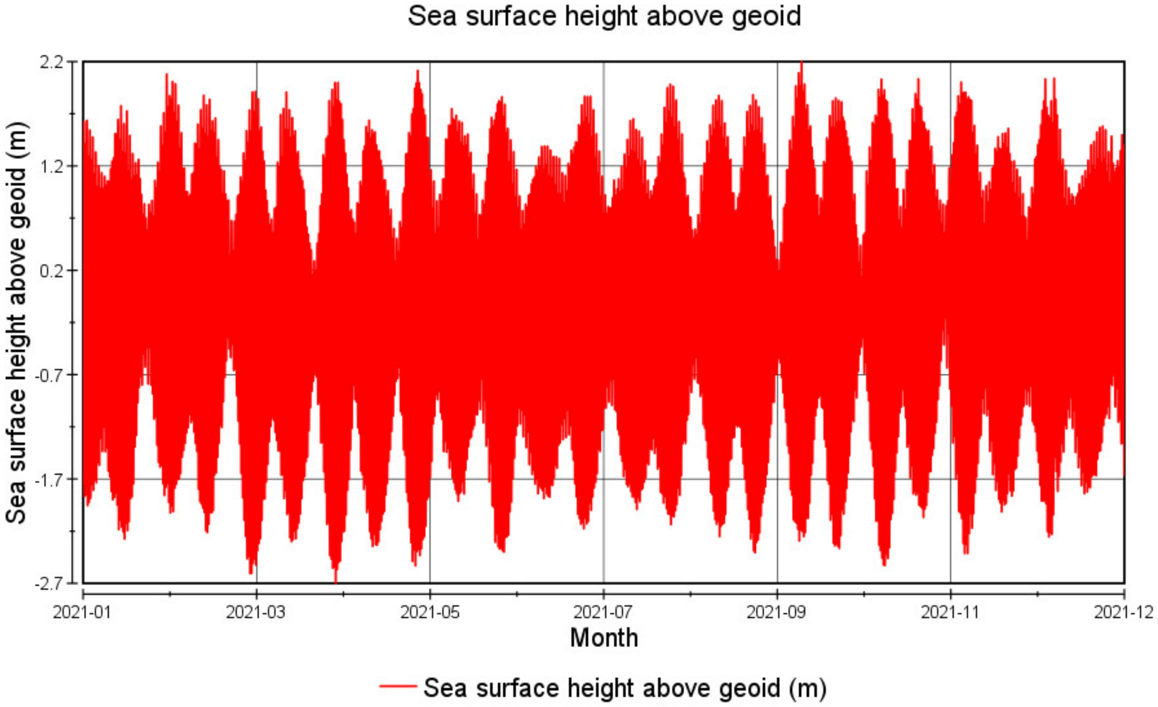


Figure 10: See surface height above geoid. (Note: the data point marked as 2021-12 corresponds to the end of December)

Along with data obtained from the ocean model NEMO, historical data regarding wind speed and direction were obtained to help with the installation of the buoys at the Brixham harbour. The following figures show the average of mean hourly wind speeds in Brixham (Figure 11), along with wind direction (Figure 12). The presented data were acquired between 2014-2022.

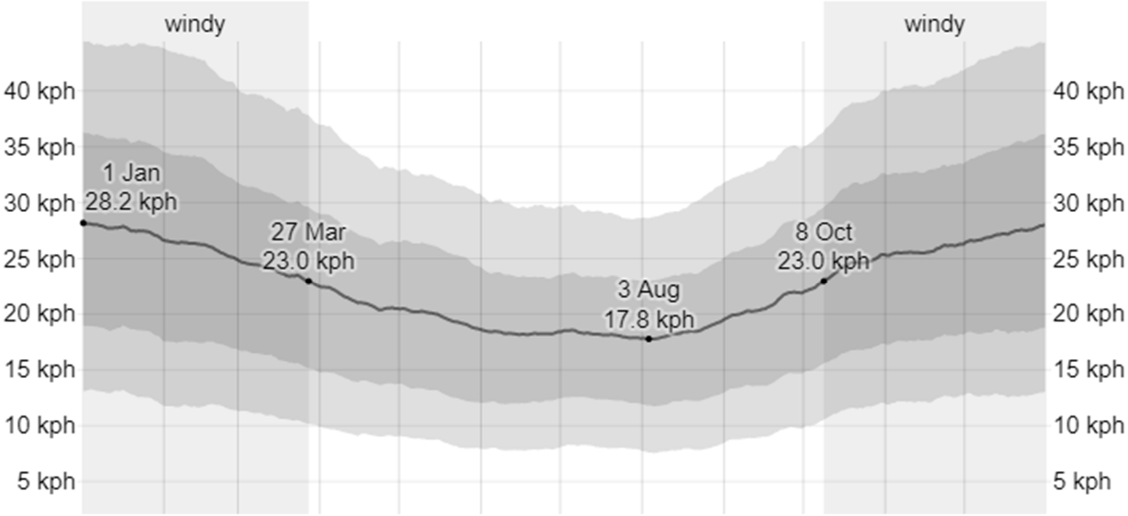


Figure 11: Average wind speed, along with 25th to 75th and 10th to 90th percentile bands (shaded areas of the graph)

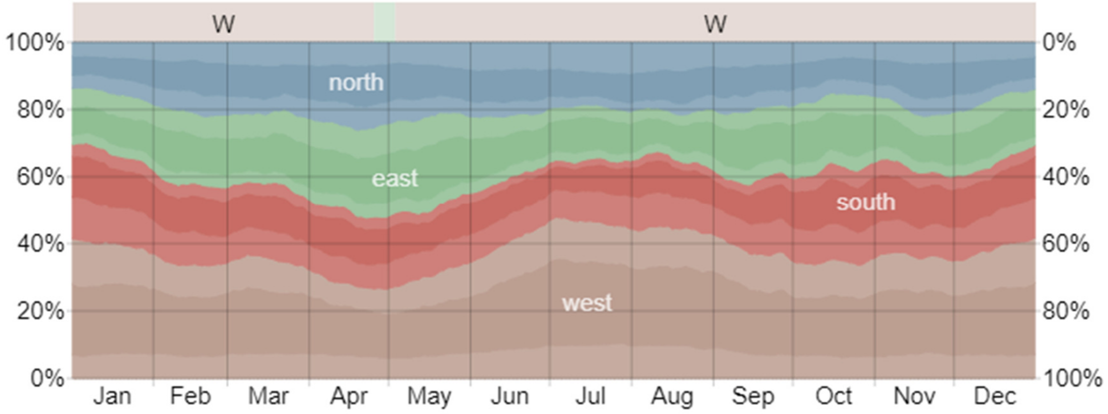


Figure 12: Percentage of hours in which the mean wind direction is from each of the four cardinal wind directions, excluding hours in which the mean wind speed is less than 1.6 kph. The lightly tinted areas at the boundaries are the percentage of hours spent in the implied intermediate directions (northeast, southeast, southwest, and northwest).

Table 1: Average Wind Speed (in kph)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
27.6	26.0	23.7	21.2	19.6	18.3	18.2	18.4	20.8	24.0	25.8	27.3

6.5. Boys and WiMo probe information

The objectives are to install two instrumented buoys on the Brixham site in order to evaluate the impact of the SWAC system in operation over 3 months (starting in June 2022). To carry out this study, NKE is in charge to design the buoys and in particular the anchoring line and anchor. NKE needed to know the hydrodynamic conditions of the site (maximum current velocity (over one year), wind speed over one year, wind direction (°) over one year and maximum wave height (Hs) over one year). Depending on the Brixham site and its hydrodynamic characteristics, the solution was oriented towards a 20L version. The two buoys are based on the following model (see figure 13).

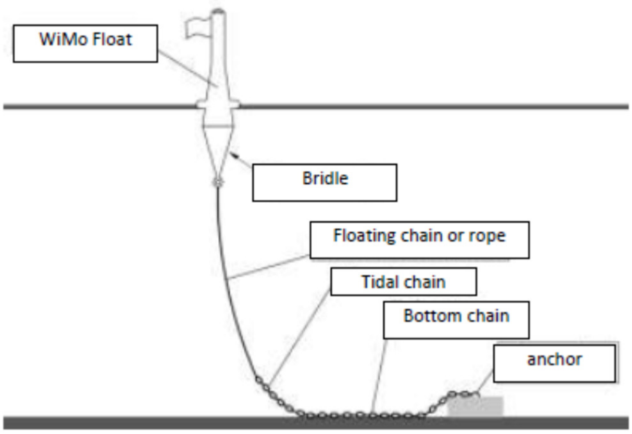


Figure 13: Description of WiMo buoy

In order to maintain a good hydrodynamic behaviour of the buoy float, NKE suggested keeping a 50-60% buoyancy reserve, meaning that the waterline must be between the half and the third of the total height of the 20L float.

The total ballast of the float is composed of the weight of the crowfeet chain Φ8 (1.2 kg/m and the weight of the mooring chain. Depending on the depth of the mooring, the floating line of the mooring will be composed of a chain only or a chain and a rope.

The buoys are designed to avoid shocks and have the following characteristics:

Total height	**1,7m**
Total weight	24 kg (chain included)
Support pole + antenna + WIMO total weight	7kg
Float with a buoyancy of 20 liters	
Material	EVA (Ethylene-vinyl acetate)
Central body	High-density polyethylene (HDPE)
Crowfeet chain	Two chains DN10 (2.2 kg/m) + Bridle and shackles
Solar Light	Yellow 0.5s/ON and 3.5s/OFF
St Andrew cross Heigth	250 mm

Figure 14: Description of WiMo float 20 liters

In addition, the buoys were equipped with WiMo multiparameter probes that are located 1 metre below the water surface. As listed in the requirements of EUROSWAC project, the probe was able to measure the water temperature, the water depth, the pH, the oxygen concentration and the dissolved oxygen saturation, the conductivity, the Total dissolved solids (TTS) and the oxidation - reduction potential (Total residual oxidants). For this purpose, the NKE probes were equipped with pH, CT, DO and ORP sensors. There was also a brush to protect the optical DO sensor cell, especially from biofouling.

Figure 15: A picture of WiMo probe

The WiMo probe is fully autonomous during the deployment time. The user can connect to the probe via a WiFi network before deployment. Via a web page, the user can configure the probe by selecting the acquisition frequency every 10' or every hour after SWAC is activated.

6.6. Measurements

Measurements using the NKE probes took place during the summer of 2022, starting at the end of June. Here, a comprehensive list of the data obtained by the buoys is presented. Please note that during the deployment, there were various issues with the optimal operation of the buoys and therefore data for some particular days may not be representative of the real picture. The buoys had also to go offline for a few hours every 2-3 weeks for maintenance purposes. Due to the volume of the exported data, they are presented in three separate months (July 2022 – September 2022).

Charts nomenclature:

Salinity_48 = Sea-water salinity measured in *PSU*

TDS_51 = Total dissolved solid measured in *mg/L*

PH_08 = pH

Oxygen_07 = Oxygen saturation *(%)*

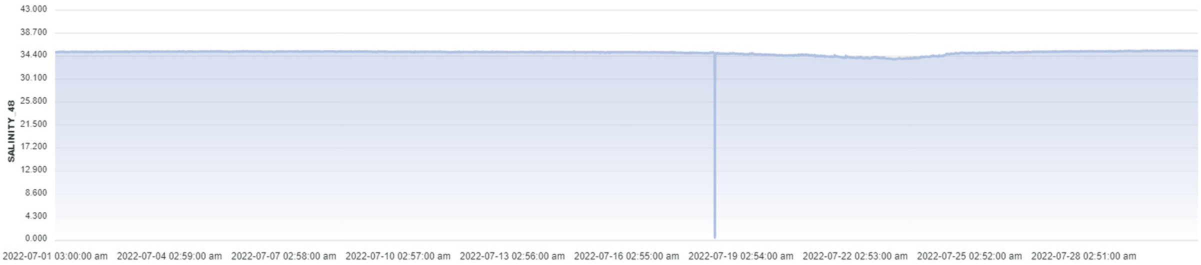
Oxygen_06 = Oxygen concentration measured in *mg/L*

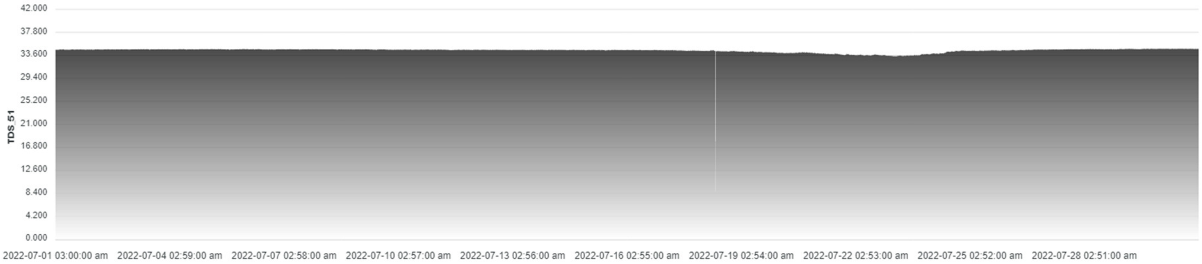
Temperature_03 = Sea-water temperature measured in ^{o}C

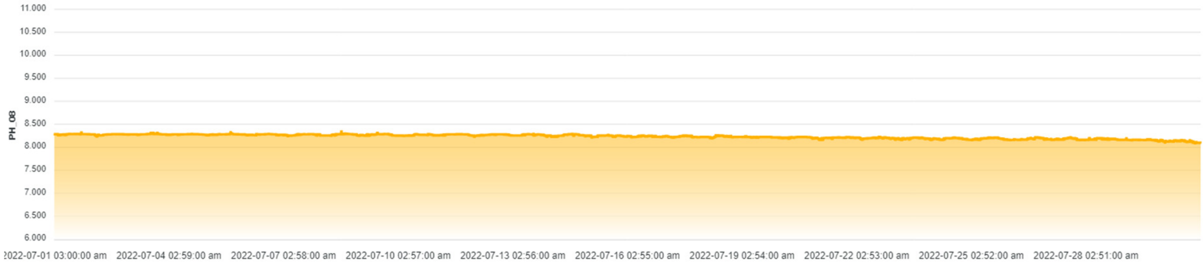
RedOx_20 = Oxidation-reduction potential measured in *mV* (only available for September 2022)

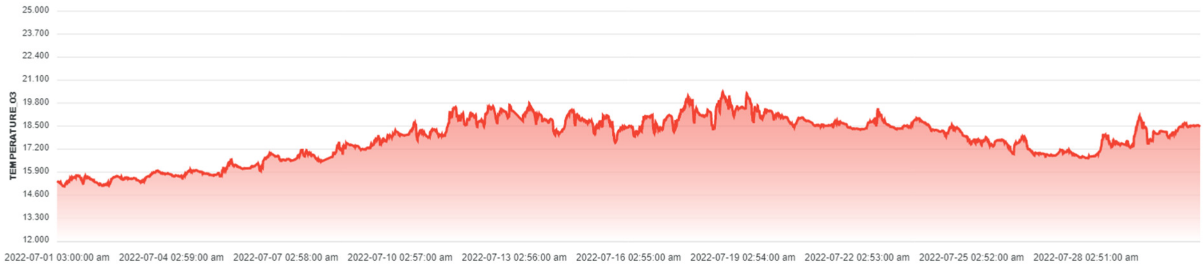
(Please zoom in the following charts to view them in higher resolution)

6.6.1. July 2022

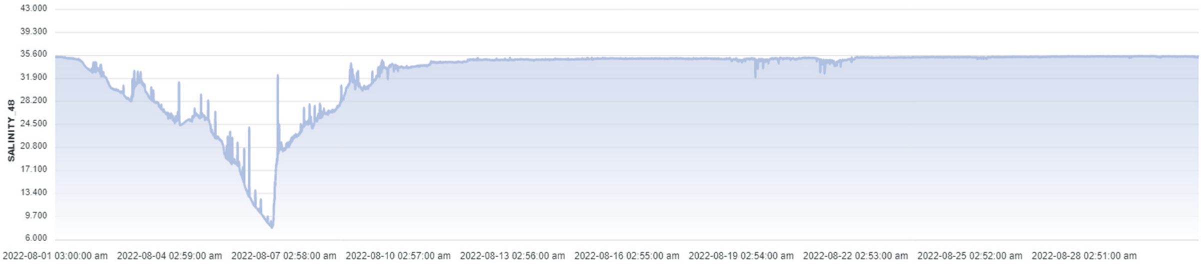


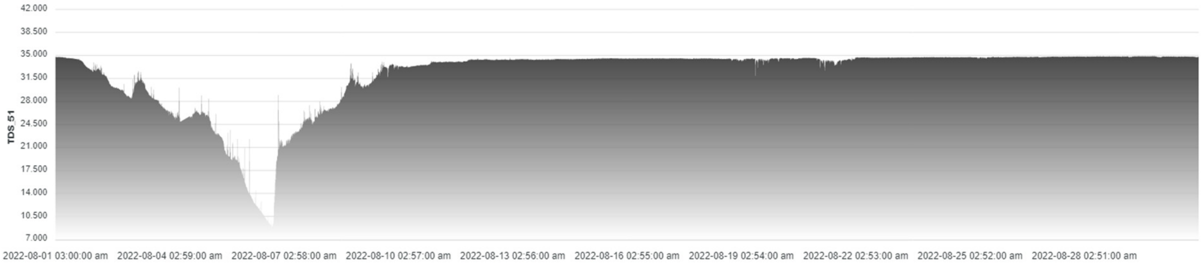


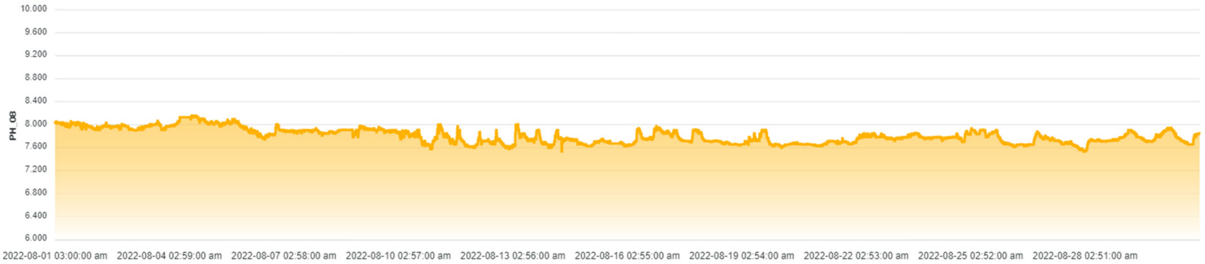


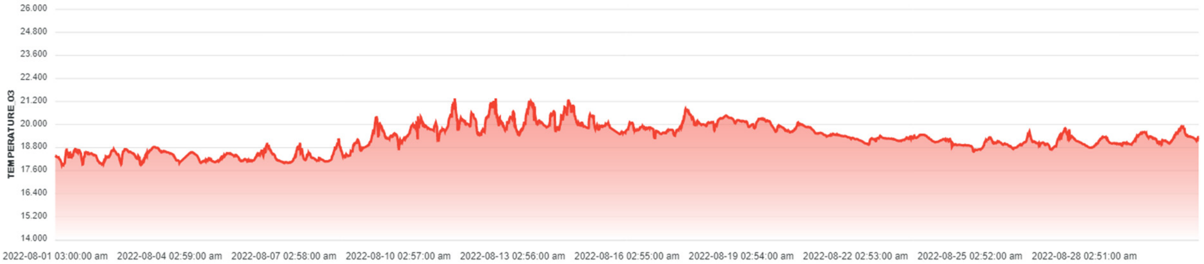


6.6.2. August 2022

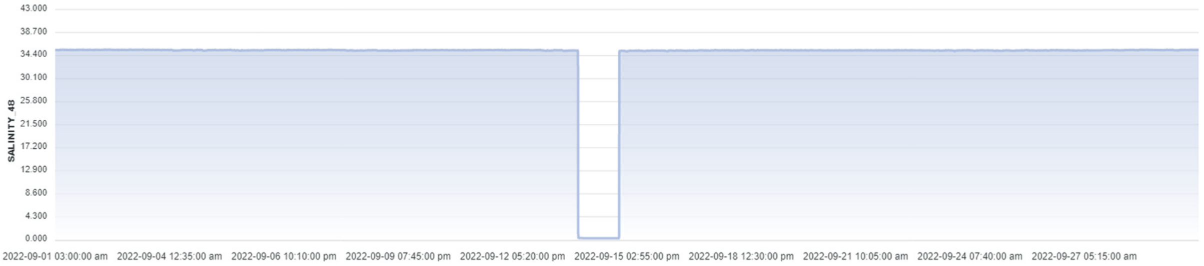


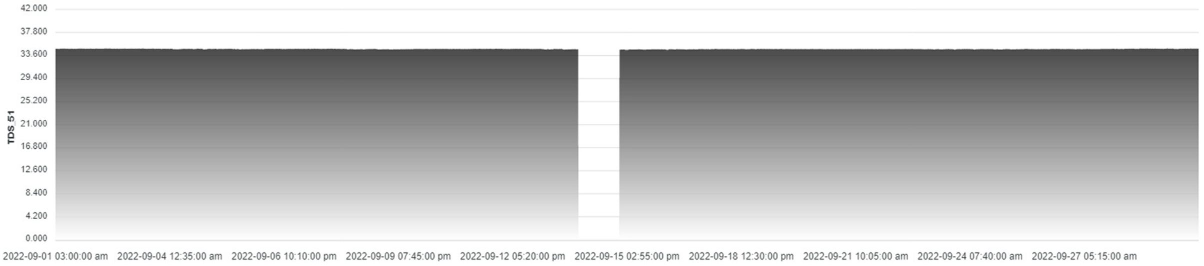


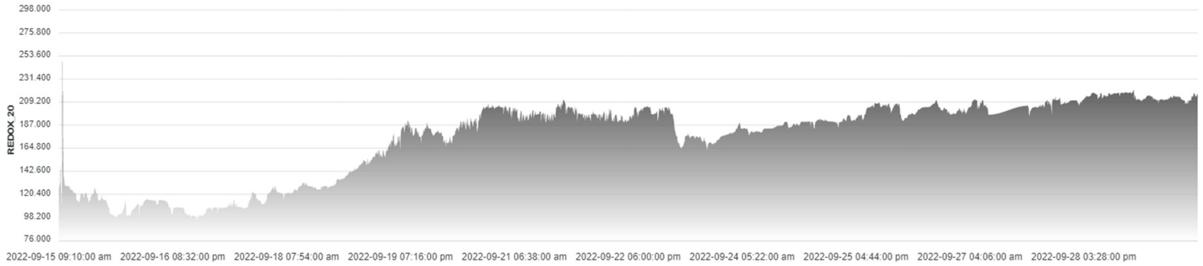


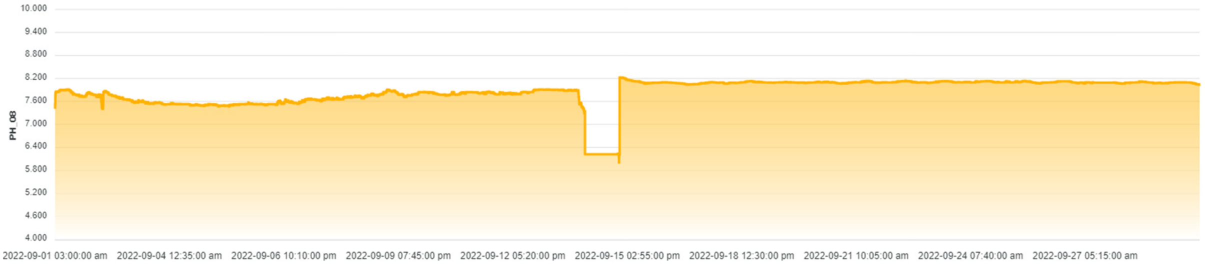


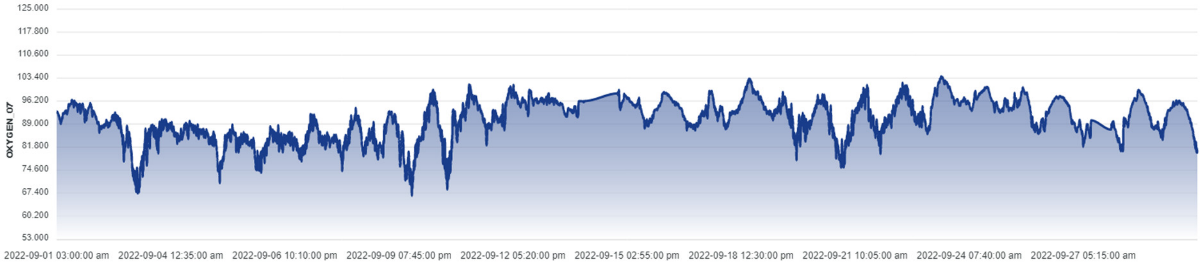
6.6.3. September 2022











7. Conclusion

The growth and development of WTEBSs raise concerns regarding their impacts on sustainability and the degradation of marine environments. The present report provided a full review of different aspects of WTEBSs’ interaction with marine environments. It detailed the relevant concerns on the development of WTEBSs including different stages of construction, operation, and decommissioning considering the other types of development in the marine environment such as coastal power plants or other marine-based renewable technologies. The construction and decommissioning phases of development of a WTEBS including installation of foundations and hard-fixed structures (such as submerged heat exchangers or pump stations), pipelines, scour-protection systems, mooring devices, and seabed mounted power cables are likely to cause significant positive and negative disturbance to local environmental resources and fundamental changes to the benthic habitat. Introduced innovative solutions by DeProfundis and DORIS Engineering such as self-burying and flexible pipe technologies can assist with minimizing the environmental impact and costs of pipeline installation. Operation wise, a WTEBS continuously disturbs the marine environment for the duration of its lifetime. A comprehensive review of the environmental impact associated with the operation of a WTEBS such as discharge of the processing seawater, power cable electromagnetic fields, acoustic effects of the WTEBS machinery and pipelines, and leakage of chemicals from the system on benthic and pelagic ecosystems was carried out. Seawater discharge dispersion as one of the main environmental impact concerns regarding the operation of a WTEBS was discussed in a separate section. Previous experimental and numerical modelling tools were reported and scopes for improving the existing models to bridge the knowledge gaps were discussed.

Additionally, the report provided information about water quality measurements that were conducted in Brixham Harbour using apparatus provided by NKE Instrumentation. Data were collected and are presented here between July 2022 and September 2022. The raw data collected by the two buoys are stored within the facilities of the University of Plymouth and can be made available at request.

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