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WILL OCEAN ENERGY HARM MARINE ECOSYSTEMS?

Linus Hammar
Department of Energy and Environment, Chalmers University of Technology*

* Division of Environmental Systems Analysis
Chapter reviewers: Anders Arvesen, Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology; Björn Sandén, Environmental Systems Analysis, Energy and Environment, Chalmers.

INTRODUCTION

Human activity tends to excavate the natural capital and degrade the ecosystem services on which civilization depends. For long-term sustainability a more proactive resource management is needed.[1] Since natural and social systems are complex, environmental impacts of new technologies can be very difficult to predict beforehand, but once technical systems have spread and have become widely accepted they tend to be hard to control. Will ocean energy development be a safe path towards sustainable power production, or will it inflict additional burden on already deprived marine life? In this chapter it will be argued that the answer is much dependent on adaptive engineering and prospective planning.

AN OCEAN FULL OF ENERGY

Ocean energy targets energy from within the ocean and commonly refers to tidal current energy, wave energy, ocean current energy, and ocean thermal energy conversion (OTEC), see Figure 8.1.[2] Although some full-scale devices have been deployed, ocean energy is not yet technically mature and fully commercial installations are yet to be installed (Chapter 4). While there are diverging views on the potential contribution of ocean energy to global power generation, it seems clear that in specific geographical areas ocean energy may contribute significantly to electricity supply, with expected commercial breakthroughs beyond 2020 (Chapter 3).[3]

1 MEA (2005) *Ecosystems and Human Well-being: Synthesis. Millennium Ecosystem Assessment,* Washington DC, USA: Island Press.

2 Ocean energy also comprises salinity gradient energy and tidal barrages but these technologies have not been included in this chapter as they seemingly are farther from expansive growth.

3 Esteban, M. and Leary, D. (2012) Current developments and future prospects of offshore wind and ocean energy. *Applied Energy,* 90:128-136. See also Chapter 3.

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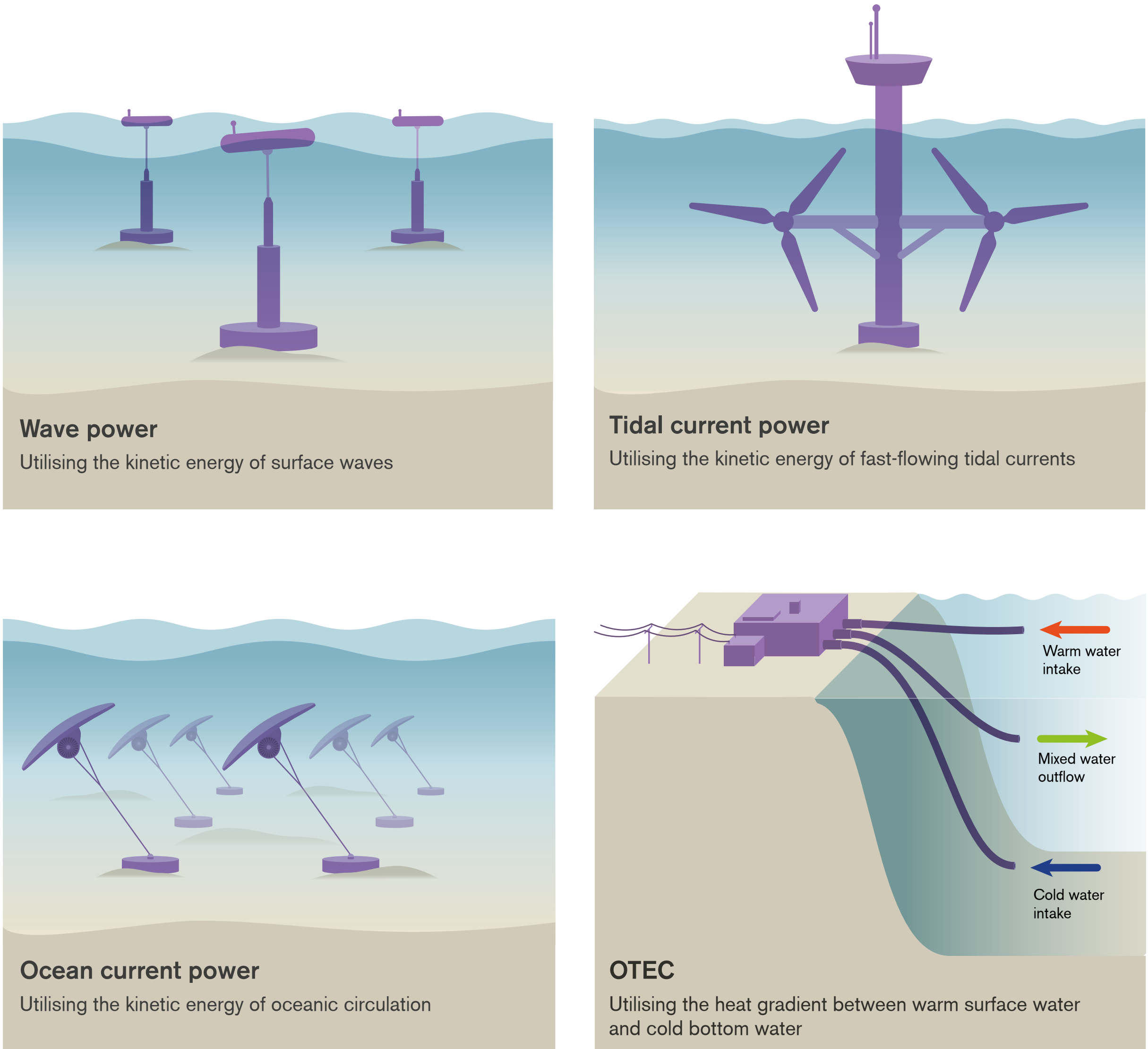

Figure 8.1 Conceptual illustrations of ocean energy technologies. Arrows indicate water flow directions. The illustrated technologies are not-to-scale examples of a large number of prototypes under development.

To large extent the extractable resource potential is limited by environmental considerations such as the risk of affecting ocean circulation patterns and local oceanography. Ocean energy resources are available across the globe, including both developing countries with rampant energy demand and industrialised countries in need of diversifying power generation.[4] Northern North America, north-western Europe and East Asia have plenty of tidal energy hotspots. West-facing coasts in the northern hemisphere and east-facing coasts in the southern hemisphere are typically exposed to high wave power. Many tropical islands and coasts with narrow continental shelves, particularly in western parts of the Pacific Ocean, have optimal conditions for OTEC technology (Figure 3.4). Should the future hold a serious utilisation of these potential power sources, ocean energy installations would become common at many locations and, as any marine activity, to some level affect marine ecosystems.

4 World Energy Council, W.E.C (2010) *2010 Survey of Energy Resources.* London, UK: World Energy Council.

AN OCEAN UNDER PRESSURE

Since prehistoric time humans have used the ocean for food and transport. By the time of the industrial revolution the ocean had played a major role for trade and economic growth, but pressure on the marine ecosystems was still limited and spatially confined. It was with the introduction of steam and later combustion engines in ships and fishing vessels that pressure intensified. By 1950, several fish stocks were overexploited and whale stocks collapsed on a global scale. Post World War II a tremendous intensification of fishing was made possible by new technologies such as the sonar systems and satellite navigation, and by governmental subsidies of fisheries. Moreover, offshore oil extraction, aquaculture, and coastal recreation added to ecosystem pressure along with marine pollution and nutrient rich agricultural runoff to coastal ecosystems. Around the millennium shift a third of the global fish stocks were overexploited or even collapsed; 90% of large predatory fish had disappeared; more than 40% of all coastal seas were heavily affected by human activity; and throughout the world there were no longer any unaffected corners of the ocean.[5]

Due to the 'shifting baseline' phenomenon[6] there is no longer a common memory of how many and how large fish that could be caught by the nearby beach a few decades ago and pristine marine ecosystems are no longer reference points. Unfortunately, there is little reason to believe that this degradation will come to a halt anytime soon.[7]

This is the background we have to keep in mind when trying to assess what would be the consequences of introducing ocean energy technologies. As will be discussed, the full effect of ocean energy or any other potential stressor to the environment can only be grasped with consideration of food-web interactions and cumulative effects. However, first we need to understand the direct environmental impacts of different ocean energy technologies.

ECOLOGICAL IMPACTS OF OCEAN ENERGY – WHAT DO WE KNOW?

Given that ocean energy is in such an early phase there is still a scarcity of scientific knowledge regarding its environmental effects. While some potential impacts are technology-specific, others are general and can be foreseen by considering effects of existing marine activities. Figure 8.2 illustrates the potential stressors from the ocean energy systems considered here, together with stressors from some other marine and coastal activities. Below follows a synthesis of the current understanding of environmental effects from ocean energy.

Offshore installations – ocean energy or other – mean that new hard substrate is introduced and that part of the previous habitat is removed. The new substrates of steel or concrete will be colonised by some species on the cost of species that prefer soft bottoms like mud and sand. In general, hard substrates are rare in marine ecosystems and in some areas natural hard substrates have been removed by years of trawling. The introduction of hard substrates, even if being artificial, can

5 Smith, H.D. (2000) The industrialisation of the world ocean. *Ocean & Coastal Management,* 43:11-28; Halpern, B.S. et al. (2008) A Global Map of Human Impact on Marine Ecosystems. *Science,* 319:948-952.; Jackson, J.B.C. (2008) Ecological extinction and evolution in the brave new ocean. *Proceedings of the National Academy of Sciences,* 105:11458-11465.

6 Pauly, D. (1995) Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology & Evolution,* 10:430.

7 Jackson, J.B.C. (2008); Pitcher, T.J. and Cheung, W.W.L. (2013) Fisheries: Hope or despair? *Marine Pollution Bulletin,* 74:506-516.

often be considered beneficial. For instance, it is shown that many fish, crayfish, and molluscs thrive at offshore wind power foundations where they find food and protection.[8] It is likely that analogous ocean energy foundations will have similar beneficial effects.

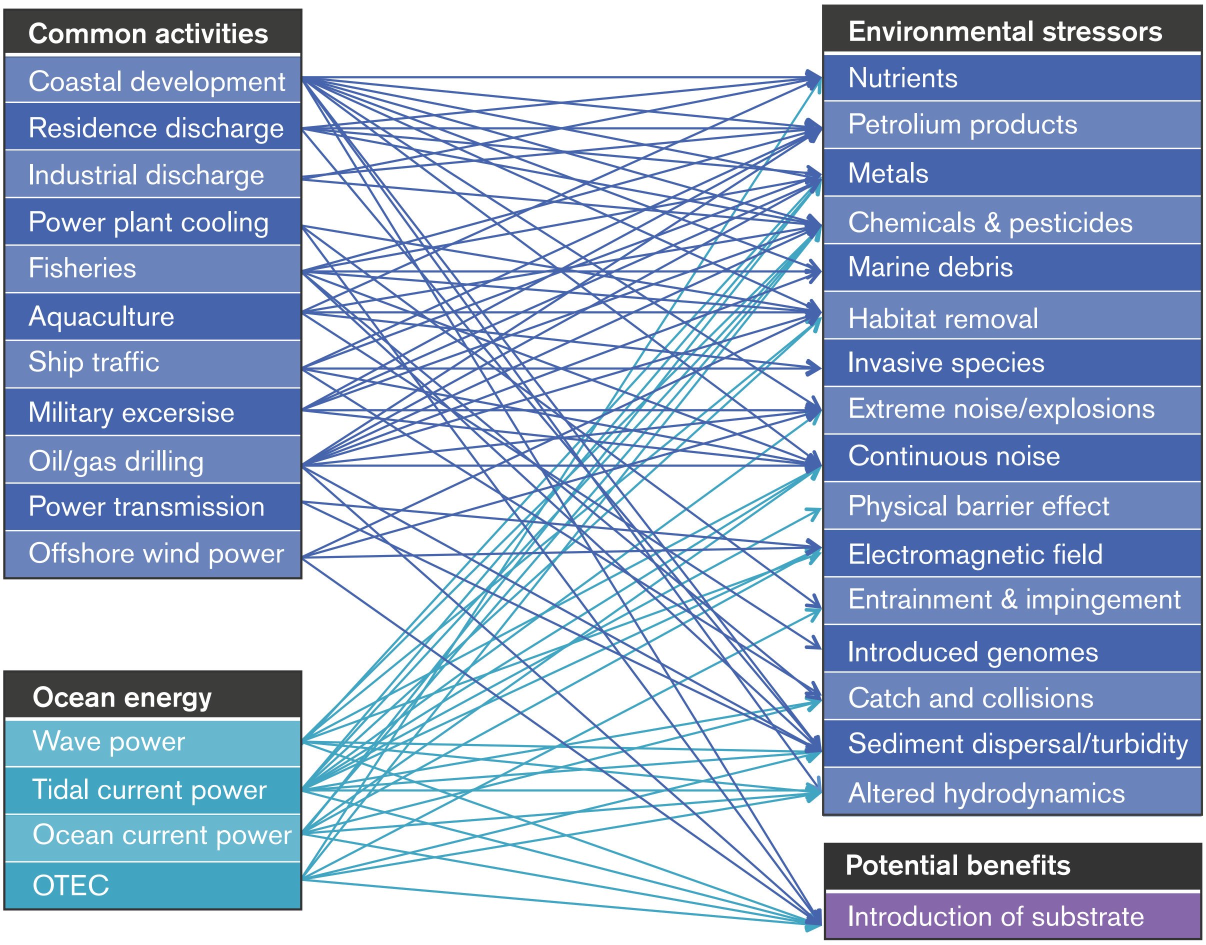

Figure 8.2 Environmental stressors and potential ecological benefits caused by some common marine and coastal human activities (blue arrows) and as proposed for ocean energy technologies (teal arrows). The illustration intend to broadly depict the situation of many concurrent activities inflicting similar stressors to the marine environment.

Noise emissions from operating turbines can be detected by fish and marine mammals. Tidal current turbines emit more noise (160-180 dB re 1 μPa at 1 m) than offshore wind power (130-150 dB re 1 μPa at 1 m) but less than cargo ships (185-195 dB re 1 μPa at 1 m). Wave power and OTEC are expected to emit lower noise levels (<140 dB re 1 μPa at 1 m). It has been argued that the noise from ocean energy and offshore wind power under certain conditions and for some species can cause stress and masking of animal communication.[9] Behavioural changes have been observed in laboratory experiments where animals were exposed to playback of noise corresponding to that created by turbines at a distance of about

8 Reubens, J. et al. (2010) The importance of marine wind farms, as artificial hard substrata, for the ecology of the ichthyo fauna. In *Offshore wind farms in the Belgian part of the North Sea: early environmental impact assessment and spatio-temporal variability* (eds S. Degraer et al.). 69-82. Brussels, Belgium: Royal Belgian Institute of Natural Sciences; Andersson, M.H. (2011) Offshore wind farms - ecological effects of noise and habitat alternation on fish. Doctoral thesis, Stockholm University; Bergström, et al. (2013) Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progess Series,* 485:199-210.

9 Slabbekoorn, H. et al. (2010) A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology and Evolution,* 25(7):419-427.

ten metres, but empirical evidence from the field is still inconclusive. A recent study shows that codfish are in good health around offshore wind power foundations and any negative impacts from operational noise are likely to be small and subtle.[10]

Other generic stressors from offshore installations are construction-related noise, dredging, and electromagnetic fields from power transmission. There is substantial evidence showing that pile-driving, which is used for mooring of for example tidal current turbines, can have detrimental impacts on individual fish and marine mammals.[11] Pulses of extreme sound may damage the swim bladder and hearing organs at a close distance, and the pulses can be detected by the animals over a distance of tens of kilometres. Dredging, if carried out in fine-grain sediment, may clog the gills of fish and reduce the survival among fish eggs and larvae. Effects of electromagnetic fields have been less studied, but fields from ocean energy cables can be detected by highly specialised animals like eels and elasmobranchs (sharks and rays). For these animals unburied cables may cause disorientation or disturbed forage behaviour. All the above mentioned stressors can to some degree be mitigated, for instance by choosing an appropriate foundation concept, by dampening pile-driving, by using silt curtains to reduce sediment dispersal, or by burying transmission cables so that the electromagnetic fields not reach out to the water. In addition, impacts to particular ecological values (e.g. endangered species) can sometimes be avoided simply by scheduling construction events out of biologically sensitive periods, such as spawning and migration seasons.[12]

Wave power is often considered environmentally benign and hitherto there are no studies indicating detrimental environmental impacts from the – very few – devices that have been in operation. It has however been postulated that floating wave power buoys may attract migrating and foraging birds and may, especially in rough sea conditions, entangle marine mammals. If wave power devices do affect the movability of birds and mammals, large wave power farms may have an impact on their migratory routes. Other possible effects of wave power concern dampening of local wave climate, affecting the vertical mixing of water and sediment transport and coastal erosion. This concern is site dependent as the beach morphology at many typical wave power locations is continuously shifting due to natural wave exposure variation. Therefore, wave power impact on erosion would not always be of concern.

Some *tidal current turbines* have rotor blades moving at speeds above 10 m/s through turbid waters with low visibility. This rotor speed is fast in relation to the swimming speed of most marine mammals, diving birds and fish and collision risks have been much discussed but rarely investigated. A recent study of daytime effects of a small tidal turbine on fish showed that all present fish avoided collision with the rotor and that there was a general decrease in the number of fish passing through the near-field of the rotor compared to fish movements through

10 Reubens, J.T. et al. (2013) Offshore wind farms as productive sites or ecological traps for gadoid fishes? – Impact on growth, condition index and diet composition. *Marine Environmental Research,* 90:66-74.

11 Popper, A.N. and Hastings, M.C. (2009) The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology,* 75:455-489.

12 Hammar, L. et al. (2008) *Adapting offshore wind power foundations to local environment.* Bromma, Sweden: Vindval, The Swedish Environmental Protection Agency (Report 6367).; Hammar, L. et al. (2014) Assessing ecological risks of offshore wind power on Kattegat cod. *Renewable Energy,* 66:414-424.

the same place when the rotor was removed.[13] It was shown that small reef fish dared to pass close to the rotor while large predatory fish kept a larger distance from the rotor. A study at another turbine, similar in size and design but differently positioned, showed that some small fish were swept into the turbine while others managed to swim away.[14] The amount of fish failing to avoid the turbine was larger during the night than during the day, indicating that avoidance success is related to water visibility. When it comes to large tidal turbines collisions is likely more difficult to avoid for the animals but no empirical studies have been presented. Probabilistic models of collision risks around large tidal turbines raise concerns though, as substantial losses of fish and marine mammals due to collisions have been calculated.[15] But since these probabilistic models do not account for active avoidance manoeuvres among the animals, the alarming results are likely to be exaggerated. Field observations of fish fauna in strong currents also indicate that the number of fish is low in the strongest currents, where turbines would be operating. Research and monitoring on animal behaviour around tidal turbines are needed. But even if collisions are rare, large tidal power arrays may have a barrier effect on large animals and multiple-turbine installations should therefore be designed with apposite migration passages between turbines.

Large tidal current power installations may also affect local hydrodynamics and thus the sediment characteristics in the area. Such alternation of hydrodynamic regimes could have large ecosystem effects and must be avoided.[16] For this and technical reasons it is usually suggested that tidal power should not extract more than about 10% of the natural flow at a given location.

Ocean current power target slower currents and deeper water than tidal power (Figure 3.2). Most turbines therefore resemble tidal current turbines, but of much larger size. Consequently, the ocean current turbines are subject to similar collision risk principles as for tidal current power. But even though the rotor blades are large the slower ocean currents ensure that most vertebrate animals will have great chance to swim away from the hazard. An interesting and different ocean current power development is the Deep Green[17] device, where a 12 m wide underwater kite carries the turbine in a trajectory transverse to the current in order to increase the water flow over the rotor. The response and ability of avoidance among fish and marine mammals approaching such a device have not yet been investigated and the uncertainties are worrisome.

Ocean Thermal Energy Conversion (OTEC) has been tested at small scale and larger plants are projected at several locations but due to the high investment costs no commercial power plants, or power plants larger than 1 MW, have yet

13 Hammar, L. et al. (2013) Hydrokinetic Turbine Effects on Fish Swimming Behaviour. *PLoS ONE,* 8:e84141.

14 Viehman, H.A. (2012) *Fish in tidally dynamic region in Maine: Hydroacoustic assessments in relation to tidal power development.* Master thesis, The University of Maine.

15 Wilson, B. et al. (2007) *Collision risks between marine renewable energy devices and mammals, fish and diving birds - Report to the Scottish Executive.* Oban, UK: Scottish Association for Marine Science.; Hammar, L. and Ehnberg, J. (2013). Who should be afraid of a tidal turbine - the good, the bad or the ugly? *10th European Wave and Tidal Energy Conference (EWTEC)*, Aalborg, Denmark, Sep. 2-5.

16 Shields, M.A. et al. (2011) Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment. *Ocean & Coastal Management,* 54:2-9.

17 The Deep Green turbine is developed by Minesto. See Minesto (2014).

been constructed. OTEC power plants utilise the vertical heat difference of tropical seas to produce power as well as desalinated water. This is made possible by heat exchange technology using large amounts of water from the cold deep sea and the warm surface and a working fluid that is vaporised and forced through turbines. The water intake of a 100 MW OTEC plant would be about 300 and 400 $m^3 s^{-1}$ at deep sea and surface respectively (for comparison the cooling water intake of a 1 GW nuclear power plant is about 75 $m^3 s^{-1}$). The number of entrained and impinged organisms can therefore be large. While such damage could be mitigated by effective screens around the intake pipes it is considered more difficult to prevent entrainment of planktonic eggs and larvae. Thus substantial losses of various recruits are expected and have been shown during pilot plant experiments.

Another possibly severe environmental impact from OTEC is the alternation of hydrological conditions, such as changes in temperature, acidity and salinity, and increase of nutrients in the surface water due to mixing with nutrient rich deep water. Increase of nutrients can lead to eutrophication which in oligotrophic tropical ecosystems can have detrimental effects on important coastal ecosystems such as coral reefs and seagrass beds. If the OTEC discharge water is released at a sufficient depth such effects can be avoided, at the expense of higher installation costs.

In summary, some ocean energy technologies raise more environmental concerns than others. To the current level of understanding it seems reasonable to believe that wave power and small-scale tidal current devices are unlikely to have negative environmental impact while the benevolence of large scale tidal power, ocean current power, and OTEC will be much depending on design and local ecological conditions.

WHAT TO DO WITH THE UNKNOWNS?

As discussed above there are still many unknowns related to the potential environmental effects from ocean energy. Because awareness of environmental issues is more developed now than it was when earlier marine activities were introduced in the ocean, the many unknowns about environmental impacts of ocean energy pose a barrier for achieving legal consent. The precautionary principle often implies that developers need to show with confidence that significant impacts will not occur. This requires either extensive applied research or long-term monitoring. Among ocean energy developers this is often considered a difficult quandary to overcome in the early phase of technical development. Therefore, the ability of making robust environmental impact assessments despite incomplete information is important.

On the project level, existing knowledge on analogous stressors can be used to predict the effects from new stressor sources (here: ocean energy technologies) by applying for instance weight-of-evidence methodology.[18] Weight-of-evidence imply that hypothetical cause-effect chains, that is, how ocean energy devices possibly can cause effects on ecological receptors, are described on the basis of arguments referring to experience from other stressors (e.g. shipping or offshore

18 Hammar, L. et al. (2014) Assessing ecological risks of offshore wind power on Kattegat cod. *Renewable Energy,* 66:414-424.

wind power). These arguments are graded on the basis of their scientific foundation. Then contradicting arguments, advocating that there is no cause-effect relationship, are added and similarly graded. By comparing the reliability among arguments it can be concluded whether a cause-effect relationship is likely, unlikely or still undecided. Each cause-effect relationship will also be assigned with a maximum temporal and spatial range that can be used to calculate the worst-case magnitude of effect.

A more quantitative approach to assessment uncertainties is to model potential impacts using Monte-Carlo simulations, where probabilistic distributions of unknown parameters are assigned instead of arbitrary means. This method allows for an assessment output with confidence intervals, though some level of understanding of the input parameters is of course required.

Once a quantity of effected environmental receptors has been estimated it is important to relate this effect magnitude to population dynamics for an understanding of how important the effect may be. For example, the removal of tens of thousands of herrings or hundred acres of soft bottom habitat may under some conditions not lead to detectable population or ecosystem effects while in another case the removal of only tens of specimens from large and endangered animals or the removal of a few acres of coral reef bottom may have large population level and ecosystem impacts. The ecological risk assessment framework can be useful here, as it separates between "what can happen?" and "how bad can it be?".[19] The ecological risk assessment framework is a transparent assessment method used within a variety of scientific fields including impacts from ocean energy.

At the strategic level, uncertainties can be reduced by applied research, in particular through rigorous monitoring[20] programs. Such undertakings are often costly for early-stage developers. Here it is important that pilot plants and, subsequently, full-scale plants are allowed to operate under intended conditions so that actual impacts are revealed. For instance, monitoring efforts at the UK based tidal turbine Seagen were of little value for a long time since the turbine was shut down when marine mammals approached the site. Only when effects are revealed and quantified appropriate mitigation measures can be developed.

A WIDER SYSTEM PERSPECTIVE

As mentioned earlier in this chapter it is not the isolated stressors of an ocean energy installation that determine environmental impact, but the combined effect of those stressors and the concurrently prevalent stressors from other human activities. This cumulative effect is what really matters for the ecosystem, but also proves quite difficult to estimate. Cumulative effects can be simply additive, synergistic (one stressor increasing the effect of another stressor) or antagonistic (one stressor reducing the effect of another). For instance, on the population

19 Suter, G. (1993) Defining the Field. In *Ecological Risk Assessment* (ed. G. Suter). Boca Raton, FL, USA: Lewis Publishers.; Biddinger, G.R. et al. (2008) Managing Risk to Ecological Populations. In *Population-Level Ecological Risk Assessment* (eds L.W. Barnthouse et al.), 7-39. Pensacola, FL, USA: SETAC Press.

20 Crain, C.M. et al. (2008) Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters,* 11:1304-1315.; Halpern, B.S. et al. (2008) Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management,* 51:203-211.

level the loss of fish from collision with tidal turbine rotors would be additive to fish losses due to fishing; nutrient enrichment from incautiously designed OTEC discharge would likely be synergetic to global warming induced coral bleaching; and the provision of new habitats around ocean energy foundations would perhaps act as antagonistic to effects from other human activities such as fishing or coastal development. While the current understanding of cumulative effects is incomplete and effects are difficult to quantify, it is still important be aware of and to consider at best practise.

The existence of multiple concurrent stressors and cumulative effects should not be interpreted as arguments for preventing growth of ocean energy in general. As long as preventative measures are taken along with ocean energy deployment, most ecological receptors are likely to be under heavier pressure from other human activities than from these new technologies. A shift from a management regime of many project-based assessments to more holistic marine spatial planning, where all uses of ocean resources are considered and regulated together, will not only benefit the marine environment but may also allow for ocean energy developments. Such management shift is currently underway in many parts of the world.

In the context of holistic assessment it is also important to understand the interactions within the marine food web. For instance, if top predators like marine mammals are affected positively or negatively by an ocean energy installation this will have an effect on other organisms in the food web. For instance, a reduction of porpoises may enhance the number of porpoise prey while a potential attraction of seals would reduce the number of seal prey (and potentially also reduce fish fitness through spreading of seal-fish hosted pathogens). As another example, nutrient enrichment from incautiously designed OTEC plants would affect the whole food web, potentially leading to shifts in entire ecosystems. More nutrients mean growth of algae, in turn shading and outcompeting corals and seagrass meadows, ultimately leading to altered and possibly irreversibly changed ecosystems. Moreover, potential barrier effects of tidal power arrays could lead to impaired fish migration and loss of habitat connectivity.[21] While holistic approaches to assessment and management are rare in practice they are highly necessary given the inevitability of accelerated utilisation of ocean resources – ocean energy and others.

ENVIRONMENTAL IMPACT DEPENDS ON MANAGEMENT

In conclusion, there are still many unknowns regarding direct environmental impacts from ocean energy, where some technologies seem to have limited negative effects and others give rise to more concern. It is even possible that ocean energy in many cases may act more positively than negatively on marine ecosystems, given the protection against destructive fishing methods in combination

21 Hammar, L. et al. (2013) Hydrokinetic Turbine Effects on Fish Swimming Behaviour. *PLoS ONE,* 8(12):e84141.

with the introduction of hard substrate habitats that benefits many species.[22] Altogether, the potential damages and benefits from ocean energy to marine ecosystems are dependent on whether hazards from particular technologies can be mitigated and if synergistic cumulative effects from ocean energy and other human activities can be avoided.[23] In short, the environmental benevolence of ocean energy depends on the level of adaptive engineering and considerate planning.

22 Inger, R. et al. (2009) Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology,* 46:1145-1153; Wilhelmsson, D. et al. (2010) *Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy*. Gland, Switzerland: IUCN (International Union for Conservation of Nature); Langhamer, O. (2012) Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art. *The Scientific World Journal*; Bergström, L. et al. (2014) Effects of offshore wind farms on marine wildlife–a generalized impact assessment. *Environmental Research Letters,* 9:034012.

23 Boehlert, G.W. and Gill, A.B. (2010) Environmental and ecological effects of ocean renewable energy development: A current synthesis. *Oceanography,* 23:68-81.