Faculty of Science and Engineering

School of Engineering, Computing and Mathematics

2023-12

# Waterbodies thermal energy based systems interactions with marine environment A review

# Bordbar, A

https://pearl.plymouth.ac.uk/handle/10026.1/20779

10.1016/j.egyr.2023.04.352 Energy Reports Elsevier BV

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.

2	
3	Waterbodies Thermal Energy Based Systems Interactions with Marine
4	Environment - A Review
5	
6	Amir Bordbar <sup>*,a</sup> , Konstantinos Georgoulas <sup>a</sup> , Yong Ming Dai <sup>a</sup> , Simone Michele <sup>a</sup> , Frank Roberts <sup>a,b</sup> , Nigel
7	Carter <sup>a,b</sup> , and Yeaw Chu Lee <sup>a</sup>
8	<sup>a</sup> University of Plymouth, Plymouth, UK, PL4 8AA.
9	<sup>b</sup> Brixham Laboratory, Freshwater Quarry, Brixham, TQ5 8BA.
10	*Corresponding author: Amir Bordbar ( <u>Abordbar182@gmail.com</u> )
11	
12	
12	
14	
15	
16	
17	
18	
19	
20 21	
21 22	
23	
24	

# Waterbodies Thermal Energy Based Systems Interactions with Marine Environment - A Review

27 Abstract. Waterbodies' thermal energy potential, as a green, renewable, and limitless source of energy, can be 28 exploited in response to the growing energy demands of islands and coastal cities. Up to now, the technologies 29 that have been developed for this purpose include seawater air-conditioning, surface water heat pump, and ocean 30 energy thermal conversion systems or their combinations, which are presented here as Waterbodies Thermal 31 Energy Based Systems (WTEBSs). The growth and development of these technologies raise concerns regarding 32 their potential impacts on sustainability of the marine environment. The present work provides a comprehensive 33 review of the available literature and state-of-the-art technologies describing potential interactions of WTEBSs 34 throughout their life-cycle (i.e. including construction, installation, operation, and decommissioning) with the 35 marine ecology. Modelling of seawater discharge dispersion as one of the main environmental impact concerns 36 regarding the operation of WTEBSs is detailed and scopes for improving existing modelling tools are discussed. 37 Potential destructive impacts of fouling and corrosion in WTEBSs are reported and deterrent recommendations 38 are highlighted. Evidence of growth of bio-fouling inside of pipelines and associated mesh filtration baskets at 39 abstraction pipe intakes are presented. The required permitting applications and licensing processes for 40 installation and operation of WTEBSs by the relevant authorities are summarised. Finally, a summary of the 41 findings from the data monitoring of water quality properties of a seawater air-conditioning pilot study performed 42 at Brixham Laboratory, University of Plymouth, United Kingdom is reported.

*Keywords:* Renewable Energy; Marine Thermal Energy; Environment Impact; Dispersion; Energy resources;
 Biofouling; Corrosion; Seawater Air Conditioning; Ocean Thermal Energy Conversion; Surface Water Heat
 Pump

#### 47 **1** Introduction

48 Anthropogenic global warming is a direct consequence of activities such as burning of fossil fuels (coal, oil and 49 gas), which causes large emission of greenhouse gases (GHG) into the atmosphere (Houghton, 2005, Meckling, 50 2018). Renewable energy technologies that exploit energy from sources such as solar, wind, wave, and ocean 51 thermal energies were developed to address the environment challenges from impacts of carbon-based fuel GHG 52 (Ullah et al., 2017, Comfort et al., 2015). The uncertainty of increasing oil prices and recent advances in efficiency 53 of renewable energy technologies coupled with increased installation capacities have accelerated development 54 of competitiveness of renewable energy alternatives in the global energy market (Gohar Ali et al., 2020, Arent et 55 al., 2011). Figure 1 illustrates the growth of renewable technologies share on global electricity production over 56 the last 35 years.

The thermal capacity of waterbodies (e.g., lakes, seas, and oceans) is by comparison an unlimited intact heat sink or source, that can help meet the high energy demands of coastal regions and islands. To illustrate the significant thermal capacity potential of waterbodies, Hunt et al. (2019) provided a comparison between energy potential in seawater with other renewable electricity generation sources for cooling purposes. Their findings highlighted the energy potential of  $1 m^3/s$  of seawater for cooling with 10 °C temperature gradient is equivalent to either a hydropower plant with a generation head of 186 *m* with ten times the flow rate, a 488,000  $m^2$  solar power plant, or typical energy generation of 21 wind turbines.

64 Waterbodies Thermal Energy Based Systems (WTEBSs) harness the thermal energy of oceans, or seas, and 65 their performance rely on the temperature of extracted seawater from waterbodies. In each waterbody region, 66 the local water temperature is a function of water depth: surface water and deep water. In case of ocean water,

67 surface water is warm water that extends to depths of a few hundred meters; beneath that is deep ocean water 68 which is cold, dense, and nutrient-rich (Hunt et al., 2021, Herrera et al., 2021). Due to the latter being higher 69 density than the former, both layers do not mix, and a transition layer called thermocline exist in between i.e., in 70 depth of between 400 m to 1,000 m (Hunt et al., 2021, Hunt et al., 2020). Figure 2 illustrates density and 71 temperature variation profiles with depth where the temperature variation in different latitudes of open oceans 72 for tropical, equatorial, and middle latitudes are different. Likewise, for waterbodies regions that are separated 73 from the deep ocean such as the Mediterranean Sea, the Sulu, Visayan, and Bohol Seas in Southwestern 74 Philippines, the temperature profiles are distinctively different from the ones in Figure 2 (Schroeder et al., 2008, 75 Ferrera et al., 2017). In the case of lakes, the water temperature below a depth of approximately 18 to 24 m may 76 remain relatively constant throughout the year (Hattemer and Kavanaugh, 2005). However, this depends highly 77 on the amount of inflow and/or outflow relative to the surface waterbody size (Mitchell and Spitler, 2013).





80 Figure 1: Global electricity production by Ritchie and Roser (2021). \*'Other renewables include biomass and waste,



82 Presently, WTEBSs is generally classed into three main categories (shown in figure 3):

83 Seawater Air Conditioning (SWAC): systems that exploit water from waterbodies for heating or cooling 84 demands using heat exchangers without heat pumps or chillers (Mitchell and Spitler, 2013). SWAC systems are 85 onshore-based plants with intake and discharge pipelines of adequate lengths that are shore-crossing and 86 deployed at the bottom of the seas or oceans. SWAC replaces the heaters and chillers used in conventional air-87 conditioning (CAC) systems. This technology aims to greatly reduce the electricity consumption cost which in ideal 88 condition can be around 80% lower than that for CAC (Hunt et al., 2020, Makai Ocean Engineering Inc., 2015a, 89 Soini et al., 2017). SWAC systems can be categorised into shallow and deep seawater systems according to the 90 depth at which seawater is extracted (Hunt et al., 2019). A comprehensive list of globally deployed SWAC systems 91 can be found in Hunt et al. (2019).

92 Surface water heat pump (SWHP): systems that benefit from heat pumps or chillers to provide heating or 93 cooling; These systems benefit from surface water as a heat source or sink (Mitchell and Spitler, 2013). Under 94 circumstances where the direct usage of seawater cannot meet the required cooling or heating demands, SWHP 95 can be introduced as a justified alternative. SWHP systems are onshore-based plants with an average coefficient 96 of performance (COP) of around 4 (Mitchell and Spitler, 2013). These systems have higher efficiency compared 97 with CAC and air source heat pump (ASHP) systems that use ambient air as a heat source/sink with an average 98 COP of around 3 (Su et al., 2020). With the rise in energy carriers' costs, SWHP has a great potential for operational 99 cost savings (Chua et al., 2010). A non-exhaustive list of SWHP around the world can be found in Su et al. (2020).

Ocean Thermal Energy Conversion (OTEC): systems that generate electricity from the natural thermal
 gradient between warm surface and cold deep ocean waters (Pelc and Fujita, 2002). 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 typically have high implementation costs and low actual efficiency of around 3% or 4%, but they are an
 attractive renewable energy technologies as they benefit from an unlimited source of energy (Herrera et al., 2021).

OTEC systems can either be built onshore or offshore on floating platforms (Pelc and Fujita, 2002). In the case of floating platforms, the energy can either be transported via seafloor cables or stored in the form of chemical energy (e.g. hydrogen, ammonia, or methanol) that are regularly transferred to the shore by tankers (Pelc and Fujita, 2002, Avery and Wu, 1994). Currently, there is a limited number of OTEC plants that operate worldwide, which are either mostly small-scale or pilot systems (Herrera et al., 2021, Kim and Kim, 2020).

111



112

Figure 2: Typical temperature and density variations with water depth in the open ocean (Hunt et al., 2019, Talley,
2011). \*ENPM is the abbreviation for Eastern North Pacific Middle, \*\*WNPM is the abbreviation for Western North
Pacific Middle.

116

To maximise energy utilisation efficiencies, WTEBSs can be combined. A hybrid SWHP and SWAC system presents 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 120 allows for it, the system can switch to the SWAC mode and utilise cool water directly for cooling purposes (Mitchell 121 and Spitler, 2013, Ciani, 1978). Such a system has been successfully deployed in different cities around the world 122 (Smebye et al., 2011, War, 2011). WTEBSs can also be combined with other technologies; for example, warmer 123 seawater outlet of SWAC systems, which can be rich in nutrients, can be used for production of algae, fish, and 124 crustaceans (Hunt et al., 2020, Von Herzen et al., 2017). In an open cycle OTEC system, which refers to systems 125 that uses seawater as the working fluid, the desalinated water (condensate) is fresh enough for municipal or 126 agricultural use, and the cold nutrient water can be applied to aquaculture (Pelc and Fujita, 2002, Avery and Wu, 127 1994). Hunt et al. (2021) proposed a combination of SWAC and reverse osmosis (RO) desalination to supply both 128 affordable water and cooling services in a one-way district cooling system that provide several advantages 129 compared to SWAC and RO individually, while reducing distribution costs. A combined system that employs an 130 offshore wind-driven hydraulic pump to supply high-pressure deep seawater to a land base cooling plant (SWAC 131 or SWHP) is proposed in many studies such as Sant and Farrugia (2013), Sant et al. (2014), Galea and Sant (2016a) 132 , Galea and Sant (2016b), (Buhagiar and Sant, 2014). With the growth of marine renewable energy technologies, 133 concerns regarding their impacts on the sustainability of marine environments have been raised (Comfort et al., 134 2015, Pelc and Fujita, 2002, Comfort and Vega, 2011, Boehlert and Gill, 2010, Gill, 2005). To address these 135 concerns, it is critical to investigate the environmental footprint of existing WTEBSs in the effort to minimize the 136 impacts for future applications.

The next section details the environmental impacts of WTEBSs throughout their life-cycle. In section 3, investigation on modelling of discharge dispersion as one of the main concerns regarding operation of the WTEBSs is discussed. This is followed by an investigation of the effects of biofouling and corrosion during optimal operation of WTEBSs and measures to control them in section 4. The subsequent section summarises the required permitting applications and licensing processes for installation and operation of WTEBS by the relevant authorities. In section 6, the results of an environmental impact assessment study to measure the water quality parameters near the

- 143 discharge area of the pilot shallow water SWAC system at Brixham laboratory at the University of Plymouth, United
- 144 Kingdom are reported. Finally, in the conclusion section, the findings of this study are summarised.
- 145
- 146



147

148 Figure 3: Simplified schematic of different types of onshore- and offshore-based WTEBSs, (a) SWAC, (b) SWHP, (c)

149 OTEC.

#### 151 **2** WTEBS Environmental Impacts

152 Anthropogenic activities are the main reasons for major changes to marine wildlife (Gill, 2005, Ferreira et al., 153 2018). Terrestrial land uses and near-shore activities such as dredging, overfishing, oil and gas operations, illegal 154 dumping of solid wastes, and other industrial processes have dramatically implicated perturbation of the marine 155 environment (Gill, 2005, Ferreira et al., 2018, Carpenter, 2019, Barletta et al., 2016, Lima et al., 2016, Blaber et al., 156 2000, McLusky et al., 1992, Costa and Barletta, 2015). Recently, Halpern et al. (2019) investigated the cumulative 157 impact of 14 stressors related to human activities at 21 different marine ecosystems globally during a 11-year 158 period from 2003–2013. As a result, they realised that most of the ocean (59%) is experiencing increasing 159 cumulative impact due to climate change but also from fishing, land-based pollution, and shipping. The growth in 160 the deployment of offshore renewable energy technologies also add to the risks from their interactions with the 161 marine environment. A list of newly emerging renewable energy technologies with a special concentration on 162 marine energy generation is found in Wilberforce et al. (2019) and Chen et al. (2018). The life-cycle (i.e. including 163 construction, installation, operation, decommissioning) environmental impact assessment of tidal and wave 164 energy generation devices are reviewed and evaluated in Frid et al. (2012), Patrizi et al. (2019), Baker et al. (2020), 165 Copping et al. (2021), Isaksson et al. (2020), Sayed et al. (2021), and Farr et al. (2021). Williamson et al. (2019) 166 used ecological and physical measurements to show the predictability of fish school characteristics (presence, 167 school area, and height above seabed) at a high-energy tidal site, and how this changes in the proximity of a 168 turbine structure. Similarly, Malinka et al. (2018) studied the behaviour and movement of small cetaceans around 169 a tidal turbine. Others, such as Seyfried et al. (2019) reviewed the potential environmental impacts of a salinity 170 gradient energy (SGE) facility through the construction, operation, and decommission phases. The life-cycle 171 environmental impact assessment of offshore wind turbines has been investigated in Sayed et al. (2021), Shadman 172 et al. (2021), and Hall et al. (2020). Gill et al. (2020) studied offshore wind development effects on fish and fisheries. 173 Tougaard et al. (2020) and Madsen et al. (2006) 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 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 (2010) noted that devices with subsurface moving parts, such as underwater turbines, are assumed to be the noisiest. An investigation on the underwater operational sound of a tidal stream turbine can be found in Risch et al. (2020). The potential impacts of submarine power cables during the installation, operation, and decommissioning phases on the marine environment have been studied in Taormina et al. (2018), Hutchison et al. (2020), and Scott et al. (2018).

181 In this section, a review of the relevant concerns and interactions of the development of WTEBSs, including 182 different stages of construction, operation, and decommissioning, with the marine environment is provided in 183 detail. Many of the associated effects of WTEBSs are common with other types of development in the marine 184 environment which facilitate the impact assessments process, but potential uncertainties may arise when their 185 impacts have not been evaluated or anticipated accurately.

186

#### 187 **2.1** Construction and Decommissioning Impacts

188 The construction and decommissioning phases of the development of a WTEBS are likely to cause significant 189 positive and negative disturbances to local environmental resources and fundamental changes to the habitat, both 190 above and below the water surface (Boehlert and Gill, 2010, Cardno Tec. Inc., 2014). Their spatial scale may have 191 ecological impacts extending over several square kilometres, while temporal scales are both short- and long-term 192 on marine environments (Gill, 2005, Iglesias et al., 2018). The magnitude of the impacts highly depends on the 193 duration and intensity of the disturbance and the stability and resilience of the marine communities (Gill, 2005, 194 Van Dalfsen et al., 2000, Lu et al., 2020, Drabsch et al., 2001). The ecological implications associated with WTEBS 195 construction can be similar to the alterations of the benthic habitats that had been subjected to fishing or marine 196 dredging (Gill, 2005, Hiddink et al., 2020, Blyth et al., 2004). In general, during construction, the seabed will be 197 disturbed by installation of foundations and hard-fixed structures (such as submerged heat exchangers or pump 198 stations), pipelines, scour-protection systems, mooring devices, and seabed-mounted power cables. Marine 199 organisms within the footprint of these objects would be smothered or crushed (Cardno Tec. Inc., 2014). These 200 artificial structures may have the greatest impact on benthic habitats and ecosystems (Boehlert and Gill, 2010). 201 They also may alter the local flow which is essential to some aquatic species such as corals (Hennige et al., 2021, 202 Georgoulas et al., 2023), lead to entrainment and deposition of sediments, and change the seabed bathymetry 203 (Montgomery et al., 2006). Conversely, the deployment of these objects on the seabed, provides artificial reefs in 204 benthic environments (Addis et al., 2006, Inger et al., 2009). This may stimulate the benthic ecosystem and lead 205 to a greater biodiversity (Inger et al., 2009, Langlois et al., 2005). The construction phase may also disturb the 206 surface and midwater with structures including spars, buoys, pipelines, and cables that may result in modifications 207 on pelagic habitats and ecosystems (Boehlert and Gill, 2010, Langhamer et al., 2009). These effects are widely 208 studied in the oil and gas platform industry where these structures can serve an equivalent function to artificial 209 reefs in benthic environments (Addis et al., 2006, Inger et al., 2009). The presence of these objects may have 210 positive effects on attraction of some species (e.g., krill, mysids, and fishes) and consequently additional predators 211 in the region. The presence of the structures may modify the local water hydrodynamics which take up significant 212 areas of the sea surface which could influence migratory surface dwellers (Boehlert and Gill, 2010).

In the rest of this section, the interaction of WTEBS construction with the marine environment is detailed separately for offshore and onshore systems, followed by the potential decommissioning impact of these systems.

215

#### 216 2.1.1 Onshore WTEBS construction

The construction of seawater pipeline systems for onshore WTEBS presents the main interaction with the ocean environment. The pipelines are mounted on the seabed, up to a few kilometres long, to reach cold deep seawater. These systems may contain submersible pumps or submerged-coils (heat exchangers) in seawater/lake heat pump systems (Wu et al., 2020, Liu et al., 2019, Sarbu and Sebarchievici, 2014, Zheng et al., 2015). The 221 pipelines are mainly made of high-density polyethylene (HDPE) material due advantages it offers, such as strength, 222 durability, flexibility, insulation, resistance to high pressure, cost-effectiveness, and slight negative buoyancy, 223 compared to alternative materials (Hunt et al., 2020, Nguyen et al., 2021, Miller et al., 2012). For pipelines that 224 are exposed to storms, tsunamis, seismic activities, and other environmental concerns, the most challenging 225 aspect of the development of the pipelines is at the coastal transition zone (sea/shore interface) aspect (War, 226 2011). In most cases, to reduce the risk of damage or incident, the pipelines are either trenched or tunnelled under 227 the shoreline, from a point before the shoreline to a point in the seabed, a few meters deep (War, 2011, Cardno 228 Tec. Inc., 2014, Lewis et al., 1989). Among these two techniques, tunnelling such as microtunnelling and horizontal 229 directional drilling (HDD) is preferable as they are more environmentally friendly (War, 2011, Cardno Tec. Inc., 230 2014, Camp et al., 2019, da Silva et al., 2013, Swartz, 2020), while trenching comes with the removal of sediments 231 and direct loss of marine habitats (Gill, 2005). The latter also increases the local water turbidity level as a result of 232 suspended particles. This may increase the risk of spreading any contaminants from the suspended particles, and 233 lead to a temporary reduction of the available oxygen which may smother the neighbouring habitats of sedentary 234 species (Gill, 2005). In general, the benefits of trench-less technologies compared to open-cut trenching are their 235 minimum impact on existing infrastructure, longer pipeline lifetime, minimum efforts to reinstate the site 236 following pipe installation, and independence from weather conditions and waves during the construction phase 237 (Hennig and zur Linde, 2011). Nevertheless, trench-less technologies do risk potential leakages of drilling mud 238 through the sediment into the water column during micro-tunnelling. This can be eliminated by grouting the void 239 between the micro-tunnel and the pipes (Cardno Tec. Inc., 2014). In the development of seawater pipelines using 240 trench-less technologies, pipeline construction impacts would be mainly related to the excavation of a breaking 241 point, where sediments would be removed, and bathymetry temporarily changed at the pit (Cardno Tec. Inc., 242 2014). The breakout point (receiving pit) is where buried pipes and seabed surface-mounted pipes are connected 243 (Figure 4). The temporary impacts of the constructions such as elevated levels of suspended sediments in water 244 adjacent to the excavation area can be minimized by the installation of sheet piles around the pit to isolate it from

the surrounding water (Cardno Tec. Inc., 2014). The long-term impacts on ocean currents are negligible as the breakout pit would be back-filled and caped with concrete similar to the original bathymetry. Apart from the coastal transition zone, the rest of the pipelines are mounted on the seabed surface which can be installed in a controlled submergence process. Detailed discussion regarding the installation of the HDPE deep seawater pipelines is found in War (2011), Cardno Tec. Inc. (2014) , Makai Ocean Engineering Inc. (2015c).

A possible long-term impact of the mounted pipelines would be associated with the scouring and sediment transportation beneath the pipes. This can be minimized with sufficient clearance between the pipes and the seabed (Cardno Tec. Inc., 2014). Some recent studies in numerical modelling of scouring can be found in the works of Bordbar et al. (2021), and Bordbar et al. (2022a), and Bordbar et al. (2022b). Nevertheless, close monitoring will be essential, and whenever required a scour counter-measure method has to be considered (Elahee and Jugoo, 2013).

256



Figure 4: Details of breakout point (receiving pit) where buried pipes and seabed surface-mounted pipes are connected (Cardno Tec. Inc., 2014).

260

To minimize the environmental impact of pipeline installation for a future onshore WTEBS application (e.g. a SWAC system), DeProfundis and DORIS Engineering have introduced an innovative intake pipe self-burying system. The system limits the impact on the underwater environment and reduces installation costs (Doris engineering, SO22). Simply put, the system includes injecting water into the sand located under the pipe placed on the ground to thin the sand so that the pipe sinks in under its own weight. The method benefits from a new concept called
"flexible pipe" which will contribute to the cost reduction of conventional onshore WTEBSs by reducing material
and installation costs (Oc´eanide, 2022).

268

#### 269 2.1.2 Offshore WTEBS construction

270 Offshore WTEBS, i.e. including platforms, intakes and outfall pipelines, and mooring systems, can affect both 271 benthic and pelagic ecosystems. The main environmental impact in pelagic zones during the installation of the 272 system is likely to be related to the seismic surveys at the start of the project, shipping movements, construction 273 noise, and potential chemical pollution associated with marine vessel operations. Brandt et al. (2009) reported 274 that marine mammals temporarily avoid an area where construction is underway. The effect disappears 275 immediately after the cessation of noisy activities. If no anti-fouling is used, the presence of the offshore WTEBS 276 structures will provide settlement habitats for a variety of organisms (Itano and Holland, 2000, Dempster and 277 Taquet, 2004). As discussed earlier in Section 2.1, for a large-scale platform the potential impacts of the local water 278 flow modification and the large area of the occupied ocean surface on migratory surface dwellers and pelagic 279 ecosystem need to be considered.

280 McHale (1979) reported the development process of a cold-water pipeline associated with a 50 *KW* mini-OTEC 281 plant at Kona, Hawaii. In OTEC systems, cold-water pipelines may serve as a combined cold-water pipe and 282 mooring line (McHale, 1979, Zhang et al., 2018, Magesh, 2010). The impact on the benthic zone is likely related to 283 the installation of mooring systems and power cables. The installation of these devices may locally disturb the 284 ecosystem and temporary increase the turbidity of the water, however, biota density is limited in that depth, i.e., 285 infra to 1000 *m* depth (Devault and Péné-Annette, 2017).

Water pipelines of floating WTEBS can be made of HDPE, or Fiber-Reinforced Plastic (FRP). For large-scale OTEC floating plants with 4 to 10 *m* diameter intake pipelines, FRP material is often employed as the use of HDPE is not available for pipelines with diameters larger than 2.5 *m* (Stoev et al., 2018). HDPE is not a biodegradable material

and at the end of its life, it should be responsibly recycled, whereas FRP pipe material is non-corrosive (Vahidi et
al., 2016, Sözen et al., 2022).

291

#### 292 2.1.3 WTEBS decommissioning

The associated environmental impacts of decommissioning for a site are often assumed to be similar to those when the site is constructed (Boehlert and Gill, 2010, Gill, 2005). The removal of existing underwater structures will cause sudden alterations in the heterogeneity of the benthic inhabitant by removing a component of the ecosystem (Kaiser and Jennings, 2002). This may disturb the local food web and also changes habitat availability (Gill, 2005).

#### 298 2.2 Operation Impacts

299 A WTEBS intakes/discharges large volumes of ocean water. For example, an OTEC plant typically needs around 5 300  $m^3/s$  of cold deep seawater, and an equal intake of warm surface water per 1 MW capacity; therefore a commercial 301 OTEC system with 100 MW capacity needs a massive volume of 500  $m^3/s$  of cold and warm intake water for 302 operation (Avery and Wu, 1994). The system mixes the water and discharges it into the ambient environment with 303 different characteristics. Considering the lifetime of a plant (25-30 years), the operation of WTEBS may change the 304 water characteristics in near-, intermediate- and far-fields, and consequently significantly affects marine 305 ecosystem (Pelc and Fujita, 2002). Furthermore, concentrated deployment of large-scale WTEBSs can accumulate 306 and intensify the impacts (Comfort and Vega, 2011). While environmental impacts associated with processing 307 seawater are the main focus, impacts from other factors such as power cable electromagnetic fields, acoustic 308 effects of the WTEBS machinery and pipelines, and leakage of chemicals from the system will be of importance 309 during the operation of the system. In the pertinent literature, most of the knowledge regarding the 310 environmental impacts of WTEBS comes from studies that investigated the pre-impact condition at a future

- 311 WTEBS site. Among them, Comfort et al. (2015), Cardno Tec. Inc. (2014), Ciani (1978), and Comfort and Vega (2011)
- 312 studied the coastal area of Hawaii for SWAC and OTEC projects.
- 313 A detailed review of the features of the marine environment that may change with the operation of a WTEBS and
- the potential impacts of these changes on marine life are presented in this section. Figure 5 illustrates part of
- 315 these impacts for an offshore and onshore WTEBS.
- 316

317



318 Figure 5: Operational impacts of offshore and onshore WTEBSs in marine environment.

#### 319 2.2.1 Impingement and entrainment of organisms

- 320 The inlet pipelines may intake marine organisms, especially those with low mobility and are smaller than the mesh
- 321 of the inlet pipe screen, into the system during operation (Avery and Wu, 1994). These organisms will be impinged
- 322 to the internal walls of the system and will encounter rapid environmental changes, such as temperature,

323 dissolved oxygen, turbidity, and light levels of the water, which to a great extent reduce their chance of survival 324 (Avery and Wu, 1994, Elahee and Jugoo, 2013, Cunningham et al., 2010). This phenomenon has been studied in 325 coastal nuclear power plants and is similar related for WTEBSs (Avery and Wu, 1994, Barnthouse et al., 2019, Chae 326 et al., 2008). Due to higher concentration of marine life in shallow waters, this is an important factor in systems 327 that intake surface water and needs to be assessed for systems that intake cold deep seawater depending on 328 existing ecology (Comfort and Vega, 2011, Elahee and Jugoo, 2013, Myers et al., 1986, Deevey and Brooks, 1971). 329 Here, the intake pipelines are designed to preserve and maintain a low approach velocity to minimize the risk of 330 marine organisms being sucked into the system (Cunningham et al., 2010). Nonetheless, plankton, small nekton, 331 and most tuna larvae are often at risk of entrainment into surface water intakes (Myers et al., 1986, Boehlert and 332 Mundy, 1994). This risk decreases significantly for larger organisms due to their swimming capabilities (Comfort 333 and Vega, 2011). In addition, pipeline vibrations during system operation may generate signals for marine 334 mammals and fishes to avoid approaching the pipelines (Comfort and Vega, 2011). The discharge outfall can also 335 be an attractive destination for marine organisms as it may be rich in nutrients; this increases the probability of 336 impingement and injury to marine organisms (Elahee and Jugoo, 2013). Using the discharged water for secondary 337 purposes can influence the water discharge quality which needs further monitoring and observations.

#### 338 2.2.2 Chemical effects

In systems with closed-cycle operations, the working fluid is normally ammonia, or R-134a, and is isolated from the water being abstracted. As ammonia is highly toxic to fish, and concerns growing regarding the impact of R-134a on marine life, many studies have focused on use of these chemicals (Emani et al., 2017, Zhao et al., 2020, Jung and Hwang, 2014). A study of a selection of working fluids in terms of toxicity, environmental performance, and flammability can be found in Jung and Hwang (2014). Leakage or spill of working fluid may endanger the local marine population if the working fluid concentration in water exceeds toxicity levels (e.g. the United State environmental protection agency considers the concentration of ammonia higher that 0.4 *mg/Litre (ppm)* toxic to 346 fish (both freshwater and marine)). To give an indicator of dangerous amount of working fluid leakage, consider 347 that a seawater flow rate through a 40 MW OTEC plant is around  $2 \times 10^7 \text{ m}^3/\text{day}$  (Avery and Wu, 1994). To exceed 348 the environmental protection agency's limit, an ammonia leakage of around over  $8 \times 10^3 kg/day$  into the seawater 349 flow is required. This could only occur if there were serious malfunctions such as a major breakdown, a collision 350 with an ocean-going vessel, an unpredicted climate condition, terrorism, or causes from human errors. It is to be 351 noted that a workflow leakage due to a malfunction of the system should be avoided at all costs (Owens and 352 Trimble, 1981). Apart from the working fluid, during normal operation, the potential of leakage from devices that 353 use a hydraulic fluid needs to be considered along with the evaluation of toxicity impact of heavy metal 354 concentrations from heat exchangers (Fast et al., 1990). Chemicals used for controlling bio-fouling and corrosion, 355 such as chlorine or protective coating materials can accumulate in the tissues of organisms and be passed up in 356 the food chain (Avery and Wu, 1994, Elahee and Jugoo, 2013). Pre-treatment before disposal of chemicals and/or 357 mechanical control of fouling should be implemented (Elahee and Jugoo, 2013).

#### 358 2.2.3 Nutrient loading

359 For WTEBSs that intake deep cold ocean water, the untreated plume will have different physical and chemical 360 properties (e.g. temperature, density, salinity, dissolved gases, nutrient level, and pH level) than the surrounding 361 ocean water where it is discharged (Comfort et al., 2015, Comfort and Vega, 2011, Boehlert and Gill, 2010). The 362 density difference between the discharge outfall and the ambient water will cause the plume to sink or rise to an 363 equilibrium depth and produce an artificial nutrient-enriched zone (Comfort and Vega, 2011). If the plume 364 equilibrium occurs in the photic zone, it may induce phytoplankton and algal blooms and subsequently, affect 365 changes in the pelagic food web ecosystem and habitat (Comfort et al., 2015, Boehlert and Gill, 2010, Devault and 366 Péné-Annette, 2017, Harrison, 1987, Richardson and Schoeman, 2004, Lilley et al., 2012). In coastal areas, this may 367 interrupt economical activities such as shore-based businesses, the fishing industry, and recreational tourism 368 (Boehlert and Gill, 2010, Elahee and Jugoo, 2013). To minimise the environmental impact of WTEBS plumes, it is

369 crucial to ensure that the nutrient-rich plume does not mix with surface waters and remains beneath the most 370 biologically productive depths (below the 1% light level) (War, 2011, Comfort and Vega, 2011, Farr et al., 2021); 371 different water depths between 90 to 200 m have been recommended for this purpose (Comfort and Vega, 2011, 372 Farr et al., 2021, Lilley et al., 2012, Deprofundis, 2016). The recommended depth depends on detailed local 373 conditions, environmental regulations, and diffuser dispersion modelling employed for each case (Makai Ocean 374 Engineering Inc., 2015b). Nutrient enhancement for WTEBS that intake water from shallow sea or lakes also needs 375 to be investigated, as many lakes and shallow sea areas show vertical stratification of water during warm seasons 376 (Boehrer and Schultze, 2008, Hickman et al., 2012).

The rich-nutrient discharge of WTEBS can also serve secondary utilisation for energy production, cooling, desalination, aquaculture, and agriculture (War, 2011, Samuel et al., 2013, Elsafty and Saeid, 2009). Nevertheless, the environmental impact of the effluent from the secondary utilization system into the ocean needs to be assessed. A comprehensive review of experimental and numerical modelling of effluent dispersion is provided in Section 3.

#### 382 2.2.4 Temperature concerns

383 If WTEBS water discharge is not returned to isothermal depths, there will be a risk of a slight change in water 384 temperature. This thermal effect may have severe consequences on marine life, as thermal changes can lead to 385 reductions in the hatching success of eggs, inhibition of larvae development, and increase in death among coral 386 and fishes (Pelc and Fujita, 2002, Elahee and Jugoo, 2013, Lilley et al., 2015). However, Avery and Wu (1994) 387 reported results from several theoretical and experimental studies (e.g. Adams et al. (1979)) concluded that 388 climatic alterations due to operation of OTEC systems are negligible, or extremely localised. In fact, over the long 389 term, the large volume of discharge plume has the potential to alter the marine ecosystem in regions near the 390 discharge outlet (Boehlert and Gill, 2010, Harrison, 1987). The impacts in the far-field region can only be noticeable 391 in the case of deployment of a very large number of OTEC plants (Avery and Wu, 1994).

#### 392 **2.2.5** *CO*<sup>2</sup> **outgas and** *pH* **level**

393 Seawater has many different gases dissolved in it, including nitrogen, oxygen, and carbon dioxide. The intake water 394 into WTEBSs are subjected to changes in temperature and pressure which lead to changes in the solubility of 395 dissolved gas. For systems that intake deep sea ocean water, it can result in dissolved CO<sub>2</sub> outgas (Elahee and 396 Jugoo, 2013). While this amount will depend on the volume of water being pumped, Avery and Wu (1994) pointed 397 out that such an amount would be smaller than emissions from a fossil-fuel-fired plant. Conversely,  $CO_2$  and other 398 carbon compounds (e.g. carbonate and bicarbonate) play an important role in the pH level of ocean water (Webb, 399 2021). Changes in the concentration of  $CO_2$  levels in water may increase concerns regarding the acidification effect 400 of the artificially upwelled water (Boehlert and Gill, 2010, Feely et al., 2008, Griffith et al., 2011). The change in 401 the pH level of the seawater can disturb the marine ecosystem, biodiversity, and marine food web (Griffith et al., 402 2011).

#### 403 **2.2.6** Acoustic effects

404 Acoustics play an important role in underwater ecosystems and are essential in animal communication, 405 reproduction, orientation, and prey and predator sensing (Boehlert and Gill, 2010). Anthropogenic underwater 406 noise will likely add to the normal background acoustic environment (Boehlert and Gill, 2010). The possible 407 impacts of artificial noise on fish, marine mammals, and crab and lobster larvae have been indicated in 408 Montgomery et al. (2006), Hastings and Popper (2005), and Southall et al. (2008). The generated noise associated 409 with the operation of WTEBS can be of concern, as the plants operate permanently over a long period of 25-30 410 years (Rucker and Friedl, 1985). The operational acoustic noises from onshore WTEBS in the marine environment 411 are caused mainly from the vibration of pipelines, however, there are no evidence of such an impact being studied 412 in the literature. For offshore systems, cold water pipelines, water pumps, and noise associated with devices in a 413 typical WTEBS plant (such as pumps associated with the transport of working fluid) are the main contributor of 414 noise (Rucker and Friedl, 1985, Janota and Thompson, 1983). Ducatel et al. (2013) conducted a preliminary study

415 to predict the potential acoustic impact of an OTEC plant due to onboard machinery and noted the potential
416 impacts of the system on marine mammals at short distances, less than 200 *m*.

#### 417 2.2.7 Electromagnetic effects

418 The generated electricity by offshore-based OTEC systems may be transmitted to shore using a network of cables 419 that are mounted on the seabed. Transmission of the produced electricity through these cables will emit low-420 frequency electromagnetic fields (EMF) (Boehlert and Gill, 2010). A number of marine organisms use 421 electroreception as a fundamental sensory mode for mate finding, feeding, and navigation (Boehlert and Gill, 422 2010, Hutchison et al., 2020, Öhman et al., 2007, Kirschvink, 1997, Whitehead and Collin, 2004). it is likely that 423 EMF from power cables will have a direct effect on these animals. Scott et al. (2018) indicated that EMF from sub-424 sea power cables affect edible crabs both behaviourally and physiologically. Westerberg and Lagenfelt (2008) 425 reported a significant change in eels migration swimming speed around the sub-sea power cables. Other growing 426 concerns regarding mounted or buried power cables include an increase in temperature of the adjacent water, 427 sedimentation, and impacts on benthic ecosystems due to electricity transmission (Boehlert and Gill, 2010). 428 Further investigation is recommended for better understanding of the impact of sub-sea power cables on marine 429 organisms.

430

#### 431 **3** 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 in other growing technologies such as desalination plants, thermal power plants, and aquafarming 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 (Jiang et al., 2014). Thermal power plants of coastal cities discharge enormous quantities of waste heat into seas and lakes (Pryputniewicz and Bowley, 1975), while aquafarming effluent is typically enriched in suspended organic solids, carbon, nitrogen, and phosphorus (Zeng et al., 2013), which may have a detrimental impact on many species living around the discharge location.

In general, wastewater discharges from industrial processes are categorized into two major groups based on their density discrepancy with the ambient water bodies (Kheirkhah Gildeh et al., 2014). If the effluent has a higher density than 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, this then rises, which is termed a buoyant plume (Bleninger et al., 2010). 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 discharge flow (Shao and Law, 2010, Jirka and Domeker, 1991).

450 In the pertinent literature, the study of submerged jet flows haves been extensively covered. Experimental 451 investigations on the characteristics of inclined brine dense jets, such as maximum jet height rise and 452 concentration field, into stagnant environment can be found in Roberts et al. (1997), Cipollina et al. (2005), and 453 Lai and Lee (2012). These studies reported that dense jets with 60° inclined angle produce the longest trajectory 454 for entrainment and thus the highest dilution. Jiang et al. (2014) and Shao and Law (2010) studied the effects of 455 stationary shallow water with mixing of 30° and 45° inclined dense jets. It was realized that the surface constraint 456 may lengthen jet-spreading distances and reduce surface dilution. They also recommended that the terminal rise 457 related to 60° inclined dense jet is rather high and therefore the angle may be too large to provide efficient mixing 458 in shallow waters.

Pryputniewicz and Bowley (1975) investigated turbulence buoyant jets that are 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. The impacts of horizontal buoyant jets discharged

462 into stationary environment and the effect of bed proximity or so known as the Coanda effect, were detailed in 463 Sharp (1975), Sharp et al. (1977), and Sobey et al. (1988). Coanda effect occurs when the jet discharge is placed 464 close to the bed boundary, the discharge will then cling to and proceed along the boundary (Shao and Law, 2010). 465 This improves the mixing efficiency of buoyant flows, while for saline dense jets, it may cause negative effects on 466 benthic communities around the impacted area (Shao and Law, 2010). Huai et al. (2010), Kheirkhah Gildeh et al. 467 (2014), Kheirkhah Gildeh et al. (2015) carried out numerical modelling of turbulent buoyant jets in stationary 468 ambient water. These studies applied Reynolds-Average Navier-Stokes (RANS) combined with different turbulence 469 closure models. Their findings showed that realizable  $k-\epsilon$  and Launder, Reece, and Rodi (LRR) turbulence models 470 were the most reliable and accurate in modelling Coanda effect, buoyant and non-buoyant jet in stagnant 471 environments.

472 Abessi et al. (2012) conducted a series of experimental tests for negatively buoyant effluents discharged 473 through a protruding surface channel into unstratified stagnant water. The results show that the influence of free-474 surface on the entrainment and mixing of the flows is small. Abessi and Roberts (2014) carried out comprehensive 475 laboratory experiments on multiport diffusers for negatively buoyant effluents into stationary water. Their results 476 recommended that to prevent reduction in entrainment, it is essential to consider sufficient spacing between the 477 designed ports. Ardalan and Vafaei (2018) developed a classification chart for thermal-saline inclined single-port 478 jet, as a result of an extensive set of laboratory experiments for thermal-saline effluent with three different 479 discharge angles of 30°, 45°, and 60° in stagnant water environments. This is subsequently followed on in Ardalan 480 and Vafaei (2019) where they carried out numerical and experimental studies of negatively buoyant jet discharged 481 with 45° inclined angle in a stationary water; simulations were conducted using a RANS model with realizable  $k-\epsilon$ 482 model and the outcome showed good consistency with the results of physical modelling. Rodríguez-Ocampo et al. 483 (2020) implemented an OpenFOAM-based solver that can be applied in modelling thermal discharge into water 484 bodies. The solver was suitable for simulating three fluid phases with different densities and temperatures, i.e., 485 two miscible liquids and air, and was validated against an experiment of a multiphase dam-break. However, the 486 model did not consider buoyancy effects. More recently, a study of submerged thermal-saline jet discharge into a 487 stagnant environment using the LES turbulence model was carried out by Azadi and Firoozabadi (2022). The results 488 illustrated that the flow patterns only depend on the density ratio, which is the thermal flux to salinity flux ratio. 489 The main drawback of the above group of studies was that they have not considered the marine environment 490 conditions including wave and current flow.

491 Investigations on the characteristics of jets into non-stationary environments have also been widely carried 492 out; notably, Roberts and Toms (1987) conducted a series of experiments on the characteristics of vertical and 493 inclined dense jets with different angles discharged into a uniform crossflow of various velocities and directions. 494 As a result, they discovered that inclined jets are generally preferable to vertical jets. When a submerged discharge 495 outlet is located where currents may flow in all directions, then vertical jets may be the preferable choice instead 496 of inclined jets (Ahmad and Baddour, 2012). Mossa (2004) conducted laboratory experiments for turbulent 497 nonbuoyant jets that are vertically discharged into two different environments, one with stagnant ambient water 498 and a second with regular waves; they observed higher entrainment velocities in the latter case. An experimental 499 study on the behaviour of horizontal non-buoyant jet located at the mid-depth of a shallow water wave 500 environment was investigated by Ryu et al. (2005). The results revealed that the influence of wave amplitude on 501 jet diffusion is substantial. Zhen et al. (2007) numerically simulated seawater temperature field to monitor the 502 environmental impacts of hot effluent discharged from a seawater-source heat pump in Dalian, using a two-503 dimensional convection-diffusion equation model; the water temperature elevation impacts on the marine 504 ecosystem were found to be negligible. Yu et al. (2009) established a two-dimensional hydrodynamic model to 505 predict and optimise the thermal plume from a Rizhao power plant discharge on Rizhao sea. Chen et al. (2012) 506 conducted numerical modelling of a buoyant and non-buoyant round jet discharge into wave environments using 507 Large Eddy Simulation (LES) where the buoyancy effect was considered using the Boussinesq assumption. The 508 results were validated against the experimental data in Chen et al. (2009). As an outcome, they realised that under 509 the buoyancy force the wave effect on jet entrainment and mixing is considerably weakened.

510 Other related work, such as Pat Grandelli et al. (2012) developed and validated a three-dimensional time-511 dependent model for predicting biological and physical impacts of OTEC. The model simulated negatively buoyant 512 discharge flows by a dynamically coupled Lagrangian jet-plume entrainment model in the near-field, and by 513 dynamic oceanic circulation and turbulence in the far-field for the water surrounding O'ahu in Hawai'i, USA (Figure 514 6). The model is used to define the effect of nutrient-rich and low-oxygen deep sea water on increased productivity 515 of phytoplankton. Similarly, Kim and Kim (2014) developed a primitive three-dimensional model to predict and 516 minimise the mixing behaviour of thermal discharges of an OTEC system in coastal water of Kosrae, Micronesia. 517 They declared that the model was capable of reproducing the plume behaviour. More recently, the effect of free-518 surface waves in temperature distribution in thermal boundary layer region close to the seabed was analytically 519 modelled in Michele et al. (2021) and Michele et al. (2023). The study suggested a need for expanding existing 520 models that neglect the effects of free-surface wave field.

521 There are also some well-known commercial models that have been widely used for predicting the effluent 522 discharges in waterbodies. In this group, Lee et al. (2003) implemented a Lagrangian interactive virtual reality 523 model (JETLAG/VISJET) based on the project-area entrainment hypothesis and a heuristic theory to treat the shear 524 to vortex entrainment transition. Frick (2004) developed the VISUAL PLUMES (VP) model which is a platform for 525 mixing zone modelling. Jirka and Domeker (1991) introduced an integral model for turbulent buoyant jets in 526 unbounded stratified flow which was coded into a Fortran program COREJET/CORMIX. Palomar et al. (2012) 527 carried out a detailed analysis of these commercial models (i.e. JETLAG, COREJET, and VP) and realized insensitivity 528 of these models in predicting the influence of crossflow direction on jet behaviour.

529 Most recently, Xu et al. (2016) investigated a nonbuoyant vertical round jet in a wave-current coexisting and 530 current-only environments, both numerically using LES, and experimentally. They observed the effluent clouds 531 phenomenon in the wave-current coexisting which leads to considerable increment of jet spread and dilution. Xu 532 et al. (2017) investigated the impact of regular waves on three dimensional scalar structures of a vertical jet in the 533 wave-following-current environment using numerical modelling of submerged non-buoyant vertical round jets.

Followed on, Xu et al. (2018) 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-followingcurrent environments. This is extended in Xu et al. (2019) where they 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. Comparably, Fang et al. (2019) implemented an integral model for predicting the characteristic behaviour of a buoyant jet in wavy crossflow environments.

A set of laboratory tests in modelling of submerged negatively buoyant outfall under typical conditions in the Mediterranean Sea was carried out by Ferrari et al. (2018). The results revealed that the strongest waves tested in the study tend to decrease dilution, while the weakest waves tend to improve it. Anghan et al. (2022) 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.



548

Figure 6: Simulated plume and nitrate (nutrient) concentration of discharge dispersion of a 100 MW OTEC plant
with four 70 *m* depth and 1 *m/s* mixed discharges by Pat Grandelli et al. (2012).

551

552 As listed above, many numerical and experimental studies have been conducted to study effluent 553 dispersion, however the literature lacks a comprehensive and sophisticated computational fluid dynamics (CFD) 554 model to simulate the hydro-thermal behaviour of discharged effluents into waterbodies under combined wave-555 current conditions. Table 1 presents the advantages and disadvantages of the numerical investigations on effluent 556 dispersion into non-stationary environments. Recent advances in development of numerical tools in simulation of 557 hydrodynamics of wave and currents in mesh-based approach (such as, Higuera et al. (2013) that developed a 558 realistic wave generator and active wave absorber for the Navier-stokes equation and Larsen and Fuhrman (2018) 559 that implemented a new turbulence model capable of predicting accurate pre- and post-breaking surface 560 elevations, as well as turbulence and undertow velocity profiles of surface waves) and mesh-less approach (such

as, Ni et al. (2018), Ni et al. (2020) that implemented a numerical wave-current flume based on Smoothed Particle

562 Hydrodynamics (SPH)) provide an opportunity to bridge this knowledge gap.

563

564 Table1: Advantages and disadvantages of numerical models in simulation of submerged jet into non-stationary

565 environment.

Submerged jet into non- stationary flow modelling	Advantages	Disadvantages
Zhen et al. (2007) and Yu et al. (2009)	<ul> <li>Simulate seawater temperature field in two-dimensional field</li> </ul>	<ul> <li>Can only be applied in shallow</li> <li>water</li> <li>Lack of validation</li> <li>No buoyancy effect modelling</li> </ul>
Chen et al. (2012)	<ul> <li>Consider buoyancy effect</li> <li>Validated against laboratory data</li> </ul>	<ul> <li>Only valid under wave condition with no current flow</li> </ul>
Pat Grandelli et al. (2012)	<ul> <li>Large-scale modelling</li> <li>Consider buoyancy effect</li> <li>Capable of biological modelling</li> </ul>	<ul> <li>Only designed for OTEC systems</li> <li>Not applicable for shallow water</li> <li>modelling</li> </ul>
Kim and Kim (2014)	- Can reproduce the plume behaviour in coastal water	- Lack of validation
JETLAG/VISJET (Lee et al., 2003), VISUAL PLUMES (Frick, 2004), COREJET/CORMIX (Jirka and Domeker, 1991)	<ul> <li>Capable of fast prediction of mixing zone characteristics</li> <li>Platform for mixing zone modelling</li> </ul>	<ul> <li>Insensitive in predicting the influence of crossflow direction on jet behaviour</li> <li>Commercial software</li> </ul>
Xu et al. (2016), Xu et al. (2017), Xu et al. (2018), and Xu et al. (2019)	<ul> <li>Simulate jet flow under different combination of current and wave conditions</li> </ul>	- No temperature distribution modelling
Fang et al. (2019)	<ul> <li>Predict the characteristic</li> <li>behaviour of a buoyant jet in a wavy</li> <li>crossflow environment</li> </ul>	- No temperature distribution modelling

566

## 567 4 Biofouling and Corrosion

Exposed surfaces of systems that use seawater as the main processing fluid can be affected by the physiochemical properties of seawater such as fouling and corrosion (Abidin et al., 2021). Fouling occurs as a result of the deposition of dissolved and particulate matter in the water on surfaces that are in contact with it (Abd El 571 Aleem et al., 1998). The undesired growth and accumulation of foulant on surfaces in contact with water can 572 potentially affect the system's efficiency, while damaging equipment in the process (Abidin et al., 2021). 573 Uncontrolled growth of fouling can have damaging consequences to WTEBSs (Abidin et al., 2021), marine vessels 574 (Magin et al., 2010), rigs (Gormley et al., 2018), marine aquaculture (Fitridge et al., 2012), and other infrastructure 575 that is submerged in the sea. Crystalline fouling, organic fouling, particle and colloidal fouling, and microbiological 576 fouling are categorised as the most important types of fouling (Flemming, 1997, Al-Juboori and Yusaf, 2012). 577 Among them, controlling biofouling (microbiological fouling) is the most complicated one (Flemming, 1997, Al-578 Juboori and Yusaf, 2012).

579 Marine biofouling is the unwanted growth of marine micro- and macro-organisms like bacteria, algae, 580 sponges, barnacles, mussels, Balanus etc. (Mahto and Pal, 2020). The growth and accumulation process of 581 biofouling on the exposed surfaces are detailed in Abidin et al. (2021), Flemming (1997), Al-Juboori and Yusaf 582 (2012), Maddah and Chogle (2017), and Mitchell and Benson (1980).

583 Figure 7 illustrates the growth of fouling inside of the pipeline and on the mesh filter basket of the intake 584 pipeline of a pilot SWAC system at Brixham laboratory, University of Plymouth, United Kingdom. The SWAC system 585 has been out of service for many years, while the intake pipeline, with an internal diameter of 5.08 cm, has been 586 used regularly for filling seawater tanks (i.e. abstracting seawater for 1 or 2 hours per day) for other activities in 587 the laboratory. The pipelines were installed in the early 1980s and no anti-fouling treatment has been carried out 588 since, whereas the pipeline and the mesh filter basket have been pressure washed once in 2007. When retrieved, 589 a growth of fouling with a thickness of 2-3 mm is observed in the pipelines, while the mesh filter basket is covered 590 with micro- and macro-organisms (e.g.bacteria, algae, barnacles, Balanus)(Euroswac, 2021).

591 Bott (2011) classified the parameters that can influence biofouling growth into three main categories of 592 chemical, physical, and biological, as listed in table 2.

593



595 Figure 7: (a) Biofouling at the intake pipeline, and (b) The mesh filter basket at the inlet of the intake pipeline of

- the pilot SWAC system at Brixham laboratory, Brixham, UK (Euroswac, 2021).
- 597

594

Table 2: Chemical, physical, and biological parameters that affect biofouling growth (Bott, 2011).

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

599

Untreated fouling can lead to increases in the thermal resistance as well as required pumping power (Mitchell and Spitler, 2013). Abidin et al. (2021) and Jenkins (1978) affirmed that in the design of OTEC systems, biofouling is an inevitable condition that cannot be avoided. They highlighted the impacts of flow velocity and temperature of the seawater intake as two main parameters on the control of biofouling growth. The relationship between flow velocity and biofouling growth is complicated to correlate due to its dual impacts. The rapid velocity of the water can provide sufficient oxygen and nutrient that favours the growth of macrofoulants, but it can also 606 prevent biofouling growth if the water shear rate surpasses the shear rate of biofouling settlement (Flemming, 607 1997, Jenkins, 1978). Panchal and Knudsen (1998) pointed out that seawater temperature in the range of between 608 20°C to 50°C is desirable for microorganisms growth which explains why high-temperature surface seawater 609 exposed to continuous sunlight accommodates the growth of biofouling (Mitchell and Spitler, 2013). Likewise, 610 higher potential for biofouling is anticipated at shallow water-based onshore facilities in comparison to offshore 611 ones owing to the high concentration of organisms in seawater adjacent to the shoreline (Avery and Wu, 1994). 612 Seasonal seawater temperature changes also influence the potential for biofouling growth, for example, low range 613 of temperature changes in tropical area, provides a steady condition for biofouling development (Affandy et al., 614 2019).

615 One of the most common techniques employed to kill organisms in WTEBSs is through the use of biocides 616 (Makhlouf and Botello, 2018) namely via oxidising and non-oxidising types. Oxidising biocides, such as chlorine, 617 peracetic acid, bromine, and sodium bromide, attack microorganisms by disrupting nutrients from passing across 618 the microorganism cell walls (Makhlouf and Botello, 2018, Ilhan-Sungur et al., 2015). On the other hand, non-619 oxidising biocides, such as 1,2-benzisothiazolin-3on and 5-chloro-2-methyl-4-isothiazolin-3-on, interfere with 620 reproduction, respiration process, and harms the microorganism cell walls (Makhlouf and Botello, 2018, Ilhan-621 Sungur et al., 2015). These biocides can target more specific biochemical pathways, thus reducing the potential of 622 unwanted side-effects, but the targeted bio-foulants may become resilient to them. In open systems, due to 623 environmental concerns of chemical discharge, only using direct injection of the oxidising agent, such as sodium 624 hypochlorite (chlorine) is allowed (Mitchell and Spitler, 2013).

Anti-fouling coating is another usual practice 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 (Chambers et al., 2006). However, its use has been prohibited as it was found harmful to marine organisms. Its replacements include use of metallic species, such as copper and zinc and many other alternatives are highlighted in detail in Chambers et al. (2006).

630 Abidin et al. (2021) elaborated on a list of common and potential techniques of biofouling assessment for OTEC 631 systems including microscopic optical, spectroscopic, physical assessment, electrical, biological and chemical 632 detecting techniques. This list can be generalized and adapted for biofouling assessments for all other types of 633 WTEBSs. Makai Ocean Eegineering Inc. (2014b) stated as a result of long-term testing of heat exchangers that 634 fouling is not a serious problem with WTEBSs that intake cold deep seawater in the range between  $3^{\circ}C$  to  $8^{\circ}C$ . 635 However, for warm water systems, e.g., OTEC systems that intake warm surface water with temperatures above 636 25°C, biofouling is unavoidable. In addition, other system components such as strainers, pumps, holding tanks and 637 pipeline fittings are among the equipment that are most at risk of being exposed to potential biofouling (Abidin et 638 al., 2021). Berger and Berger (1986) recommended that injection of chlorine at a concentration between 50 to 70 639 ppb for 1 hour per day (24-h average of 2-3 ppb) can completely prevent fouling in systems and can be used as a 640 continuous and non-destructive method of prevention.

Apart from biofouling, corrosion can also impact WTEBSs' performance due to seawater interactions with system components and structures. Corrosion is defined as the process of destruction of material under the chemical or electrochemical action of the surrounding environment (Pourbaix, 2012). An essential key to improving the marine structures' optimum service life against corrosion is understanding the type of marine environment, materials used, appropriate design, and corrosion control measures (Shifler, 2005).

646 An important controlling factor in structures made using metals and alloys is the formation of a passive film 647 that reduces ionic transport of reactive species (Shifler, 2005). In seawater, the dissolved oxygen and chloride ions 648 lead the formation and repair or breaking down of passive films (Shifler, 2005). Environment parameters such as 649 atmospheric salt concentration, temperature, oxygen concentration, salinity, and flow-related corrosion 650 parameters (e.g. Erosion-corrosion (Shifler, 1999) and cavitation (Hoyt and Furuya, 1985)) need to be considered. 651 The presence of bio-films also increase the corrosion rate of a structure or operate as a passive deterrent (Shifler, 652 2005, Videla and Characklis, 1992). Proper design, including a selection of compatible materials from both 653 corrosion and mechanical aspects, optimizing geometries and joining processes that minimize corrosion, and

654 utilization of corrosion control measures, is the most effective way to reduce corrosion costs (Shifler, 2005). 655 Typically, corrosion can be controlled by using coatings that act as either ionic filters, oxygen diffusion barriers or 656 cathodic protection that can be very cost-effective solutions (Shifler, 2005, Diler et al., 2020). For WTEBSs that 657 need to have pipelines across large depths, it is advised that polyethylene is an excellent choice of material as the 658 pipelines will not corrode or contaminate the water (Elsafty and Saeid, 2009). In heat exchanger systems, corrosion 659 due to the salty seawater can be eliminated using either titanium or aluminium heat exchangers; titanium is 660 proposed as a low-risk solution for a condenser, especially when employed in cold seawater (Elsafty and Saeid, 661 2009, Van Ryzin and Leraand, 1991, Makai Ocean Eegineering Inc., 2014a).

#### 662 **5** Permits and Licensing

670

Brixham Laboratory at the University of Plymouth has its pilot shallow-water-based SWAC system installed but was not used since 1990s. Through a project, EUROSWAC (Euroswac, 2021), the facility was reawakened and modified to enable the SWAC performance to be monitored. This required obtaining the necessary permitting and licensing approvals from the relevant authorities in the United Kingdom, such as the Marine Management Organization and Environmental Agency. All necessary permits in order to construct and operate have been identified and simplified in a licensing flow-chart presented in Figure 8. This flow chart is applicable and valid for the installation and operation of other types of WTEBSs in English waters.



671 Figure 8: Permits and licensing flow chart for installation and operation a SWAC facility in the United Kingdom.

672

In the United Kingdom, the Marine Management Organization defines the deployment of new WTEBSs, or any extension of an existing system including installation of new pipelines, fits into the construction, dredging and deposit category. The Marine Management Organization offers an assistance tool to guide and check if the construction of a new WTEBS or any extension of an existing system, requires a marine licence. Generally, the tool provides three options regarding the marine licence:

Exemption: In certain circumstances, the need for a marine licence can be removed. Note that an
 exemption is not applicable for the construction of new underwater structures for example non-oil and gas
 pipeline.

Self-service marine licence: This licence covers a number of activities that can be considered low risk activities. This excludes deploying a new WTEBS or any extension of an existing systems.

• Standard marine licence: If a proposed activity does not meet the exemption or self-service marine license criteria. Application for a standard marine licence is required for both new WTEBS and extension of existing systems that includes the installation of new pipelines which needs to be authorised by the Marine Management Organization.

687 Abstraction and discharge licences are controlled by the Environmental Agency. A full licence is required when 688 the abstraction volume flow rate surpasses 20  $m^3$  a day. For heat exchangers and discharge to surface water, the 689 Environmental Agency requires that the maximum temperature of water at the borders of the mixing zone should 690 not exceed 23 °C. Furthermore, it requires that the maximum temperature rise outside of the mixing zone should 691 not be higher than 3 °C. The size of a mixing zone is not directly defined or constrained by the Environmental 692 Agency and is on a case-by-case basis, dependent on local geography and environment data. This is not true for 693 Scotland where the mixing zone is defined as 100 m from the centre outward in every direction. If biofouling 694 control measures are taken, their effects on the discharge water need to be considered.

695	In the case of the WTEBSs, the Environmental Agency offers an option for submitting a single application for			
696	abstraction and discharge licenses as long as the following conditions are met:			
697	•	Discharge volume is lower than 1000 $m^3$ a day.		
698	•	Temperature regulations outlined for discharge to surface water as mentioned above are met.		
699	•	No polluting chemicals present in the discharge.		
700	•	Discharge is to the same water body as the abstracted water, but not close to 200 $m$ to another		
701	heated discharge.			
702	•	Discharge is not at any water body containing protected species or within 100 <i>m</i> from a local		
703	wildlife site.			
704	•	Discharge must not be a watercourse point where salmon spawn.		
705	Interested readers are referred to government websites for more details on each application. A similar flow			
706	chart can be designed to summarise the required permits and licensing process for other territorial waters.			

707

## 708 6 Environmental Impact Assessment of Pilot SWAC System at Brixham

#### 709 Laboratory

In the EUROSWAC project, an environmental impact assessment study was performed to measure water quality parameters near the discharge area of the pilot shallow-water SWAC system at Brixham laboratory (Euroswac, 2021). For this purpose, two buoys which were equipped with sensors for monitoring water properties (such as water temperature, pH, oxygen concentration, dissolved oxygen saturation, conductivity, total dissolved solids, and the oxidation-reduction potential) were deployed for nine months at different positions between 5 *m* and 40 *m* from the discharge outlet situated near the shoreline; the SWAC system had a discharge flow rate of around 150 *litre/min*. During this period, the pilot system was run for short periods of up to 8 hours to assess changes in water quality, but no significant and detectable change in water properties were observed.

718 To ensure that the discharge complies with mixing zone requirements outlined in the temperature regulations by 719 the Environmental Agency, a numerical model was developed in OpenFOAM®. The model solves governing hydro-720 thermal equations to predict temperature distribution field created by submerged hot seawater discharge into 721 cold seawater while accounting for marine environment influences from dynamic interactions of currents and 722 waves, where it is verified against a wide range of analytical and experimental data. Different scenarios were 723 modelled using data from the pilot SWAC discharge with varying ambient environmental conditions. Figure 9 724 shows the set conditions and geometry specified for the computational domain in one of the simulated cases 725 based on experimental discharge data captured at the bay in Brixham. Simulations were conducted with the aid 726 of high-performance computing due to heavy computational requirements to predict the dynamic thermo-fluid 727 current-wave interactions in three-dimensions. A snapshot of the results in Figure 9 depicts the iso-surface of 728 mean seawater temperature discharge at T = 16 °C when the flow is fully developed which means that the 729 seawater temperature rise beyond that area is less than 1 °C. It clearly delineated the operational condition of the 730 SWAC at Brixham produces a small impact footprint of detectable temperature alterations only between 4 to 5 731 meters in size from the discharge point, which conform to the abovementioned temperature regulations for 732 abstraction and discharge licenses of WTEBSs.



- 733
- 734

Figure 9: Numerical modelling setup and iso-surface of mean seawater temperature discharge for T = 16 °C for a fully developed flow condition.

737

738

#### 739 7 Conclusion

The growth and development of WTEBSs raise concerns regarding their impacts on sustainability and degradation of marine environments. The present paper provides a full review of previous studies and state-of-the-art in different aspects of WTEBSs' interactions with marine environments. The study highlighted the relevant concerns on the development of WTEBSs including different stages of construction, operation, and decommissioning based on other types of development in the marine environment such as coastal power plants or other marine-based 745 renewable technologies. The construction and decommissioning phases of a WTEBS, including installation of 746 foundations and hard-fixed structures (such as submerged heat exchangers or pump stations), pipelines, scour-747 protection systems, mooring devices, and seabed mounted power cables are likely to cause significant positive 748 and negative disturbances to local environmental resources and fundamental changes to the benthic habitat. 749 Innovative new solutions such as those proposed by DeProfundis and DORIS Engineering in self-burying and 750 flexible pipe technologies can assist with minimising the environmental impact and costs of pipeline installations. 751 Operation-wise, WTEBS continuously affects the marine environment throughout its lifetime of between 25 to 30 752 years. A comprehensive review of the environmental impact associated with discharge of processed seawater, 753 power cable electromagnetic fields, acoustic effects from the WTEBS machinery and pipelines, and leakage of 754 chemicals from the system on benthic and pelagic ecosystems was presented. As discharge dispersion is one of 755 the main environmental concerns, related experimental works in the area are reported, following by numerical 756 tool employed to predict their effects. The lack of a comprehensive and sophisticated computational fluid 757 dynamics (CFD) model to simulate the hydro-thermal behaviour of discharged effluents into waterbodies under 758 combined wave-current conditions was discovered, and scopes for improving the existing models to bridge the 759 knowledge gaps were discussed.

The potential destructive impacts of fouling and corrosion in WTEBSs were subsequently presented, followed by an example observed at Brixham laboratory. Deterrent recommendations, such as using HDPE pipelines, materials for heat exchangers, appropriate designing and assessment, as well as injection of chlorine as a continuous and non-destructive method were highlighted.

Required permitting applications and licensing processes for installation and operation of new WTEBS or modification of an existing one by the relevant authorities in the United Kingdom are summarized. Current regulations may subject to changes in future with growth in the development, deployment, and adoption of WTEBSs.

768 Most of the information regarding the environmental impacts of WTEBS came from studies that investigated pre-769 impact conditions at a potential WTEBS site, or those that have been adapted from other marine technologies 770 environmental impacts. Actual monitoring of the environmental impact of WTEBSs during operation is therefore 771 lacking and thus necessary. The finding from data monitoring of water quality properties for short term operation 772 of a pilot SWAC system at Brixham Laboratory at the University of Plymouth in the United Kingdom was discussed. 773 It was found that no large detectable changes in water quality are measured, with seawater mixing zone 774 temperature variation being very localised that complies within limits to what is allowable by permits and licensing 775 regulations. However, further studies would be required if demand for abstraction and therefore discharge of 776 seawater flow rate increases, and if the SWAC system was to operate continuously to assess long term effects.

777

#### 778 Acknowledgements

- The authors would like to acknowledge the support received from EUROSWAC (Project number 216) funded by Interreg France (Channel) England program and European Regional Development Fund (ERDF), and Engineering and Physical Science Research Council (EPSRC) High End Computing Consortium for Wave Structure Interaction HEC WSI, EP/X035751/1.
- 783

#### 784 **References:**

ABD EL ALEEM, F., AL-SUGAIR, K. & ALAHMAD, M. 1998. Biofouling problems in membrane
processes for water desalination and reuse in Saudi Arabia. *International biodeterioration & biodegradation*, 41, 19-23.

- ABESSI, O. & ROBERTS, P. J. 2014. Multiport diffusers for dense discharges. *Journal of Hydraulic Engineering*, 140, 04014032.
- ABESSI, O., SAEEDI, M., BLENINGER, T. & DAVIDSON, M. 2012. Surface discharge of negatively
   buoyant effluent in unstratified stagnant water. *Journal of Hydro-environment Research*,
   6, 181-193.
- ABIDIN, M. Z. Z., RODHI, M. N. M., HAMZAH, F. & GHAZALI, N. A. Assessing biofouling in Ocean
   Thermal Energy Conversion (OTEC) power plant–A review. Journal of Physics:
   Conference Series, 2021. IOP Publishing, 012011.
- ADAMS, E. E., FRY, D. J. & COXE, D. H. 1979. Results of a near field physical model study. *Ocean Thermal Energy for the*, 80.
- ADDIS, P., CAU, A., MASSUTÍ, E., MERELLA, P., SINOPOLI, M. & ANDALORO, F. 2006. Spatial and temporal changes in the assemblage structure of fishes associated to fish aggregation devices in the Western Mediterranean. *Aquatic Living Resources*, 19, 149-160.
- AFFANDY, M., MADIN, J., JAKOBSEN, K. & AULUCK, M. Development and succession of sessile
   macrofouling organisms on the artificial structure in the Shallow Coastal Waters of
   Sabah, Malaysia. IOP Conference Series: Earth and Environmental Science, 2019. IOP
   Publishing, 012046.
- AHMAD, N. & BADDOUR, R. E. 2012. Dilution and penetration of vertical negatively buoyant thermal jets. *Journal of Hydraulic Engineering*, 138, 850-857.
- AL-JUBOORI, R. A. & YUSAF, T. 2012. Biofouling in RO system: mechanisms, monitoring and controlling. *Desalination*, 302, 1-23.
- ANGHAN, C., BADE, M. H. & BANERJEE, J. 2022. A review on fundamental properties of the jet in
   the wave environment. *Ocean Engineering*, 250, 110914.
- ARDALAN, H. & VAFAEI, F. 2018. Hydrodynamic classification of submerged thermal-saline
   inclined single-port discharges. *Marine pollution bulletin*, 130, 299-306.
- ARDALAN, H. & VAFAEI, F. 2019. CFD and experimental study of 45° inclined thermal-saline
   reversible buoyant jets in stationary ambient. *Environmental Processes*, 6, 219-239.
- ARENT, D. J., WISE, A. & GELMAN, R. 2011. The status and prospects of renewable energy for
   combating global warming. *Energy Economics*, 33, 584-593.
- AVERY, W. H. & WU, C. 1994. *Renewable energy from the ocean: a guide to OTEC*, Oxford university
   press.
- AZADI, A. & FIROOZABADI, B. 2022. New criterion for characterization of thermal-saline jets
   discharged from thermal desalination plants. *International Journal of Heat and Mass Transfer*, 195, 123142.
- BAKER, A. L., CRAIGHEAD, R. M., JARVIS, E. J., STENTON, H. C., ANGELOUDIS, A., MACKIE, L.,
   AVDIS, A., PIGGOTT, M. D. & HILL, J. 2020. Modelling the impact of tidal range energy on
   species communities. *Ocean & coastal management*, 193, 105221.
- BARLETTA, M., CYSNEIROS, F. & LIMA, A. 2016. Effects of dredging operations on the demersal
   fish fauna of a South American tropical-subtropical transition estuary. *Journal of fish biology*, 89, 890-920.
- BARNTHOUSE, L. W., FIETSCH, C.-L. & SNIDER, D. 2019. Quantifying restoration offsets at a
   nuclear power plant in Canada. *Environmental management*, 64, 593-607.
- BERGER, L. R. & BERGER, J. A. 1986. Countermeasures to microbiofouling in simulated ocean
   thermal energy conversion heat exchangers with surface and deep ocean waters in
   Hawaii. Applied and environmental microbiology, 51, 1186-1198.
- BLABER, S. J., CYRUS, D., ALBARET, J.-J., CHING, C. V., DAY, J., ELLIOTT, M., FONSECA, M., HOSS, D.,
   ORENSANZ, J. & POTTER, I. 2000. Effects of fishing on the structure and functioning of
   estuarine and nearshore ecosystems. *iCES Journal of marine Science*, 57, 590-602.
- BLENINGER, T., NIEPELT, A. & JIRKA, G. 2010. Desalination plant discharge calculator.
   *Desalination and Water Treatment*, 13, 156-173.

- BLYTH, R. E., KAISER, M. J., EDWARDS-JONES, G. & HART, P. J. 2004. Implications of a zoned
  fishery management system for marine benthic communities. *Journal of Applied Ecology*,
  41, 951-961.
- 841 BOEHLERT, G. W. & GILL, A. B. 2010. Environmental and ecological effects of ocean renewable 842 energy development: a current synthesis. *Oceanography*, 23, 68-81.
- BOEHLERT, G. W. & MUNDY, B. C. 1994. Vertical and onshore-offshore distributional patterns of
   tuna larvae in relation to physical habitat features. *Marine Ecology Progress Series*, 1-13.
   DOELIDER R. & SCHULTZE M. 2000. Stratification of labor. *Parisum of Coordinates Accessible*, 1000.
- 845 BOEHRER, B. & SCHULTZE, M. 2008. Stratification of lakes. *Reviews of Geophysics*, 46.
- BORDBAR, A., SHARIFI, S., GUO, Z. & HEMIDA, H. 2022a. Estimating the equilibrium scour depth
   around two side-by-side piers with different spacing ratios in live-bed conditions. *Ocean Engineering*, 257, 111641.
- BORDBAR, A., SHARIFI, S. & HEMIDA, H. 2021. Investigation of the flow behaviour and local scour
   around single square-shaped cylinders at different positions in live-bed. *Ocean Engineering*, 238, 109772.
- BORDBAR, A., SHARIFI, S. & HEMIDA, H. Numerical investigation of sand sliding methods for
   hydro-morphodynamic modelling. Proceedings of the Institution of Civil Engineers Maritime Engineering, 2022b. Thomas Telford Ltd, 1-11.
- 855 BOTT, T. R. 2011. *Industrial biofouling*, Elsevier.
- BRANDT, M. J., DIEDERICHS, A. & NEHLS, G. 2009. Harbour porpoise responses to pile driving at
   the Horns Rev II offshore wind farm in the Danish North Sea. *Final report to DONG Energy. Husum, Germany, BioConsult SH.*
- BUHAGIAR, D. & SANT, T. 2014. Steady-state analysis of a conceptual offshore wind turbine
  driven electricity and thermocline energy extraction plant. *Renewable energy*, 68, 853861 867.
- CAMP, C., LYNN, S., GEORGE, K., STRATER, N. & DORWART, B. 2019. HDD Design for Construction
   Ocean Outfall. *Pipelines 2019: Condition Assessment, Construction, and Rehabilitation.* American Society of Civil Engineers Reston, VA.
- CARDNO TEC. INC. 2014. Final environmental impact statement for the proposed Honolulu
   Seawater Air Conditioning Project, Honolulu, Hawaii. Honolulu: US Army Corps Of
   Engineers.
- CARPENTER, A. 2019. Oil pollution in the North Sea: the impact of governance measures on oil
   pollution over several decades. *Hydrobiologia*, 845, 109-127.
- CHAE, J., CHOI, H. W., LEE, W. J., KIM, D. & LEE, J. H. 2008. Distribution of a pelagic tunicate, Salpa
  fusiformis in warm surface current of the eastern Korean waters and its impingement on
  cooling water intakes of Uljin nuclear power plant. *J Environ Biol*, 29, 585-590.
- CHAMBERS, L. D., STOKES, K. R., WALSH, F. C. & WOOD, R. J. 2006. Modern approaches to marine
   antifouling coatings. *Surface and Coatings Technology*, 201, 3642-3652.
- CHEN, H., TANG, T., AÏT-AHMED, N., BENBOUZID, M. E. H., MACHMOUM, M. & ZAÏM, M. E.-H. 2018.
  Attraction, challenge and current status of marine current energy. *IEEE Access*, 6, 1266512685.
- CHEN, Y.-P., LI, C.-W., ZHANG, C.-K. & XU, Z.-S. 2012. Numerical study of a round buoyant jet under
   the effect of JONSWAP random waves. *China Ocean Engineering*, 26, 235-250.
- CHEN, Y. P., LI, C. W. & ZHANG, C. K. 2009. Experimental study on flow characteristics of round
  vertical buoyant jet under random waves. *Shuili Xuebao/Journal of Hydraulic Engineering*, 40, 1444-1451.
- CHUA, K. J., CHOU, S. K. & YANG, W. 2010. Advances in heat pump systems: A review. *Applied energy*, 87, 3611-3624.
- CIANI, J. 1978. Sea/Lake Water Cooling for Naval Facilities. CIVIL ENGINEERING LAB (NAVY)
   PORT HUENEME CALIF.

- CIPOLLINA, A., BRUCATO, A., GRISAFI, F. & NICOSIA, S. 2005. Bench-scale investigation of
   inclined dense jets. *Journal of Hydraulic Engineering*, 131, 1017-1022.
- COMFORT, C. M., MCMANUS, M. A., CLARK, S. J., KARL, D. M. & OSTRANDER, C. E. 2015.
  Environmental properties of coastal waters in Mamala Bay, Oahu, Hawaii, at the future
  site of a seawater air conditioning outfall. *Oceanography*, 28, 230-239.
- COMFORT, C. M. & VEGA, L. Environmental assessment for ocean thermal energy conversion in
   Hawaii: Available data and a protocol for baseline monitoring. OCEANS'11 MTS/IEEE
   KONA, 2011. IEEE, 1-8.
- COPPING, A. E., HEMERY, L. G., VIEHMAN, H., SEITZ, A. C., STAINES, G. J. & HASSELMAN, D. J. 2021.
   Are fish in danger? A review of environmental effects of marine renewable energy on
   fishes. *Biological Conservation*, 262, 109297.
- COSTA, M. F. & BARLETTA, M. 2015. Microplastics in coastal and marine environments of the
   western tropical and sub-tropical Atlantic Ocean. *Environmental Science: Processes & Impacts*, 17, 1868-1879.
- 901 CUNNINGHAM, J., MAGDOL, Z. & KINNER, N. 2010. Ocean thermal energy conversion: Assessing
   902 potential physical, chemical, and biological impacts and risks. *Coastal Response Research* 903 *Center, University of New Hamphsire, Durham, NH*, 33.
- DA SILVA, D. M. L., SOLANO, R. F., DE MEDEIROS, A. R., RODRIGUES, M. V. & DE AZEVEDO, F. B.
   Pipeline Shore Approach Installation by Horizontal Directional Drilling. International
   Conference on Offshore Mechanics and Arctic Engineering, 2013. American Society of
   Mechanical Engineers, V04BT04A005.
- DEEVEY, G. B. & BROOKS, A. L. 1971. THE ANNUAL CYCLE IN QUANTITY AND COMPOSITION OF
   THE ZOOPLANKTON OF THE SARGASSO SEA OFF BERMUDA. II. THE SURFACE TO 2,000
   m 1. Limnology and Oceanography, 16, 927-943.
- DEMPSTER, T. & TAQUET, M. 2004. Fish aggregation device (FAD) research: gaps in current
   knowledge and future directions for ecological studies. *Reviews in Fish Biology and Fisheries*, 14, 21-42.
- 914DEPROFUNDIS. 2016. Sea Water Air Conditioning: Services and Solutions (report) [Online].915Available:916http://www.deprofundis.com/wp-916content/uploads/2016/12/DPIEN October 2016.pdf. [Accessed].
- DEVAULT, D. A. & PÉNÉ-ANNETTE, A. 2017. Analysis of the environmental issues concerning the
   deployment of an OTEC power plant in Martinique. *Environmental Science and Pollution Research*, 24, 25582-25601.
- DILER, E., LARCHÉ, N. & THIERRY, D. 2020. Carbon Steel Corrosion and Cathodic Protection Data
   in Deep North Atlantic Ocean. *Corrosion*, 76.
- DORIS ENGINEERING 2022. Innovation: DORIS Engineering and Deprofundis conduct new tests
   for the SWAC.
- DRABSCH, S. L., TANNER, J. E. & CONNELL, S. D. 2001. Limited infaunal response to experimental trawling in previously untrawled areas. *ICES Journal of Marine Science*, 58, 1261-1271.
- DUCATEL, C., AUDOLY, C. & AUVRAY, C. Prediction of OTEC underwater radiated noise and
   assessment of noise disturbance on cetaceans. 1st Underwater Acoustics international
   conference and exhibition. Corfu, 2013.
- ELAHEE, K. & JUGOO, S. 2013. Ocean thermal energy for air-conditioning: Case study of a green
   data center. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* 35,
   679-684.
- ELSAFTY, A. & SAEID, L. 2009. Sea water air conditioning [SWAC]: a cost effective alternative.
   *International Journal of Engineering*, 3, 346-358.
- EMANI, M. S., ROY, R. & MANDAL, B. K. 2017. Development of refrigerants: a brief review. *Indian J. Sci. Res*, 14, 175-181.

- EUROSWAC. 2021. *Highly-efficient innovative shallow-water based Sea Water Air Conditioning solution for the Channel Area* [Online]. Available:
   https://euroswac.fr/?page id=834&lang=en [Accessed].
- 939 FANG, S., CHEN, Y. & XU, Z. 2019. WAVE AND CURRENT EFFECTS ON A BUOYANT JET: AN 940 INTEGRAL MODEL.
- FARR, H., RUTTENBERG, B., WALTER, R. K., WANG, Y.-H. & WHITE, C. 2021. Potential
  environmental effects of deepwater floating offshore wind energy facilities. *Ocean & Coastal Management*, 207, 105611.
- FAST, A. W., D'ITRI, F. M., BARCLAY, D. K., KATASE, S. A. & MADENJIAN, C. 1990. Heavy Metal
  Content of Coho Oncorhynchus kisutch and Chinook Salmon O. tschawytscha Reared in
  Deep Upwelled Ocean Waters in Hawaii 1. *Journal of the World Aquaculture Society*, 21,
  271-276.
- FEELY, R. A., SABINE, C. L., HERNANDEZ-AYON, J. M., IANSON, D. & HALES, B. 2008. Evidence for upwelling of corrosive" acidified" water onto the continental shelf. *science*, 320, 1490-1492.
- FERRARI, S., BADAS, M. G. & QUERZOLI, G. 2018. On the effect of regular waves on inclined
   negatively buoyant jets. *Water*, 10, 726.
- FERREIRA, G. V., BARLETTA, M., LIMA, A. R., MORLEY, S. A., JUSTINO, A. K. & COSTA, M. F. 2018.
  High intake rates of microplastics in a Western Atlantic predatory fish, and insights of a direct fishery effect. *Environmental Pollution*, 236, 706-717.
- FERRERA, C. M., JACINTO, G. S., CHEN, C.-T. A., SAN DIEGO-MCGLONE, M. L., DATOC, M. F. K. T.,
  LAGUMEN, M. C. T. & SENAL, M. I. S. 2017. Carbonate parameters in high and low
  productivity areas of the Sulu Sea, Philippines. *Marine Chemistry*, 195, 2-14.
- FITRIDGE, I., DEMPSTER, T., GUENTHER, J. & DE NYS, R. 2012. The impact and control of
  biofouling in marine aquaculture: a review. *Biofouling*, 28, 649-669.
- FLEMMING, H.-C. 1997. Reverse osmosis membrane biofouling. *Experimental thermal and fluid science*, 14, 382-391.
- FRICK, W. E. 2004. Visual Plumes mixing zone modeling software. *Environmental Modelling & Software*, 19, 645-654.
- FRID, C., ANDONEGI, E., DEPESTELE, J., JUDD, A., RIHAN, D., ROGERS, S. I. & KENCHINGTON, E.
   2012. The environmental interactions of tidal and wave energy generation devices. *Environmental Impact Assessment Review*, 32, 133-139.
- GALEA, M. & SANT, T. 2016a. Coupling of an offshore wind-driven deep sea water pump to an air
   cycle machine for large-scale cooling applications. *Renewable Energy*, 88, 288-306.
- GALEA, M. & SANT, T. 2016b. Using offshore wind technology for large-scale cooling applications.
   Wind Engineering, 40, 447-454.
- GEORGOULAS, K., HENNIGE, S. & LEE, Y. C. 2023. Smoothed Particle Hydrodynamics for modelling cold-water coral habitats in changing oceans. *Journal of Sea Research*, 102358.
- GILL, A. B. 2005. Offshore renewable energy: ecological implications of generating electricity in
   the coastal zone. *Journal of applied ecology*, 605-615.
- GILL, A. B., DEGRAER, S., LIPSKY, A., MAVRAKI, N., METHRATTA, E. & BRABANT, R. 2020. Setting
   the context for offshore wind development effects on fish and fisheries. *Oceanography*,
   33, 118-127.
- GOHAR ALI, H., VILANOVA ARBOS, R., HERRERA, J., TOBÓN, A. & PELÁEZ-RESTREPO, J. 2020.
   Non-linear sliding mode controller for photovoltaic panels with maximum power point tracking. *Processes*, 8, 108.
- GORMLEY, K., MCLELLAN, F., MCCABE, C., HINTON, C., FERRIS, J., KLINE, D. I. & SCOTT, B. E. 2018.
   Automated image analysis of offshore infrastructure marine biofouling. *Journal of Marine Science and Engineering*, 6, 2.

- GRIFFITH, G. P., FULTON, E. A. & RICHARDSON, A. J. 2011. Effects of fishing and acidification related benthic mortality on the southeast Australian marine ecosystem. *Global Change Biology*, 17, 3058-3074.
- HALL, R., JOÃO, E. & KNAPP, C. W. 2020. Environmental impacts of decommissioning: Onshore
   versus offshore wind farms. *Environmental Impact Assessment Review*, 83, 106404.
- HALPERN, B. S., FRAZIER, M., AFFLERBACH, J., LOWNDES, J. S., MICHELI, F., O'HARA, C.,
   SCARBOROUGH, C. & SELKOE, K. A. 2019. Recent pace of change in human impact on the
   world's ocean. *Scientific reports*, 9, 1-8.
- HARRISON, J. T. 1987. The 40 MWe OTEC plant at Kahe Point, Oahu, Hawaii: a case study of
   potential biological impacts, National Oceanic and Atmospheric Administration, National
   Marine Fisheries ....
- HASTINGS, M. C. & POPPER, A. N. 2005. Effects of sound on fish. California Department of
   Transportation.
- HATTEMER, B. & KAVANAUGH, S. P. 2005. Design Temperature Data for Surface Water Heating
   and Cooling Systems. *ASHRAE Transactions*, 111.
- HENNIG, P. & ZUR LINDE, L. Trenchless installation methods of Sea Outfalls. International
   Symposium on Outfall Systems, 2011. 15-18.
- HENNIGE, S., LARSSON, A., OREJAS, C., GORI, A., DE CLIPPELE, L., LEE, Y., JIMENO, G.,
  GEORGOULAS, K., KAMENOS, N. & ROBERTS, J. 2021. Using the Goldilocks Principle to
  model coral ecosystem engineering. *Proceedings of the Royal Society B*, 288, 20211260.
- HERRERA, J., SIERRA, S. & IBEAS, A. 2021. Ocean thermal energy conversion and other uses of
   deep sea water: A review. *Journal of Marine Science and Engineering*, 9, 356.
- HICKMAN, A. E., MOORE, C. M., SHARPLES, J., LUCAS, M. I., TILSTONE, G. H., KRIVTSOV, V. &
   HOLLIGAN, P. M. 2012. Primary production and nitrate uptake within the seasonal
   thermocline of a stratified shelf sea. *Marine Ecology Progress Series*, 463, 39-57.
- HIDDINK, J. G., KAISER, M. J., SCIBERRAS, M., MCCONNAUGHEY, R. A., MAZOR, T., HILBORN, R.,
   COLLIE, J. S., PITCHER, C. R., PARMA, A. M. & SUURONEN, P. 2020. Selection of indicators
   for assessing and managing the impacts of bottom trawling on seabed habitats. *Journal* of Applied Ecology, 57, 1199-1209.
- HIGUERA, P., LARA, J. L. & LOSADA, I. J. 2013. Realistic wave generation and active wave
  absorption for Navier–Stokes models: Application to OpenFOAM®. *Coastal Engineering*,
  71, 102-118.
- 1017 HOUGHTON, J. 2005. Global warming. *Reports on progress in physics*, 68, 1343.
- HOYT, J. & FURUYA, O. 1985. Cavitation and multiphase flow forum-1985. American Society of
   Mechanical Engineers, New York, NY.
- HUAI, W.-X., LI, Z.-W., QIAN, Z.-D., ZENG, Y.-H., HAN, J. & PENG, W.-Q. 2010. Numerical simulation
   of horizontal buoyant wall jet. *Journal of Hydrodynamics*, 22, 58-65.
- HUNT, J. D., BYERS, E. & SÁNCHEZ, A. S. 2019. Technical potential and cost estimates for seawater
   air conditioning. *Energy*, 166, 979-988.
- HUNT, J. D., WEBER, N. D. A. B., ZAKERI, B., DIABY, A. T., BYRNE, P., LEAL FILHO, W. & SCHNEIDER,
   P. S. 2021. Deep seawater cooling and desalination: Combining seawater air conditioning
   and desalination. *Sustainable Cities and Society*, 74, 103257.
- HUNT, J. D., ZAKERI, B., NASCIMENTO, A., GARNIER, B., PEREIRA, M. G., BELLEZONI, R. A., DE
   ASSIS BRASIL WEBER, N., SCHNEIDER, P. S., MACHADO, P. P. B. & RAMOS, D. S. 2020. High
   velocity seawater air-conditioning with thermal energy storage and its operation with
   intermittent renewable energies. *Energy Efficiency*, 13, 1825-1840.
- HUTCHISON, Z. L., SECOR, D. H. & GILL, A. B. 2020. The interaction between resource species and
   electromagnetic fields associated with electricity production by offshore wind farms.
   *Oceanography*, 33, 96-107.

- 1034 IGLESIAS, G., TERCERO, J. A., SIMAS, T., MACHADO, I. & CRUZ, E. 2018. Environmental effects.
   1035 Wave and tidal energy, 364-454.
- 1036 ILHAN-SUNGUR, E., UNSAL-ISTEK, T. & CANSEVER, N. 2015. Microbiologically influenced
   1037 corrosion of galvanized steel by Desulfovibrio sp. and Desulfosporosinus sp. in the
   1038 presence of Ag–Cu ions. *Materials chemistry and physics*, 162, 839-851.
- INGER, R., ATTRILL, M. J., BEARHOP, S., BRODERICK, A. C., JAMES GRECIAN, W., HODGSON, D. J.,
   MILLS, C., SHEEHAN, E., VOTIER, S. C. & WITT, M. J. 2009. Marine renewable energy:
   potential benefits to biodiversity? An urgent call for research. *Journal of applied ecology*,
   46, 1145-1153.
- ISAKSSON, N., MASDEN, E. A., WILLIAMSON, B. J., COSTAGLIOLA-RAY, M. M., SLINGSBY, J.,
  HOUGHTON, J. D. & WILSON, J. 2020. Assessing the effects of tidal stream marine
  renewable energy on seabirds: A conceptual framework. *Marine Pollution Bulletin*, 157,
  111314.
- 1047 ITANO, D. G. & HOLLAND, K. N. 2000. Movement and vulnerability of bigeye (Thunnus obesus)
  1048 and yellowfin tuna (Thunnus albacares) in relation to FADs and natural aggregation
  1049 points. *Aquatic Living Resources*, 13, 213-223.
- JANOTA, C. P. & THOMPSON, D. E. 1983. Waterborne noise due to ocean thermal energy conversion plants. *The Journal of the Acoustical Society of America*, 74, 256-266.
- JENKINS, J. F. 1978. Corrosion and Biofouling of OTEC System Surfaces-Design Factors. CIVIL
   ENGINEERING LAB (NAVY) PORT HUENEME CA.
- JIANG, B., LAW, A. W.-K. & LEE, J. H.-W. 2014. Mixing of 30 and 45 inclined dense jets in shallow
   coastal waters. *Journal of hydraulic engineering*, 140, 241-253.
- JIRKA, G. H. & DOMEKER, R. L. 1991. Hydrodynamic classification of submerged single-port
   discharges. *Journal of hydraulic engineering*, 117, 1095-1112.
- JUNG, H. & HWANG, J. 2014. Feasibility study of a combined ocean thermal energy conversion
   method in South Korea. *Energy*, 75, 443-452.
- KAISER, M. & JENNINGS, S. 2002. Ecosystem effects of fishing. *Handbook of fish biology and fisheries*. Blackwell Science.
- 1062 KHEIRKHAH GILDEH, H., MOHAMMADIAN, A., NISTOR, I. & QIBLAWEY, H. 2014. Numerical
   1063 modeling of turbulent buoyant wall jets in stationary ambient water. *Journal of Hydraulic* 1064 *Engineering*, 140, 04014012.
- KHEIRKHAH GILDEH, H., MOHAMMADIAN, A., NISTOR, I. & QIBLAWEY, H. 2015. Numerical modeling of 30 and 45 degree inclined dense turbulent jets in stationary ambient. *Environmental Fluid Mechanics*, 15, 537-562.
- 1068 KIM, H.-J. & KIM, A. S. 2020. Ocean Thermal Energy Conversion (OTEC): Past, Present, and Progress.
- 1069 KIM, J. & KIM, H.-J. 2014. Numerical Modeling Of OTEC Thermal Discharges In Coastal Waters.
- 1070 KIRSCHVINK, J. L. 1997. Homing in on vertebrates. *Nature*, 390, 339-340.
- LAI, C. C. & LEE, J. H. 2012. Mixing of inclined dense jets in stationary ambient. *Journal of hydro- environment research*, 6, 9-28.
- LANGHAMER, O., WILHELMSSON, D. & ENGSTRÖM, J. 2009. Artificial reef effect and fouling
   impacts on offshore wave power foundations and buoys-a pilot study. *Estuarine, coastal and shelf science,* 82, 426-432.
- LANGLOIS, T. J., ANDERSON, M. J. & BABCOCK, R. C. 2005. Reef-associated predators influence
   adjacent soft-sediment communities. *Ecology*, 86, 1508-1519.
- LARSEN, B. E. & FUHRMAN, D. R. 2018. On the over-production of turbulence beneath surface
   waves in Reynolds-averaged Navier–Stokes models. *Journal of Fluid Mechanics*, 853, 419 460.
- LEE, J. H.-W., CHU, V. & CHU, V. H. 2003. *Turbulent jets and plumes: a Lagrangian approach*,
   Springer Science & Business Media.

- 1083 LEWIS, L. F., VAN RYZIN, J. & VEGA, L. 1989. Steep slope seawater supply pipeline. *Coastal* 1084 *Engineering 1988.*
- LILLEY, J., KONAN, D. E., LERNER, D. & KARL, D. 2012. Potential Benefits, Impacts, and Public
   Opinion of seawater air conditioning in Waikiki.
- LILLEY, J., KONAN, D. E. & LERNER, D. T. 2015. Cool as a (sea) cucumber? Exploring public
  attitudes toward seawater air conditioning in Hawai 'i. *Energy Research & Social Science*,
  8, 173-183.
- LIMA, A., BARLETTA, M., COSTA, M., RAMOS, J., DANTAS, D., MELO, P., JUSTINO, A. & FERREIRA,
   G. 2016. Changes in the composition of ichthyoplankton assemblage and plastic debris in
   mangrove creeks relative to moon phases. *Journal of Fish biology*, 89, 619-640.
- LIU, L., WANG, M. & CHEN, Y. 2019. A practical research on capillaries used as a front-end heat
   exchanger of seawater-source heat pump. *Energy*, 171, 170-179.
- LU, Z., ZHAN, X., GUO, Y. & MA, L. 2020. Small-Scale Effects of Offshore Wind-Turbine Foundations
   on Macrobenthic Assemblages in Pinghai Bay, China. *Journal of Coastal Research*, 36, 139 147.
- MADDAH, H. & CHOGLE, A. 2017. Biofouling in reverse osmosis: phenomena, monitoring, controlling and remediation. *Applied Water Science*, 7, 2637-2651.
- MADSEN, P. T., WAHLBERG, M., TOUGAARD, J., LUCKE, K. & TYACK 2006. Wind turbine
   underwater noise and marine mammals: implications of current knowledge and data
   needs. *Marine ecology progress series*, 309, 279-295.
- MAGESH, R. OTEC technology-a world of clean energy and water. Proceedings of the World
   Congress on Engineering, 2010. WCE London, UK, 1-6.
- MAGIN, C. M., COOPER, S. P. & BRENNAN, A. B. 2010. Non-toxic antifouling strategies. *Materials today*, 13, 36-44.
- MAHTO, L. & PAL, D. Preparation and characterization of amphiphilic polymer coating for marine
   biofouling control. IOP Conference Series: Materials Science and Engineering, 2020. IOP
   Publishing, 012005.
- MAKAI OCEAN EEGINEERING INC. 2014a. OTEC Heat Exchanger Development and Testing. awaii
   Natural Energy Institute.
- 1112MAKAI OCEAN EEGINEERING INC. 2014b. OTEC HX Testing Program 2014 Annual Report1113[Online]. Available: https://tethys-engineering.pnnl.gov/publications/otec-xh-1114testingprogram-2014-annual-report [Accessed].
- 1115MAKAI OCEAN ENGINEERING INC. 2015a. New renewable energy report released: seawater air1116conditioning in the Caribbean (report). [Online]. Available:1117https://www.makai.com/makai-
- 1118 news/2015\_07\_24\_new\_renewable\_energy\_report\_released/ [Accessed].
- 1119MAKAI OCEAN ENGINEERING INC. 2015b. A Pre-Feasibility Study for Deep Seawater Air1120conditioning Systems in the Caribbean (report). [Online]. Available:1121http://scioteca.caf.com/handle/123456789/806 [Accessed].
- 1122 MAKAI OCEAN ENGINEERING INC. 2015c. A Pre-Feasibility Study for Deep Seawater Air 1123 conditioning Systems in the Caribbean (report).
- MAKHLOUF, A. S. H. & BOTELLO, M. A. 2018. Failure of the metallic structures due to
   microbiologically induced corrosion and the techniques for protection. *Handbook of Materials Failure Analysis*. Elsevier.
- MALINKA, C. E., GILLESPIE, D. M., MACAULAY, J. D., JOY, R. & SPARLING, C. E. 2018. First in situ
   passive acoustic monitoring for marine mammals during operation of a tidal turbine in
   Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, 247-266.
- MCHALE, F. Construction and deployment of an operational OTEC plant at Kona, Hawaii.
   Offshore technology conference, 1979. OnePetro.

- MCLUSKY, D. S., BRYANT, D. M. & ELLIOTT, M. 1992. The impact of land-claim on macrobenthos,
   fish and shorebirds on the forth estuary, eastern Scotland. *Aquatic conservation: marine and freshwater ecosystems*, 2, 211-222.
- 1135 MECKLING, J. 2018. The developmental state in global regulation: Economic change and climate 1136 policy. *European Journal of International Relations*, 24, 58-81.
- MICHELE, S., BORTHWICK, A. & VAN DEN BREMER, T. 2023. The laminar seabed thermal
   boundary layer forced by propagating and standing free-surface waves. *Journal of Fluid Mechanics*, 956, A11.
- MICHELE, S., STUHLMEIER, R. & BORTHWICK, A. 2021. Heat transfer in the seabed boundary
   layer. *Journal of Fluid Mechanics*, 928.
- MILLER, A., ROSARIO, T. & ASCARI, M. 2012. Selection and validation of a minimum-cost cold
   water pipe material, configuration, and fabrication method for ocean thermal energy
   conversion (OTEC) systems. *Proceedings of SAMPE*, 1-28.
- MITCHELL, M. S. & SPITLER, J. D. 2013. Open-loop direct surface water cooling and surface water
   heat pump systems—A review. *HVAC&R Research*, 19, 125-140.
- 1147 MITCHELL, R. & BENSON, P. H. 1980. Micro-and macrofouling in the OTEC program: an overview.
- MONTGOMERY, J. C., JEFFS, A., SIMPSON, S. D., MEEKAN, M. & TINDLE, C. 2006. Sound as an
   orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. *Advances in marine biology*, 51, 143-196.
- MOSSA, M. 2004. Experimental study on the interaction of non-buoyant jets and waves. *Journal of Hydraulic Research*, 42, 13-28.
- MYERS, E. P., HOSS, D. E., MATSUMOTO, W. M., PETERS, D. S., SEKI, M. P., UCHIDA, R. N., DITMARS,
  J. D. & PADDOCK, R. A. 1986. The potential impact of ocean thermal energy conversion
  (OTEC) on fisheries.
- NGUYEN, K. Q., MWISENEZA, C., MOHAMED, K., COUSIN, P., ROBERT, M. & BENMOKRANE, B.
   2021. Long-term testing methods for HDPE pipe-advantages and disadvantages: a review. *Engineering Fracture Mechanics*, 246, 107629.
- NI, X.-Y., FENG, W.-B., HUANG, S.-C., HU, Z.-J. & LIU, Y. 2020. An SPH wave-current flume using
   open boundary conditions. *Journal of Hydrodynamics*, 32, 536-547.
- NI, X., FENG, W., HUANG, S., ZHANG, Y. & FENG, X. 2018. A SPH numerical wave flume with non reflective open boundary conditions. *Ocean Engineering*, 163, 483-501.
- 1163OC'EANIDE.2022.Oc'eanide,aEuroSwacPartner.[Online].Available:1164https://euroswac.fr/?p=1417&lang=en [Accessed].
- 1165 ÖHMAN, M. C., SIGRAY, P. & WESTERBERG, H. 2007. Offshore windmills and the effects of 1166 electromagnetic fields on fish. *AMBIO: A journal of the Human Environment*, 36, 630-633.
- 1167 OWENS, W. & TRIMBLE, L. 1981. Mini-OTEC operational results.
- PALOMAR, P., LARA, J. & LOSADA, I. 2012. Near field brine discharge modeling part 2: Validation
   of commercial tools. *Desalination*, 290, 28-42.
- PANCHAL, C. & KNUDSEN, J. 1998. Mitigation of water fouling: technology status and challenges.
   Advances in Heat Transfer, 31, 431-474.
- PAT GRANDELLI, P., ROCHELEAU, G., HAMRICK, J. & CHURCH, M. 2012. Modeling the physical and biochemical influence of ocean thermal energy conversion plant discharges into their adjacent waters. Makai Ocean Engineering, Inc.
- PATRIZI, N., PULSELLI, R. M., NERI, E., NICCOLUCCI, V., VICINANZA, D., CONTESTABILE, P. &
   BASTIANONI, S. 2019. Lifecycle environmental impact assessment of an overtopping
   wave energy converter embedded in breakwater systems. *Frontiers in Energy Research*,
   7, 32.
- 1179 PELC, R. & FUJITA, R. M. 2002. Renewable energy from the ocean. *Marine Policy*, 26, 471-479.
- 1180 POURBAIX, M. 2012. Lectures on electrochemical corrosion, Springer Science & Business Media.

- PRYPUTNIEWICZ, R. & BOWLEY, W. 1975. An experimental study of vertical buoyant jets
   discharged into water of finite depth.
- RICHARDSON, A. J. & SCHOEMAN, D. S. 2004. Climate impact on plankton ecosystems in the
   Northeast Atlantic. *Science*, 305, 1609-1612.
- RISCH, D., VAN GEEL, N., GILLESPIE, D. & WILSON, B. 2020. Characterisation of underwater
   operational sound of a tidal stream turbine. *The Journal of the Acoustical Society of America*, 147, 2547-2555.
- 1188 RITCHIE, H. & ROSER, M. 2021. Electricity production by source, world.
- 1189 ROBERTS, P. J., FERRIER, A. & DAVIERO, G. 1997. Mixing in inclined dense jets. *Journal of* 1190 *Hydraulic Engineering*, 123, 693-699.
- 1191ROBERTS, P. J. & TOMS, G. 1987. Inclined dense jets in flowing current. Journal of Hydraulic1192Engineering, 113, 323-340.
- RODRÍGUEZ-OCAMPO, P. E., RING, M., HERNÁNDEZ-FONTES, J. V., ALCÉRRECA-HUERTA, J. C.,
   MENDOZA, E. & SILVA, R. 2020. CFD simulations of multiphase flows: Interaction of
   miscible liquids with different temperatures. *Water*, 12, 2581.
- 1196RUCKER, J. & FRIEDL, W. Potential impacts from OTEC-generated underwater sounds.1197OCEANS'85-Ocean Engineering and the Environment, 1985. IEEE, 1279-1283.
- 1198RYU, Y., CHANG, K.-A. & MORI, N. 2005. Dispersion of neutrally buoyant horizontal round jet in1199wave environment. Journal of Hydraulic Engineering, 131, 1088-1097.
- SAMUEL, D. L., NAGENDRA, S. S. & MAIYA, M. 2013. Passive alternatives to mechanical air
   conditioning of building: A review. *Building and Environment*, 66, 54-64.
- SANT, T., BUHAGIAR, D. & FARRUGIA, R. N. Offshore floating wind turbine-driven deep sea water
   pumping for combined electrical power and district cooling. Journal of Physics:
   Conference Series, 2014. IOP Publishing, 012074.
- SANT, T. & FARRUGIA, R. N. Performance modelling of an offshore floating wind turbine-driven
   deep sea water extraction system for combined power and thermal energy production:
   a case study in a central Mediterranean context. International Conference on Offshore
   Mechanics and Arctic Engineering, 2013. American Society of Mechanical Engineers,
   V008T09A044.
- SARBU, I. & SEBARCHIEVICI, C. 2014. General review of ground-source heat pump systems for
   heating and cooling of buildings. *Energy and buildings*, 70, 441-454.
- SAYED, E. T., WILBERFORCE, T., ELSAID, K., RABAIA, M. K. H., ABDELKAREEM, M. A., CHAE, K.-J.
  & OLABI, A. 2021. A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal. *Science of the total environment*, 766, 144505.
- SCHROEDER, K., RIBOTTI, A., BORGHINI, M., SORGENTE, R., PERILLI, A. & GASPARINI, G. 2008.
   An extensive western Mediterranean deep water renewal between 2004 and 2006.
   *Geophysical Research Letters*, 35.
- SCOTT, K., HARSANYI, P. & LYNDON, A. R. 2018. Understanding the effects of electromagnetic
   field emissions from Marine Renewable Energy Devices (MREDs) on the commercially
   important edible crab, Cancer pagurus (L.). *Marine Pollution Bulletin*, 131, 580-588.
- 1222 SEYFRIED, C., PALKO, H. & DUBBS, L. 2019. Potential local environmental impacts of salinity 1223 gradient energy: A review. *Renewable and Sustainable Energy Reviews*, 102, 111-120.
- SHADMAN, M., AMIRI, M. M., SILVA, C., ESTEFEN, S. F. & LA ROVERE, E. 2021. Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil. *Renewable and Sustainable Energy Reviews*, 144, 110994.
- SHAO, D. & LAW, A. W.-K. 2010. Mixing and boundary interactions of 30 and 45 inclined dense
   jets. *Environmental fluid mechanics*, 10, 521-553.
- SHARP, J., VYAS, B. & FROUDE 1977. The buoyant wall jet. *Proceedings of the Institution of Civil Engineers*, 63, 593-611.

- SHARP, J. J. 1975. THE USE OF A BUOYANT WALL JET TO IMPROVE THE DILLUTION OF A
   SUBMERGED OUTFALL. Proceedings of the Institution of Civil Engineers, 59, 527-534.
- SHIFLER, D. A. Environmental Effects on Flow-Assisted Corrosion in Naval Systems. CORROSION
   99, 1999. OnePetro.
- SHIFLER, D. A. 2005. Understanding material interactions in marine environments to promote
   extended structural life. *Corrosion Science*, 47, 2335-2352.
- SMEBYE, H., MIDTTØMME, K. & STENE, J. 2011. Energi fra overflatevann i Norge-kartlegging av
   økonomisk potensial.
- SOBEY, R. J., JOHNSTON, A. J. & KEANE, R. D. 1988. Horizontal round buoyant jet in shallow water.
   *Journal of Hydraulic Engineering*, 114, 910-929.
- SOINI, M., BÜRER, M., MENDOZA, D., PATEL, M., RIGTER, J. & SAYGIN, D. 2017. Renewable Energy
   in District Heating and Cooling: A Sector Roadmap for Remap. *International Renewable Energy Agency, Abu Dhabi.*
- SOUTHALL, B. L., BOWLES, A. E., ELLISON, W. T., FINNERAN, J. J., GENTRY, R. L., GREENE JR, C. R.,
   KASTAK, D., KETTEN, D. R., MILLER, J. H. & NACHTIGALL, P. E. 2008. Marine mammal
   noise-exposure criteria: initial scientific recommendations. *Bioacoustics*, 17, 273-275.
- SÖZEN, A., NEŞER, G. & BENGISU, M. 2022. Effect of the geometry on the structural performance
  of high-density polyethylene small craft joints. *Ships and Offshore Structures*, 17, 19391946.
- 1250 STOEV, L., GEORGIEV, P. & GARBATOV, Y. 2018. Offshore sulfide power plant for the Black Sea.

1251 SU, C., MADANI, H., LIU, H., WANG, R. & PALM, B. 2020. Seawater heat pumps in China, a spatial 1252 analysis. *Energy Conversion and Management*, 203, 112240.

- SWARTZ, J. T. 2020. "Underground, under Where?" How Many Communities Are Turning to
   Trenchless Applications to Solve Their Challenges. *Pipelines 2020.* American Society of
   Civil Engineers Reston, VA.
- 1256 TALLEY, L. D. 2011. *Descriptive physical oceanography: an introduction*, Academic press.
- TAORMINA, B., BALD, J., WANT, A., THOUZEAU, G., LEJART, M., DESROY, N. & CARLIER, A. 2018.
   A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, 96, 380-391.
- TOUGAARD, J., HERMANNSEN, L. & MADSEN, P. T. 2020. How loud is the underwater noise from
   operating offshore wind turbines? *The Journal of the Acoustical Society of America*, 148,
   2885-2893.
- 1264 ULLAH, N., ALI, M. A., IBEAS, A. & HERRERA, J. 2017. Adaptive fractional order terminal sliding
   mode control of a doubly fed induction generator-based wind energy system. *IEEE* 1266 Access, 5, 21368-21381.
- VAHIDI, E., JIN, E., DAS, M., SINGH, M. & ZHAO, F. 2016. Environmental life cycle analysis of pipe
   materials for sewer systems. *Sustainable Cities and Society*, 27, 167-174.
- VAN DALFSEN, J., ESSINK, K., MADSEN, H. T., BIRKLUND, J., ROMERO, J. & MANZANERA, M. 2000.
   Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. *ICES Journal of Marine Science*, 57, 1439-1445.
- VAN RYZIN, J. & LERAAND, T. Air conditioning with deep seawater; a reliable, cost effective
   technology. OCEANS 91: ocean technologies and opportunities in the Pacific for the 90's,
   October 1-3, 1991, Honolulu HI, 1991.
- 1275 VIDELA, H. A. & CHARACKLIS, W. G. 1992. Biofouling and microbially influenced corrosion.
   1276 International Biodeterioration & Biodegradation, 29, 195-212.
- VON HERZEN, B., THEURETZBACHER, T., NEWMAN, J., WEBBER, M., ZHU, C., KATZ, J. S. &
   RAMASWAMY, M. A feasibility study of an integrated air conditioning, desalination and
   marine permaculture system in Oman. ICTEA: International Conference on Thermal
   Engineering, 2017.

- WAR, J. C. Seawater Air Conditioning (SWAC) a renewable energy alternative. OCEANS'11
   MTS/IEEE KONA, 2011. IEEE, 1-9.
- 1283 WEBB, P. 2021. *Introduction to oceanography*, Roger Williams University.
- 1284 WESTERBERG, H. & LAGENFELT, I. 2008. Sub-sea power cables and the migration behaviour of 1285 the European eel. *Fisheries Management and Ecology*, 15, 369-375.
- WHITEHEAD, D. & COLLIN, S. 2004. The functional roles of passive electroreception in non electric fishes. *Animal Biology*, 54, 1-25.
- WILBERFORCE, T., EL HASSAN, Z., DURRANT, A., THOMPSON, J., SOUDAN, B. & OLABI, A. G. 2019.
  Overview of ocean power technology. *Energy*, 175, 165-181.
- WILLIAMSON, B., FRASER, S., WILLIAMSON, L., NIKORA, V. & SCOTT, B. 2019. Predictable
   changes in fish school characteristics due to a tidal turbine support structure. *Renewable Energy*, 141, 1092-1102.
- WU, Z., YOU, S., ZHANG, H. & ZHENG, W. 2020. Model development and performance investigation of staggered tube-bundle heat exchanger for seawater source heat pump.
   *Applied Energy*, 262, 114504.
- XU, Z., CHEN, Y. & PAN, Y. 2018. Initial dilution equations for wastewater discharge: Example of
   non-buoyant jet in wave-following-current environment. *Ocean Engineering*, 164, 139 147.
- XU, Z., CHEN, Y., TAO, J., PAN, Y., SOWA, D. M. & LI, C.-W. 2016. Three-dimensional flow structure
  of a non-buoyant jet in a wave-current coexisting environment. *Ocean Engineering*, 116,
  42-54.
- XU, Z., CHEN, Y., WANG, Y. & ZHANG, C. 2017. Near-field dilution of a turbulent jet discharged
   into coastal waters: Effect of regular waves. *Ocean Engineering*, 140, 29-42.
- XU, Z., OTOO, E., CHEN, Y. & DING, H. 2019. 2D PIV measurement of twin buoyant jets in wavy
   cross-flow environment. *Water*, 11, 399.
- YU, J., LIU, Z. & LI, Y. Optimization of Thermal Discharge Scheme for the Phase II Project of Rizhao
   Power Plant. 2009 Asia-Pacific Power and Energy Engineering Conference, 2009. IEEE,
   1308 1-4.
- ZENG, Q., GU, X., CHEN, X. & MAO, Z. 2013. The impact of Chinese mitten crab culture on water
   quality, sediment and the pelagic and macrobenthic community in the reclamation area
   of Guchenghu Lake. *Fisheries Science*, 79, 689-697.
- 1312ZHANG, W., LI, Y., WU, X. & GUO, S. 2018. Review of the applied mechanical problems in ocean1313thermal energy conversion. *Renewable and Sustainable Energy Reviews*, 93, 231-244.
- 1314 ZHAO, M., YAO, D., LI, S., ZHANG, Y. & AWEYA, J. J. 2020. Effects of ammonia on shrimp physiology
   1315 and immunity: a review. *Reviews in Aquaculture*, 12, 2194-2211.
- ZHEN, L., LIN, D., SHU, H., JIANG, S. & ZHU, Y. 2007. District cooling and heating with seawater as
   heat source and sink in Dalian, China. *Renewable energy*, 32, 2603-2616.
- ZHENG, W., YE, T., YOU, S. & ZHANG, H. 2015. The thermal performance of seawater-source heat
   pump systems in areas of severe cold during winter. *Energy conversion and management*,
   90, 166-174.
- 1321