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Offshore Platforms. From Offshore Renewable Energy Sources, their Potentials and Synergies, with a focus in the Mediterranean Basin, to the Concept of Multi-Use Offshore Platforms and the Alternative Uses of Decommissioned Offshore Oil and Gas Infrastructure.

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Athens, Greece, January 2025

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## Abstract

The need of energy transition from fossil fuels to renewable sources, in order for greenhouse gas emissions to be minimized, is in the epicenter of environmental discussions during recent years. However, the limited land-space, as well as the huge potentials of the oceans for energy harnessing, are shifting the interest towards the use of sea-space for production of renewable energy. This interest mainly focuses offshore, due to limitations in nearshore areas and to the greater potentials, renewable energy sources' present offshore.

The cost of offshore energy production is currently high, though, while mainly wind turbines are used for offshore renewable energy production. How can we create a renewable energy offshore system which is cost-effective, while at the same time it can exploit additional sources and assist in reduction of greenhouse gases? This dissertation tries to give answers to the following questions: how can the capital and operational cost of offshore renewable energy harvesting devices be reduced, how can infrastructure-sharing assist towards this goal, how can operating oil & gas platforms offshore currently be benefited from offshore renewable energy, how can old infrastructure from offshore oil & gas sector be repurposed for cost reduction, how can more offshore renewable energy sources be incorporated into the system for additional energy production and higher efficiency, which geographical areas present better potentials and what are the potentials of the Mediterranean basin, how can sea-space be used optimally in order for other uses to be able to co-exist, how can additional tools assist in cost reduction or other operations be benefited from such synergies, and finally how can such a system moves towards sustainability and achievement of Paris Agreement's net zero goal by 2050.

For answering these questions, the use of offshore renewable energy platforms is discussed. What are the sources that can be used for energy harnessing offshore, what technologies for renewable energy harnessing currently exist, what is their level of maturity and how these technologies can be combined to minimize the capital and operational costs of offshore devices and systems through synergies. Additional tools towards sustainability, incorporation of other sources into such systems and methods for decarbonization are further examined.

General considerations to be taken into account when designing an offshore synergic system are described and the global potentials of offshore renewable energy are analyzed, based on academic studies and metrics from institutions and organizations. Gravity is, further, drawn to the Mediterranean Sea basin and its local potentials for offshore renewable energy harnessing.

Potential synergies between operational offshore oil & gas platforms and ways renewables can assist fossil fuels' sector to reduce their environmental footprint, during the transitional phase to their final withdrawal, are further detected. Alternative uses of oil and gas platforms after their decommissioning phase are discussed and the role such structures can play in the cost reduction of offshore renewable energy sector is pinpointed.

Based on the concepts that were analyzed in this study, a theoretical framework of an offshore synergic system is presented. This system is located close to a depleted offshore oil & gas field and is benefiting from the field's infrastructure. Geographical restrictions have not been taken into account in this case. Such theoretical frameworks can act as a compass when designing new offshore synergic systems, where components can be added or extracted from the new system under study.

In the final section, the political, legal, economic, social, technological and environmental key-factors and challenges of offshore renewable energy harnessing are described.

According to our findings, offshore synergic systems can reduce capital and operational cost of devices through infrastructure-sharing, repurposed infrastructure and common operation and maintenance. They can, also, assist in CO<sub>2</sub> reduction through storage in underwater cavities or through algae absorption. The sea-space occupancy of these platforms is limited, while additional sources, such as multitrophic aquaculture, can be incorporated into such systems and benefit from them. However, the sources and devices that can be incorporated into such systems present geographical restrictions, while more trials on synergic effects of renewable energy harvesting devices need to be done for better understanding of the effects of such systems into marine environment. Legal framework for synergic platforms, liability of the different operators and permission procedures need to evolve further.

## **Keywords**

Sustainability, Synergies, Offshore multi-use platforms, Renewables, Decarbonization, Life Cycle Extension

Υπεράκτιες Πλατφόρμες. Από τις Υπεράκτιες Ανανεώσιμες Πηγές  
Ενέργειας, τις Δυνατότητές τους και τις μεταξύ τους Συνέργειες, με  
Εστίαση στη Λεκάνη της Μεσογείου, στην Έννοια των  
Υπεράκτιων Πλατφορμών Πολλαπλών Χρήσεων και στις  
Εναλλακτικές Χρήσεις της Παροπλισμένης Υπεράκτιας Υποδομής  
Πετρελαίου και Φυσικού Αερίου.

Παναγιώτα Θεοδώρου

## Περίληψη

Η ανάγκη ενεργειακής μετάβασης από τα ορυκτά καύσιμα προς τις ανανεώσιμες πηγές, προκειμένου να ελαχιστοποιηθούν οι εκπομπές αερίων του θερμοκηπίου, βρίσκεται στο επίκεντρο των περιβαλλοντικών συζητήσεων τα τελευταία χρόνια. Ωστόσο, ο περιορισμένος χερσαίος χώρος, καθώς και οι τεράστιες δυνατότητες των ωκεανών για αξιοποίηση ενέργειας, μετατοπίζουν το ενδιαφέρον προς τη χρήση του θαλάσσιου χώρου για την παραγωγή ανανεώσιμης ενέργειας. Το ενδιαφέρον αυτό επικεντρώνεται κυρίως στις υπεράκτιες περιοχές, λόγω των περιορισμών που παρουσιάζουν οι παράκτιες περιοχές, αλλά και των μεγαλύτερων δυνατοτήτων των υπεράκτιων περιοχών στην παραγωγή ενέργειας από ανανεώσιμες πηγές.

Ωστόσο, το κόστος παραγωγής ενέργειας υπεράκτια είναι υψηλό επί του παρόντος, ενώ η υπεράκτια παραγωγή ανανεώσιμης ενέργειας βασίζεται κυρίως σε ανεμογεννήτριες. Πώς μπορούμε να δημιουργήσουμε ένα υπεράκτιο σύστημα ανανεώσιμων πηγών ενέργειας που



να είναι οικονομικά αποδοτικό, ενώ ταυτόχρονα να μπορεί να εκμεταλλευτεί πρόσθετους πόρους και να συμβάλλει στη μείωση των αερίων του θερμοκηπίου; Αυτή η διατριβή προσπαθεί να δώσει απαντήσεις στα ακόλουθα ερωτήματα: πώς μπορεί να μειωθεί το κεφαλαιουχικό και λειτουργικό κόστος των υπεράκτιων συσκευών συλλογής ανανεώσιμης ενέργειας, πώς μπορεί η κοινή χρήση υποδομών να βοηθήσει προς αυτόν τον στόχο, πώς μπορούν να επωφεληθούν οι εν λειτουργία υπεράκτιες πλατφόρμες πετρελαίου και φυσικού αερίου από την υπεράκτια παραγωγή ανανεώσιμης ενέργειας, πώς μπορούν οι παλιές υποδομές του κλάδου υπεράκτιας εξόρυξης πετρελαίου και φυσικού αερίου να επαναχρησιμοποιηθούν ώστε να μειωθεί το κόστος, πώς μπορούν να ενσωματωθούν στο σύστημα περισσότερες υπεράκτιες ανανεώσιμες πηγές ενέργειας ώστε να επιτευχθεί πρόσθετη παραγωγή ενέργειας και υψηλότερη απόδοση, ποιες γεωγραφικές περιοχές παρουσιάζουν καλύτερες δυνατότητες και ποιες είναι οι δυνατότητες της λεκάνης της Μεσογείου, πώς μπορεί να χρησιμοποιηθεί βέλτιστα ο θαλάσσιος χώρος προκειμένου να συνυπάρχουν και άλλες χρήσεις του, πώς πρόσθετα εργαλεία μπορούν να βοηθήσουν στη μείωση του κόστους ή άλλες λειτουργίες να επωφεληθούν από τέτοιες συνέργειες και τελικά πώς μπορεί ένα τέτοιο σύστημα να προωθήσει τη βιωσιμότητα και να βοηθήσει στην επίτευξη του στόχου της Συμφωνίας του Παρισιού για μηδενικές εκπομπές αερίων του θερμοκηπίου ως το 2050.

Προς απάντηση αυτών των ερωτημάτων συζητείται η χρήση υπεράκτιων πλατφορμών ανανεώσιμων πηγών ενέργειας. Ποιοι είναι οι πόροι που μπορούν να χρησιμοποιηθούν για την αξιοποίηση ενέργειας υπεράκτια, ποιες τεχνολογίες υπάρχουν σήμερα για την αξιοποίηση ανανεώσιμων πηγών ενέργειας, ποιο είναι το επίπεδο ωριμότητάς τους και πώς αυτές οι τεχνολογίες μπορούν να συνδυαστούν, έτσι ώστε να ελαχιστοποιηθεί, μέσω συνεργειών, το κεφαλαιουχικό και λειτουργικό κόστος των υπεράκτιων συσκευών και συστημάτων. Εξετάζονται, επίσης, περαιτέρω μέσα καθώς και η ενσωμάτωση πρόσθετων πόρων που έχουν τη δυνατότητα να συνεισφέρουν στη μετάβαση προς πιο βιώσιμες εναλλακτικές, αλλά και μέθοδοι μείωσης του παραγόμενου διοξειδίου του άνθρακα.

Περιγράφονται παράγοντες που πρέπει να λαμβάνονται υπόψη κατά το σχεδιασμό ενός υπεράκτιου συνεργικού συστήματος και αναλύονται οι δυνατότητες υπεράκτιας παραγωγής ανανεώσιμης ενέργειας παγκοσμίως, βάσει ακαδημαϊκών μελετών και μετρήσεων που έχουν πραγματοποιηθεί από ιδρύματα και οργανισμούς. Ιδιαίτερη βαρύτητα δίνεται στη

λεκάνη της Μεσογείου και τις δυνατότητές της ως προς την τοπική αξιοποίηση υπεράκτιων ανανεώσιμων πηγών ενέργειας.

Εντοπίζονται περαιτέρω πιθανές συνέργειες μεταξύ υπεράκτιων πλατφορμών πετρελαίου και φυσικού αερίου που βρίσκονται ακόμη εν λειτουργία και οι τρόποι με τους οποίους οι ανανεώσιμες πηγές μπορούν να βοηθήσουν τον τομέα των ορυκτών καυσίμων να μειώσει το περιβαλλοντικό του αποτύπωμα, κατά τη διάρκεια της μεταβατικής φάσης και μέχρι την τελική απόσυρσή τους. Συζητούνται εναλλακτικές χρήσεις πλατφορμών πετρελαίου και φυσικού αερίου μετά τη φάση παροπλισμού τους και επισημαίνεται ο ρόλος που μπορούν να παίξουν τέτοιες δομές στη μείωση του κόστους του υπεράκτιου τομέα ανανεώσιμων πηγών ενέργειας.

Βάσει των εννοιών που αναλύθηκαν στην τρέχουσα μελέτη, παρουσιάζεται ένα θεωρητικό πλαίσιο ενός υπεράκτιου συνεργικού συστήματος. Αυτό το σύστημα βρίσκεται κοντά σε ένα εξαντλημένο υπεράκτιο κοίτασμα πετρελαίου και φυσικού αερίου και επωφελείται από την υποδομή αυτού του κοιτάσματος. Σε αυτήν την περίπτωση δεν έχουν ληφθεί υπόψη γεωγραφικοί περιορισμοί του συστήματος. Τέτοια θεωρητικά πλαίσια μπορούν να λειτουργήσουν ως πυξίδα κατά το σχεδιασμό νέων υπεράκτιων συνεργικών συστημάτων, βάσει των οποίων μπορούν να προστεθούν ή να απαλειφθούν στοιχεία από το νέο υπό μελέτη σύστημα.

Στην τελευταία ενότητα, περιγράφονται οι βασικοί πολιτικοί, νομικοί, οικονομικοί, κοινωνικοί, τεχνολογικοί και περιβαλλοντικοί παράγοντες που επηρεάζουν την υπεράκτια αξιοποίηση ανανεώσιμων πηγών ενέργειας, καθώς και οι προκλήσεις του κλάδου.

Σύμφωνα με τα ευρήματά μας, τέτοια συστήματα μπορούν να μειώσουν το κεφαλαιουχικό και λειτουργικό κόστος των συσκευών μέσω της κοινής χρήσης υποδομής, της αλλαγής χρήσης παλαιότερων υποδομών και της κοινής λειτουργίας και συντήρησης τέτοιων συστημάτων. Μπορούν, επίσης, να συμβάλλουν στη μείωση του CO<sub>2</sub> μέσω της αποθήκευσής του σε υποθαλάσσιες κοιλότητες ή μέσω της απορρόφησής του από φύκια. Ο θαλάσσιος χώρος που καταλαμβάνουν τέτοιου είδους πλατφόρμες είναι περιορισμένος, ενώ πρόσθετοι πόροι, όπως η πολυτροφική υδατοκαλλιέργεια, μπορούν να ενσωματωθούν και να επωφεληθούν από αυτά τα συστήματα. Ωστόσο, οι πόροι και οι συσκευές που μπορούν να ενσωματωθούν σε τέτοια συστήματα παρουσιάζουν γεωγραφικούς περιορισμούς, ενώ χρειάζονται περισσότερες δοκιμές αναφορικά με τις συνεργικές επιδράσεις των συσκευών

συλλογής ανανεώσιμων πηγών ενέργειας, προκειμένου να κατανοηθούν καλύτερα οι επιπτώσεις τέτοιων συστημάτων στο θαλάσσιο περιβάλλον. Είναι, επίσης, σημαντικό να εξελιχθούν περαιτέρω το νομικό πλαίσιο αναφορικά με τις συνεργικές πλατφόρμες, η ευθύνη των διαφόρων φορέων και οι διαδικασίες αδειοδότησης.

### **Λέξεις – Κλειδιά**

Βιωσιμότητα, Συνέργειες, Υπεράκτιες Πλατφόρμες Πολλαπλών Χρήσεων, Ανανεώσιμες Πηγές Ενέργειας, Απαλλαγή από Ανθρακούχες Εκπομπές, Επέκταση Κύκλου Ζωής

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## List of Abbreviations

AEM – Anion Exchange Membrane

BESS – Battery Energy Storage System

BiMEP – Biscay Marine Energy Platform

CCS – Carbon Capture and Storage

CCU – Carbon Capture and Utilization

CDI – Capacitive Deionization

CEM – Cation Exchange Membrane

CfD – Contract for Difference

CSP – Concentrated Solar-thermal Power

DNI – Direct Normal Irradiance

ED – Electro Dialysis

EDR – Electrical Dialysis Reversal

EOR – Enhanced Oil Recovery

FO – Forward Osmosis

GHI – Global Horizontal Irradiation

GHG – Green-House Gas

GTI – Global Tilted Irradiation (GTI)

H – Hydrogen

HAWT – Horizontal-Axis Wind Turbines

HDI – Human Development Index human devel

IEA – International Energy Association

IRENA – International Renewable Energy Agency

LCOE – Levelized Cost of Energy



LOHC – Liquid Organic Hydrogen Carriers

MB – Membrane Bioreactor

MD – Membrane distillation

MED – Multi-Effect Distillation

MF – Micro Filtration

MSF – Multi-Stage Flash Distillation

MUOP – Multi-Use Offshore Platforms

MVC – Mechanical Vapour Compression

NF – Nano Filtration

NSPV – Nearshore Floating Photo-Voltaic

O&M – Operation and Maintenance

OFPV – Offshore Floating Photo-Voltaic

ORE – Offshore Renewable Energy

ORES – Offshore Renewable Energy Sources

OTEC – Ocean Thermal Energy Conversion

OWC – Oscillating Water Column

OWT – Offshore Wind Turbine

O&G – Oil and Gas

PEH – Piezoelectric Energy Harvesting

PEM – Proton Exchange Membrane

PRO – Pressure-Related Osmosis

PTO – Power Take-Off system

R&D – Research and Development

RE – Renewable Energy

RED – Reversed Electro Dialysis

RES – Renewable Energy Source

RO – Reverse Osmosis

SOEC – Solid Oxide Electrolysis Cell

SPV – Solar Photo-Voltaic

STS – Solar Tracking Systems

SWAC – Sea Water Air Conditioning

SWHP – Sea Water Heat Pump

TEC – Tidal Energy Converter

TEG – Thermo-Electric Generator

TLP – Tension Leg Platform

TRL – Technological Readiness Level

TVC – Thermal Vapour Compression

UF – Ultra Filtration

UNCLOS – UN Convention on the Law of the Sea

VAWT – Vertical-Axis Wind Turbine

WEC – Wave Energy Converter

## 1. Introduction

As contemporary economies are moving towards sustainability and decarbonization, a holistic approach in the use of offshore platforms and their potentials from cradle-to-grave needs to be examined as mean of cost reductions, elimination of usage of limited recourses and extension of offshore projects' life cycle.

From reduction of costs to more sustainable options in energy, alternatives for storage of CO<sub>2</sub> emissions and desalination of water, it is highly important for future energy projects to move towards a more holistic approach. At the same time, an effort of taking advantage of the parameters and resources in every aspect should be targeted.

Under the spectrum of decarbonization targets and during the transition from fossil fuels to Renewable Energy Sources (RES) a proposal of extended life cycle, as well as cost reduction and environmentally sustainable solutions for a set of offshore platforms is being described and assessed, implementing PESTEL analysis. The reason PESTEL analysis was chosen is that it has the ability to analyze, in a structured way, different sectors that may influence the system. It can, further, determine the key-factors that affect each sector and assess their impact. Thus, corrective actions can be taken at early stages. The suitability of subject method lies in the fact that it has the ability to identify weaknesses and challenges when scientific fields with small number of empirical data is explored, such as the one under examination.

Subject essay is examining a cooperative / integrated structure of offshore oil and gas (O&G) platforms, as well as wind platforms, offshore floating photovoltaic platforms and other offshore energy-producing structures, how these structures can be combined and used in an efficient and sustainable way, the synergies from which they could be benefited from and the alternative uses during the production and decommissioning phase.

According to projections, the global demand for energy seems to be following an upward trend in the forthcoming decades, although the total primary energy consumption requirements of individual regions do not, always, follow the same trend (Ahmad & Zhang, 2020).

While Africa's and Asia's total primary energy consumption requirements are expecting to increase significantly, Canada, Middle East and Europe show signs of slowed-down rate of increase by 2040. However, Asia, North America and Europe keep their position as top-energy-

consumers in the following years (Ahmad & Zhang, 2020). The rapid growth of energy demand in China and India seems to be led by the pace of their economies' growth, as well as the growth of their population and its living standards (ExxonMobil's Outlook for energy 2015: A View to 2040, IEA, World Energy Outlook 2017).

Same drivers seem to be leading growth of energy demand in the African countries (World Energy Outlook Special Report Africa Energy Outlook 2022, n.d., pp. 60-62), but in this case, and although Africa is a relatively small energy consumer and Green-House Gases' (GHG) emitter, holding a 6% of global energy consumption (Africa – Countries & Regions - IEA, n.d.), it is obvious that rise in demand for energy is expected to be boosted further, due to the acceleration of rise in temperature and the need for use of cooling devices, such as air-conditioners and electric fans (World Energy Outlook Special Report Africa Energy Outlook 2022, n.d., pp. 70, 73-74).

Studies show that African countries are suffering disproportionately from climate change, as the acceleration of temperature in this continent rises faster than anywhere else in the world, while severe weather conditions, as extreme heat and long-lasting drought periods are becoming more common (Africa Suffers Disproportionately from Climate Change, 2023). Occasional rainfalls are becoming more severe and, in many cases, lead to disastrous floodings and tropical cyclones (State of the Climate in Africa 2022, 2023).

The growth for energy demand, however, has to be aligned with the efforts for sustainability and the need for actions to combat climate change and its impacts, as described in the 2015 Paris Agreement (United Nations Framework Convention on Climate Change, 2015). These needs, in relation to shortage of land space (Flikkema & Waals, 2019, Esteban et al., 2011, Floating Island Development and Deployment Roadmap, 2021), public opposition for onshore renewable energy harvesting structures (Esteban et al., 2011) and greater opportunities for harvesting renewable energy (RE) from offshore installations (Soukissian et al., 2023), lead to two global trends: the increase of the portion of energy renewable sources in the energy mix and the expansion in locating the producing and other complementary units offshore.

And, although there is reluctance towards the abandonment of use of fossil fuels, especially oil and gas, in the following decades (Scheffran et al., 2020), energy security of countries, which was heavily affected during the outbreak of the COVID-19 pandemic, and continued to be at risk after the start of the Ukrainian-Russian conflict, needed more alternatives in energy

sources. These two facts acted as catalysts in the acceleration of development of technologies connected to renewable energy resources and the choice for their spatial location offshore.

These acts were mainly led by North European countries, due to their close dependence on the Russian Gas and Oil supplies. On the other hand, their accelerated and more intense efforts towards renewables' options would act as a mean to mitigate the GHGs' emissions, through CO<sub>2</sub> reduction, which would bring them closer to their sustainability commitments of net Zero by 2050, as set by the Paris Agreement.

At the same time, and due to positioning energy security high in the ranking of National Security Strategies, most of the developed countries continued their search for fossil fuels' deposits, following a seemingly contradictory strategy of targeting in expansion of both environmental-friendly sources, as well as fossil fuels. One of the most distinctive cases of such a controversial strategy was UK's decision to give permission of drilling (issuance of new license) to the newly discovered Rosebank oil and gas field in the North Sea (Consent Granted for Rosebank Project, 2023).

As it can be inferred by the above, current phase of energy mix is a transitional one. Economies are investigating their options and alternatives, as they are moving to more environmental-friendly choices and offshore energy harvesting.

Within this frame, the reduction of Levelized Cost of Energy (LCOE) for offshore renewables plays a vital role. Technological elevation and maturity of inventions in subject fields are helping towards this aim. In addition, synergies and co-locations of offshore renewables can further assist in LCOE reduction, since in this case, maintenance cost, cables, power stations and infrastructure sharing in general, can be implemented. Circular economies, in the context of reusing, sharing and extending of life cycle of structures and materials, are further oriented towards this direction.

Two are the directions towards which reduction of costs and optimized use of sources should be examined. The first direction focuses to those offshore platforms that already exist and how their current or future use can be optimized in financial, social, environmental terms. The second direction examines how the newly deployed offshore structures or sets of structures can be designed prior entering seawater, taking into account cost savings, high productivity, environmental sustainability and reduction of decommissioning issues and costs.

Current study is based on the development of a theoretical framework, which attempts to connect different sources, means and technologies of offshore energy sector, among renewables on one hand and between renewables and oil and gas sector on the other, with final purpose the minimization of costs and the increase of system's efficiency.

For its completion, secondary data were used, which derived mainly from peer-viewed academic literature, in order for high quality of data to be ensured. Other sources included researches from international or European energy agencies and organizations, the United Nations, Meteorological Organizations, the World Bank, the Pacific Northwest National Laboratory, as well as press-articles from Reuters, National Geographic or more energy-oriented press such as PV Magazine and Offshore Energy. Additional sources included energy providers or producers of offshore devices, such as Equinor or Carnegie, respectively.

Most studies and data used have been published with-in the last 8 years, while more gravity was given to even more recent researches, especially from 2020 onwards, in order for the latest advancements and studies' results to be included. Keywords at literature search-engines were used to source and refine the data, while in many cases citation chaining was, also, performed. The literature was critically reviewed, in order for us to move from coupling of 2 or 3 offshore renewables to more complex energy systems.

Limitations of this study mainly stemmed from the narrow time-frame for its compilation and preparation. Other limitations emerged from the fact that current study combines different academic fields, from oceanography to fluids mechanics, engineering etc., thus a team of researchers from multiple sectors would be able to better detect specific challenges in each of the components of such complex systems. The different technological level, the limited prototypes that have been tested until now and the data scarcity regarding their cost and environmental impacts, posed additional barriers in the choice of the means that could efficiently be included into the system.

The main sources from which energy can be harnessed offshore and the relative technologies were described in the second chapter. Additional tools which could be included into the system to reduce cost, make the system more efficient, versatile or capture and store or use carbon emissions have been analyzed in the third chapter. The fourth chapter concentrated on the notion of multi-use platforms and the synergies that could potentially arise. A PESTEL

analysis was performed in the fifth chapter, while in the sixth chapter the conclusions were presented.

## 2. Offshore Energy Alternatives and Different Structures

In this section, a brief description of the alternatives, in terms of offshore energy production structures, will be attempted. Initially, fossil fuels and the platforms available today will be discussed, followed by a short description of main Offshore Renewable Energy Sources' (ORES) technologies available currently.

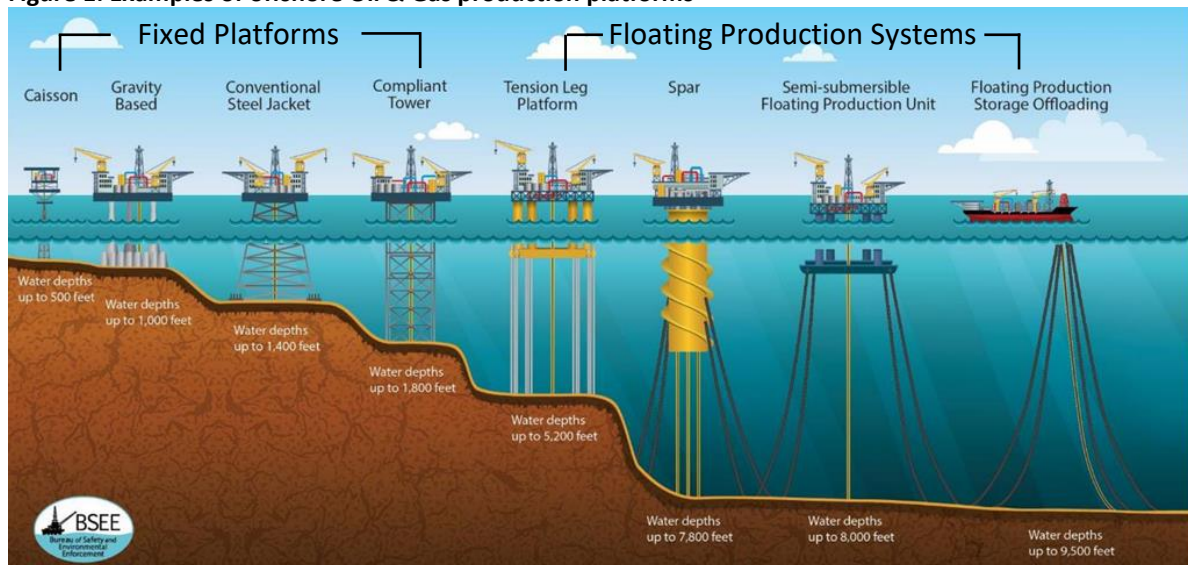
### 2.1 Offshore Sources of Energy and Structures Used Currently

#### 2.1.1 Fossil Fuels

##### 2.1.1.1 Offshore Oil and Gas Platforms

Offshore Oil and Gas (O&G) platforms can be categorised into fixed and floating. Fixed are the platforms attached to the seabed, either by piles or by gravity bases, mainly built of steel or concrete or a mixture of these two elements. Floating platforms are anchored to the seabed either by cables or by mooring lines. Offshore fixed Oil platforms are used for more shallow waters, while floating constructions are used in waters deeper than 450 meters. Fig. 1 presents some of the most common types of O&G production platforms.

**Figure 1: Examples of offshore Oil & Gas production platforms**



Source: Bureau of Safety and Environmental Enforcement (BSEE). Examples of Production Platforms 2020. (BSEE-USCG Offshore Information for Area Contingency Planning Offshore Oil and Gas Infrastructure for the GOM, Technical Document #1 Record of Changes, n.d.)

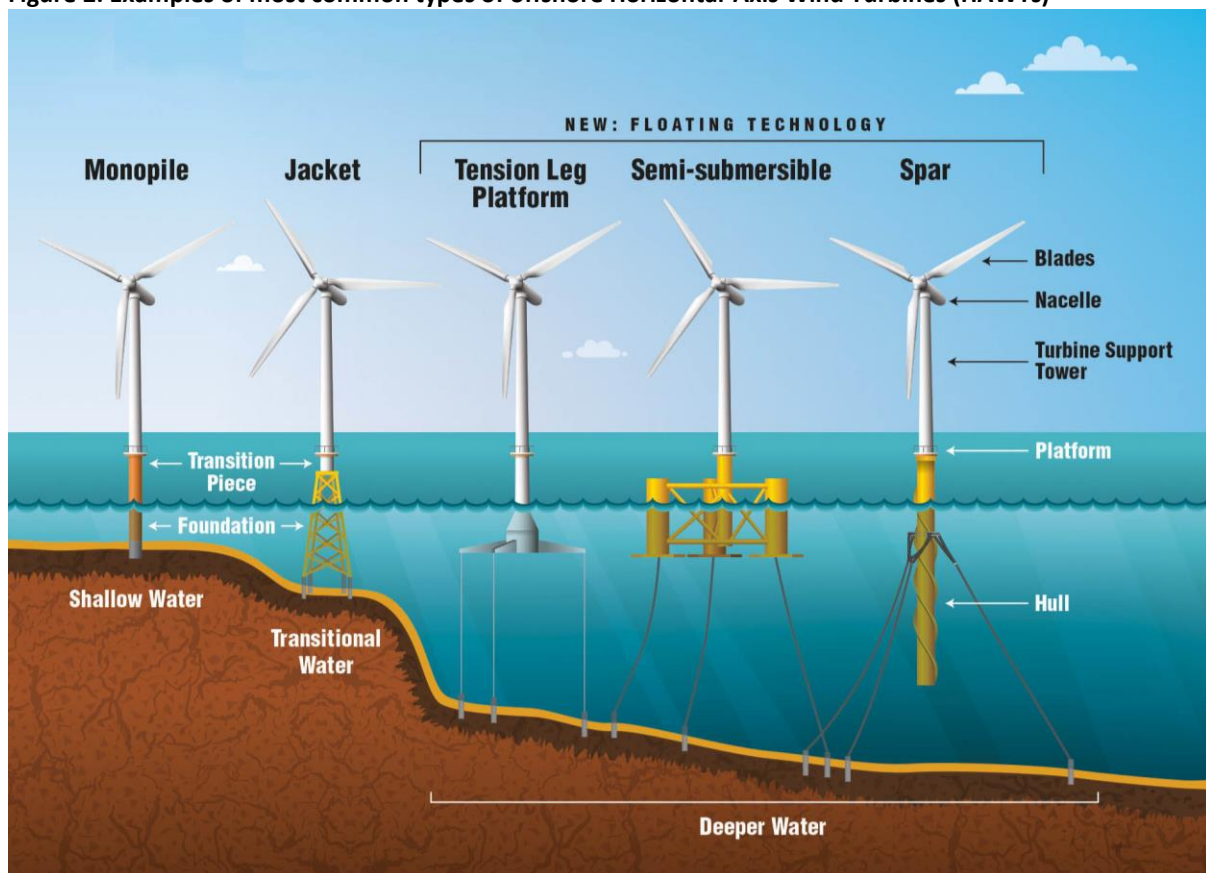


## 2.1.2 Renewable Energy Sources and Relative Technology

### 2.1.2.1 Wind Power – Offshore Wind Turbines (OWTs)

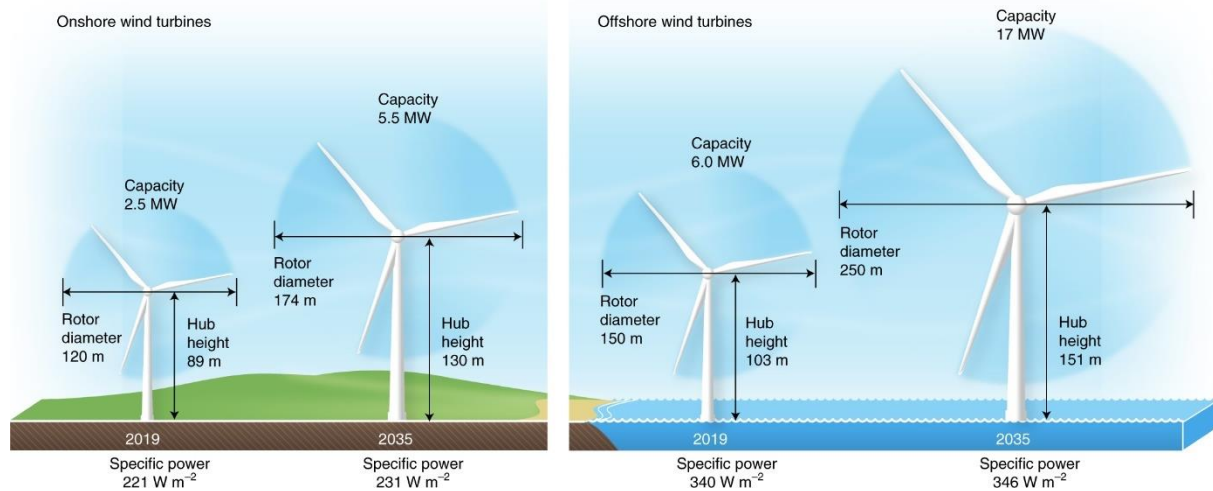
As per O&G platforms, OWTs can, also, be categorised into fixed and floating. Design technology is largely adopted from offshore O&G industry. In this case, too, fixed structures are used for shallow waters, while floating turbines are designed for greater depths. Most common type of rotation axis is horizontal with 3 blades, similar to airplane propellers (Fig. 2). The main change in the characteristics of these turbines over the years and as they are moving from shore to sea is that the height of their rotor hub and the length of their blades' radius are increasing (Fig. 3). This, in turn, is increasing their power capacity.

**Figure 2: Examples of most common types of offshore Horizontal-Axis Wind Turbines (HAWTs)**



Source: (Hesam, 2022)

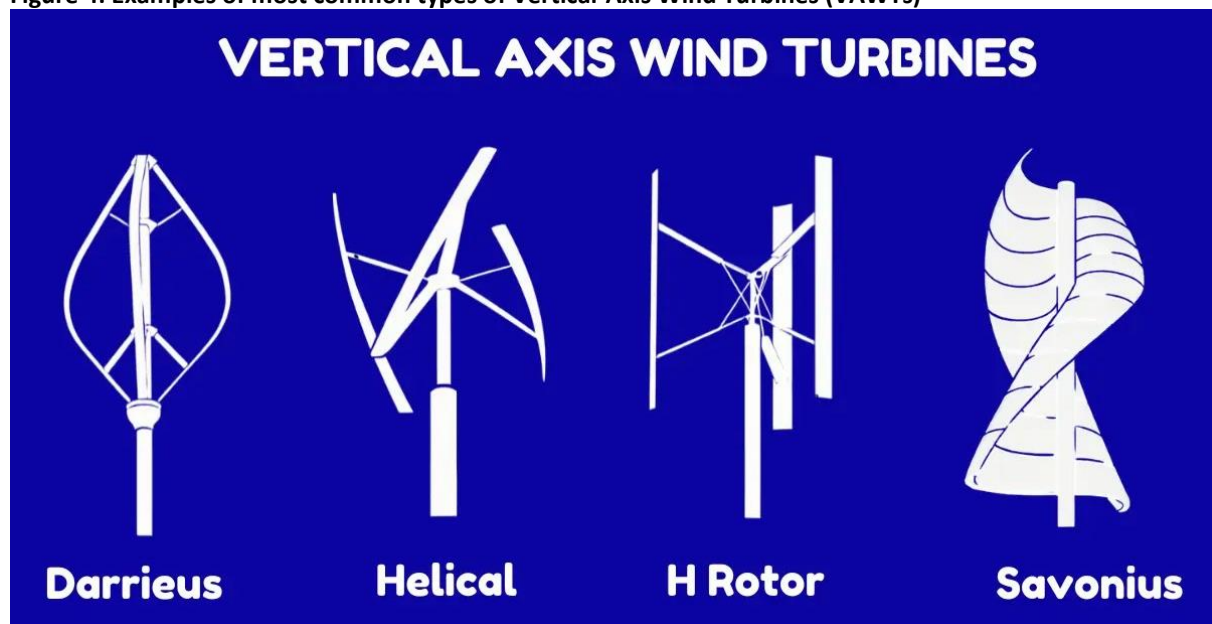
**Figure 3: Examples of increase of rotor hub heigh and blades' radius length of wind turbines throughout the years and as they are moving from shore to sea**



Source: (Wiser et al., 2021)

On the other hand, there are studies and trials with different typologies of wind turbines, such as Vertical-Axis Wind Turbines (VAWTs) (Hand & Cashman, 2020), double-rotor (wind turbines, also known as twin-rotor or dual-rotor wind turbines (Guenoune et al., 2017, Sahebzadeh et al., 2022, Zhang et al., 2023), and multi-rotor wind turbines (Jamieson et al., 2022). A sample of these different typologies is presented in Fig. 4, 5 and 6, respectively.

**Figure 4: Examples of most common types of Vertical-Axis Wind Turbines (VAWTs)**



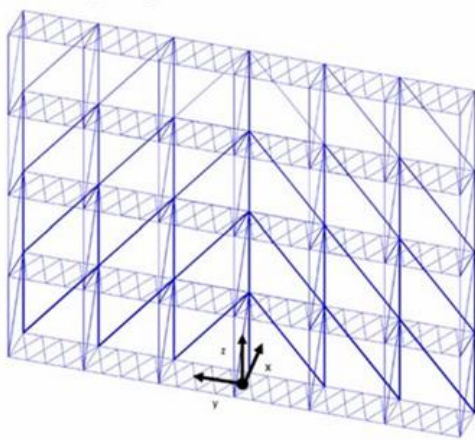
Source: (Vertical Axis Wind Turbines - Windmills Tech, 2024)

**Figure 5: Offshore double-rotor wind turbine (MingYang Smart Energy's model: OceanX)**



Source: MingYang Smart Energy

**Figure 6: Multi-Rotor Wind Turbines**



a. Support Frame Design



b. Example of final design of multi-rotor offshore structure

Source (a): (Jamieson et al., 2022)

Source (b): (Arup, 2024)

### **2.1.2.2 Solar Power – Offshore Solar Photovoltaic Systems & Concentrated Solar Power Systems**

In the field of solar energy, two are the main technologies for electricity generation. The most common technology is that of Solar Photo-Voltaic (SPV) systems, while systems generating electricity through Concentrated Solar-thermal Power (CSP) are less common. One of the main benefits of solar systems is that they are noiseless, but they need a relatively large area for installation (Hammoumi et al., 2022). The problem of land-use can be overcome, by placing these installations offshore. A short description on both systems and their current technological maturity in offshore environments is presented here below.

#### *i. Offshore Floating Photovoltaic (OFPV) Systems*

OFPV panels are using the same technology as per land-based SPV panels, while the substructure used, for keeping the solar platforms firm and floating, in most cases derives from the technological designs used in floating O&G platforms. These designs enable platforms to operate in great sea depths, with proven efficiency in offshore harsh environments of high winds and waves (López et al., 2024). A challenge that needs to be overcome in the case of OFPVs is that of corrosion of the panels, due to the salinity of the environment within they operate.

While solar radiation is the main element affecting OFPVs' generation of energy, other factors, such as temperature, dust, dirt, shading, orientation of OFPVs and panels' tilt angle can have significant effect on the final energy production (Hammoumi et al., 2022).

Temperature should be kept below 25°C, since the efficiency of the panels is declining, as temperature is increasing above this threshold. Sea water in OFPVs has a cooling effect, which is assisting the panels in keeping a lower temperature, especially when they are closer to the sea-level. Apart from natural modes, PV panels can be cooled by forced modes. In this context, a cooling system, using sea-water can be applied (Zapałowicz & Zeńczak, 2022).

Dust and dirt are preventing the solar radiation from reaching the cells of the panel, while shading is causing loss of power efficiency. According to Mondal & Bansal (Mondal & Bansal, 2015), dust and dirt can reduce solar intensity by 20% - 50%, reducing panels' final production. The most efficient way of combating dust and dirt are the automatic cleaning systems and, mainly, the robotic cleaning systems.

The problem of shading is not present in the solar offshore field, especially if the structure does not include components that block the sun.

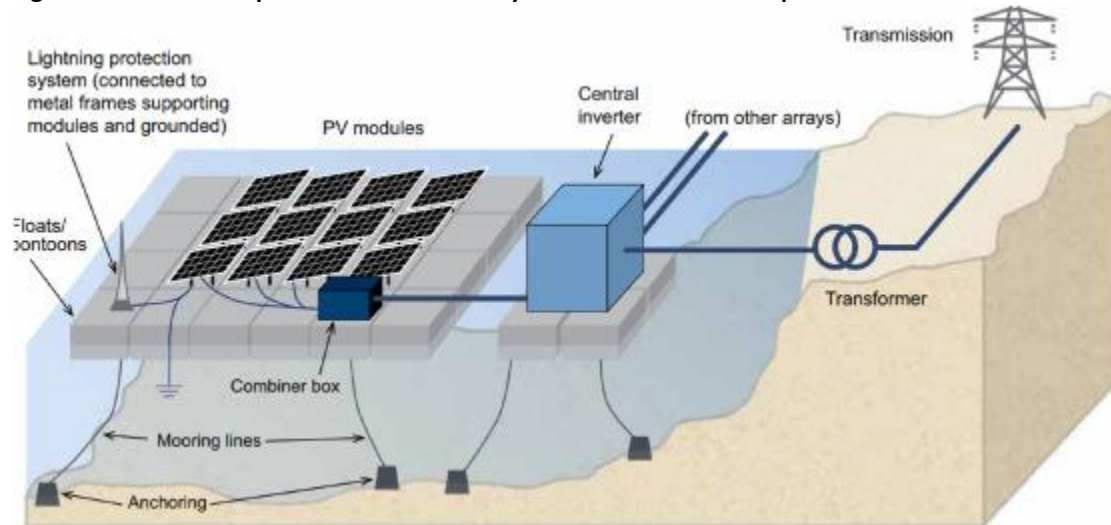
The tilt angle of the panels is, also, important, as right angle enables them to catch more solar radiation. Technologies of Solar Tracking Systems (STS) with night return mechanisms have evolved in order to enable maximum energy harvesting, based on the tilt angle. In this case, the energy consumed for solar tracking should be less than that gained by their new positioning (Hammoumi et al., 2022). It must be added, though, that these systems may not be suitable for hot climates, because they may increase the temperature of the panels (Eldin et al., 2015).

The production of energy in OFPV can further be boosted by bifacial panels. These panels can absorb irradiance from both sides of the cells, but enough evidence on their efficiency on the offshore field are yet to be collected. The structure of the OFPV, though, is expected to have significant effect in regards to energy addition from bifacial panels, since a structure that is floating at a high level over the sea (e.g. a semi-submersible structure) is expected to produce more additional power than a structure, the panels of which stand at closer proximity to the sea-level, since, in the first case, more reflectance from the sea is expected to reach the lower side of the bifacial panel. Furthermore, an increase of the height between the structure and sea-level is expected to reduce the self-shading, optimizing the performance of bifacial panel (López et al., 2024, Sun et al., 2018).

Fig. 7 is a schematic representation of OFPV system with its main components, while Fig. 8.a, 8.b and 8.c are presenting some of the latest OFPV structures.



**Figure 7: Schematic representation of OFPV system with its main components**

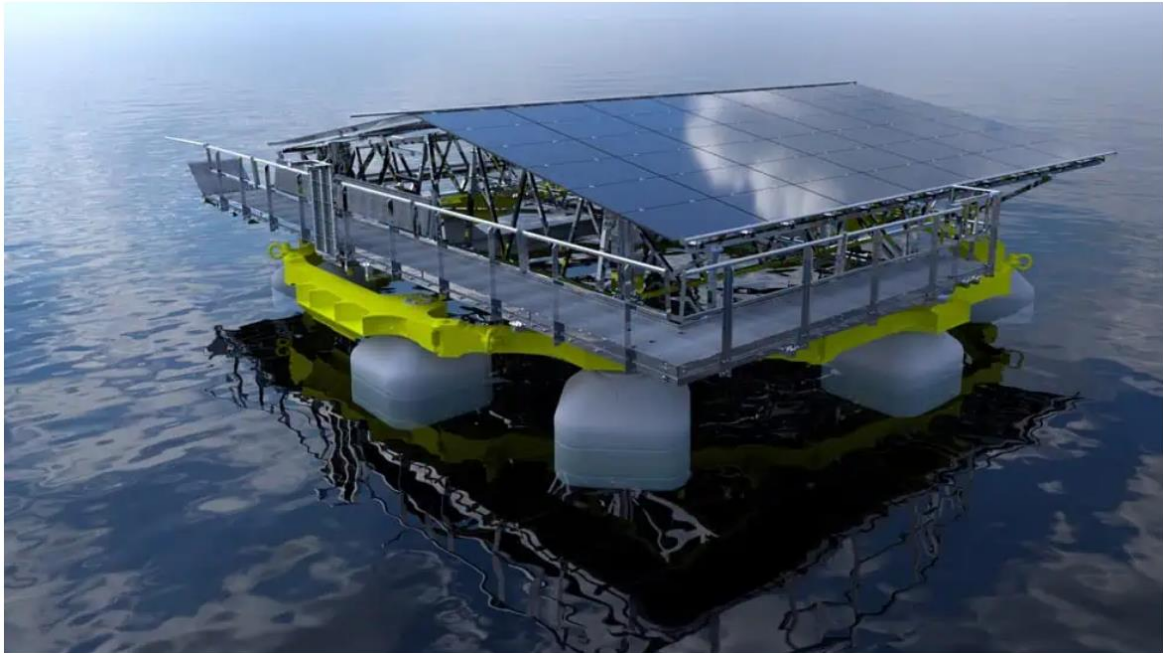


Source: World Bank Group ESMAP SERIS, 2019)

**Figure 8: OFPVs**



**a. SeaVolt by DEME, Tractebel and Jan De Nul**



**b. XolarSurf by Saipem/ Moss Maritime**



**c. Merganser by SolarDuck, TU Delft, TNO, MARIN and Deltares**

Source (a): (SeaVolt - Focus Magazine\_11, n.d.)

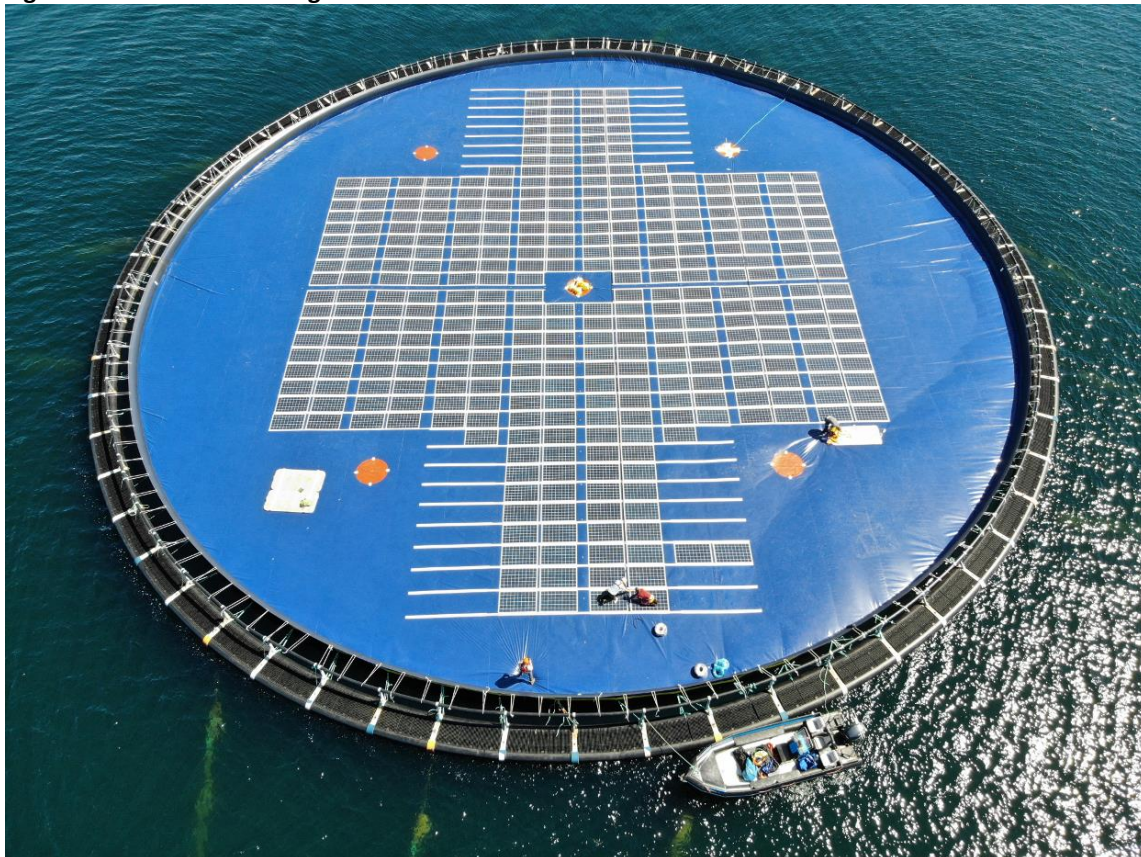
Source (b): (Workboat, 2024)

Source (c): (SolarDuck)



There are, however, simpler floating designs, such as pontoons, membranes or flexible foils, but these are more commonly used to Nearshore Floating Photo-Voltaic (NSPV) structures. In this case, the panels are closer to the water surface, as the membranes or other materials are actually the barriers between the panels and the sea, enabling them to transfer direct heat to the water, reducing the cells' temperature, while increasing their efficiency. Fig. 9 presents an example of a membrane floating PV structure.

**Figure 9: Membrane floating PV structure**



Source: (Kyrholmen | Ocean Sun, 2018)

In recent years the ability of such structures to withstand harsh offshore environments, typhoons and hurricanes is being tested in real-life conditions, but studies (Kaymak & Şahin, 2021), as well as accidents, such as the 2019 fire, as impact of Faxai Typhoon, at Japan's largest floating PV plant, located at Yamakura Dam (Bellini, 2019), the 2021 damage of floating solar installation at Banja reservoir, Albania, due to stormy weather, days after its connection to the grid (Garanovic, 2021, Garanovic, 2021b), the 2022 fire from storm at France's O'Mega 1 floating power plant (Beyer, 2022) or the 2024 damage by storm of the world' largest floating



solar plant at Omkareshwar Dam, Madhya Pradesh, India (Tnn, 2024), have proved that current technology of such floating structures, closely attached to the water surface, is not yet sufficiently robust for harsh offshore environments. Thus, semi-submersible options of OFPV platforms, as well as designs using the technology deriving from O&G industry, which has already been tested in harsh environments, may be better choices at present.

The important issue of fighting high winds, storms and extreme weather conditions in offshore environments can be alleviated significantly in the case of submerged photovoltaics. Two of the main problems, which reduce the efficiency of photovoltaic panels, that is dust / dirt and high temperatures, can be overcome to a great extent by submerging photovoltaic panels underwater. The intensity of the sunlight, though, decreases rapidly as the depth increases (Stachiw, 1980, Enaganti et al., 2020). Thus, an optimal depth, where the gain of the lower water temperature overcomes the loss due to radiation absorption, needs to be estimated (Cazzaniga et al., 2018).

In submerged panels, challenges associate, also, with the need of electrical connectors to remain dry and unaffected by salinity corrosion, as well as the need to be free from biofouling. Dryness and protection of the panels from corrosion can be achieved by the use of transparent protectors, usually made of silicon, while biofouling can be fought either passively, by chemical coatings, or actively, by mechanical cleaning systems (Stachiw, 1980).

Submerged photovoltaic panels were found to perform successfully (Stachiw, 1980, Rosa-Clot et al., 2010), but the depth of the submerged panels plays a pivotal role on their performance (Lanzafame et al., 2009, Rosa-Clot et al., 2010, Tina et al., 2011). Panels submerged few centimetres below water surface can be benefited from the reduction of light reflection, the lower water temperature and the homogeneity of the temperatures within the day, while panels submerged in greater depths are losing their efficiency due to changes in solar spectrum, since light absorption occurs in the infra-red region, which is reduced as panels are placed to greater depths and practically eliminated at depths below 2meters. Water reduction of light effect in comparison to reduction of temperatures of submerged PVs was found to increase the production of energy by 10% - 12% in temperate zones' areas (Cazzaniga et al., 2018).

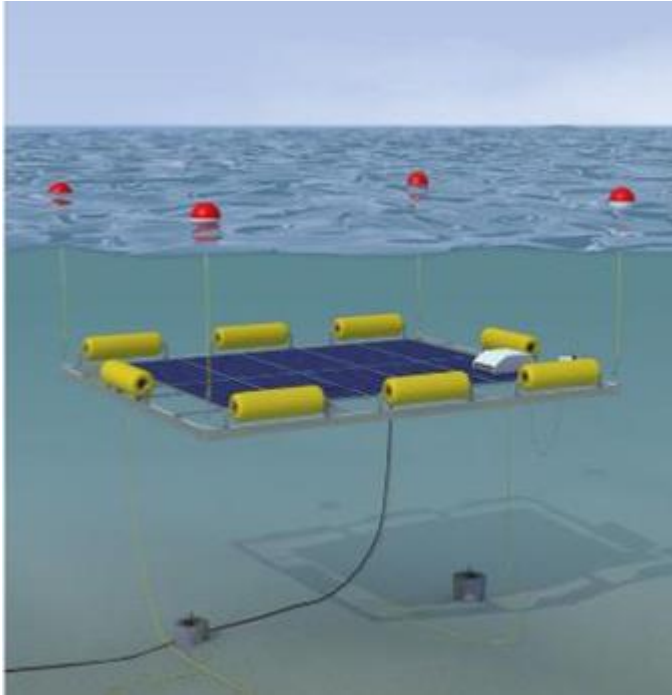
At their 2014 study, Mehrotra et al. (Mehrotra et al., 2014) concluded that panels submerged 1cm below water presented the maximum efficiency in regards to non-submerged panels or to panels submerged to greater depths. Underwater panels submerged to 2-5cm were, also,

performing better than that of greater depths or that not being submerged. Similar conclusions had been reached in the 2009 study by Rosa-Clot et al. (Rosa-Clot et al., 2010), according to which “a sizeable increase of electric power output is found for shallow water”.

In addition, the underwater performance of the solar panels seems to be, also, affected by their building materials’ technology. For example, the performance of the -relatively new technologically- perovskite solar panels seems to be less affected underwater, in comparison to silicon solar panels, since environments with low-light do not affect perovskite panels as much as that of silicon (Samantaray et al., 2022).

Latest studies explore the possibility of underwater PV panels with the ability to submerge deeper when the weather conditions are harsh, combining, this way, the concepts of both shallow and deep submersion of devices (Cazzaniga et al., 2018). Such a structure is presented in Fig. 10.

**Figure 10: PV solar module (SP2) with the ability to submerge to different depths**



Source: (Cazzaniga et al., 2018).

## *ii. Offshore Concentrated Solar Power Systems*

CSP is a RES that can exploit sun irradiance by concentrating it, through mirrors, to a specific spot, where a receiver is placed. A fluid in the receiver is heated, due to high temperature resulting from irradiance concentration, and a machine, usually a steam turbine, is set into motion, producing power.

Although CSP's concept is not a new one, the system has not been studied extensively in the offshore field. And, although LCOE of land-based CSP plants has fallen below 0.1\$/kWh in 2021 (Alami et al., 2023), offshore technology faces significant challenges, such as platform motion, which affects stability of the mirrors in regards to the receiver, "as the efficiency of solar concentrators decreases significantly for even small misalignments" (Diendorfer et al., 2014). In their 2014 study of an offshore floating CSP system in the Mediterranean Sea, South of Malaga, Spain, Diendorfer et al. (Diendorfer et al., 2014), however, concluded to the technical feasibility of the venture, stating that the platform design proposed in subject study reduces the motion of the waves to a minimum, where the influence to the performance of the system is very small and can be neglected.

Subject study, further, stressed the offshore installations' advantages of easiness in sun-tracking and avoidance of shading between the rows of collectors, as well as the cooling effect of water, which increases system's efficiency. In the case of CSP systems the advantage of cheap energy storage should, also, be taken into consideration (Baigorri et al., 2023), since energy produced from RESs is highly variable. As per Alami et al. (Alami et al., 2023), however, the distance between production and consumption centres still remains the main challenge for CSP expanding. Thus, further studies and trials need to be done, in order for possible issues to be solved and costs to be better estimated, before offshore CSPs incorporate into offshore platforms' system.

### **2.1.2.3 Wave Power – Wave Energy Converters (WECs)**

In recent years, a lot of WECs' studies and trials are completed or are under process, but technology of conversion of wave into energy is still immature. This means that production of wave energy is facing comparatively low conversion efficiency and high costs (Ning et al.,

2024) which makes it uncompetitive compared to wind and solar. However, waves have the advantage of being able to produce energy even at night or during unsunny days, when solar energy is difficult to be harvested and they can be better predicted than wind and sun. WECs can act complementary to other forms of renewable energy and cost can be reduced by common infrastructure sharing. Corrosion, as in all offshore structures, poses a challenge for the long-term survival and maintenance of these devices.

The conversion of wave energy into electric power is done in two stages. During the first stage, devices known as Wave Energy Converters (WECs) are capturing the wave energy and transforming it into mechanical. At the second stage, Power Take-Off (PTO) systems are, further, converting mechanical energy into electrical power (Barua & Rasel, 2023).

In regards to WECs, there are multiple different technologies and devices, which are adding complexity in the classification of the converters. A classification can be done based on their working principal in capturing the wave, before converting it to energy.

*i. Attenuator*

Based on this classification, one of the most common types of WECs is the attenuator. This type of device is, usually, comprised of multiple interconnecting parts, forming a single unit. This unit is floating at the sea-surface, taking advantage of the movement of swells. Pelamis (Fig. 11), the latest version of which was decommissioned in 2016 (devices P2-001 & P2-002), is considered one of the most representative structures of this type, while spine-like Waveline Magnet (Fig. 12) is probably one of the most promising technologies of such a WEC in the field.

**Figure 11: Pelamis WEC**



**Source: (Güney, 2015)**

**Figure 12: Waveline Magnet WEC**



Source: (SwEI – Sea Wave Energy Ltd, n.d.)

*ii. Point Absorber*

Another very common type of WEC is the point absorber. The design of this converter is very simple. It, usually, comprises of a buoy, floating at the sea-surface or just below it. The buoy is either connected to the seabed or to a submerged base, locked at a specific height above the seabed. As the waves move the buoy closer to the base or further from it, a piston-like mechanism, inside the converter, is converting wave energy into mechanical. Fig 13.a presents a picture of the total aspect of CorPower Ocean's point absorber, while Fig. 13.b and 13.c are depicting the internal mechanism and an array of subject absorbers in the open sea, respectively (Wave Energy Technology – CorPower Ocean, 2024).



**Figure 13: CorPower Ocean's point absorber**



Source: CorPower Ocean

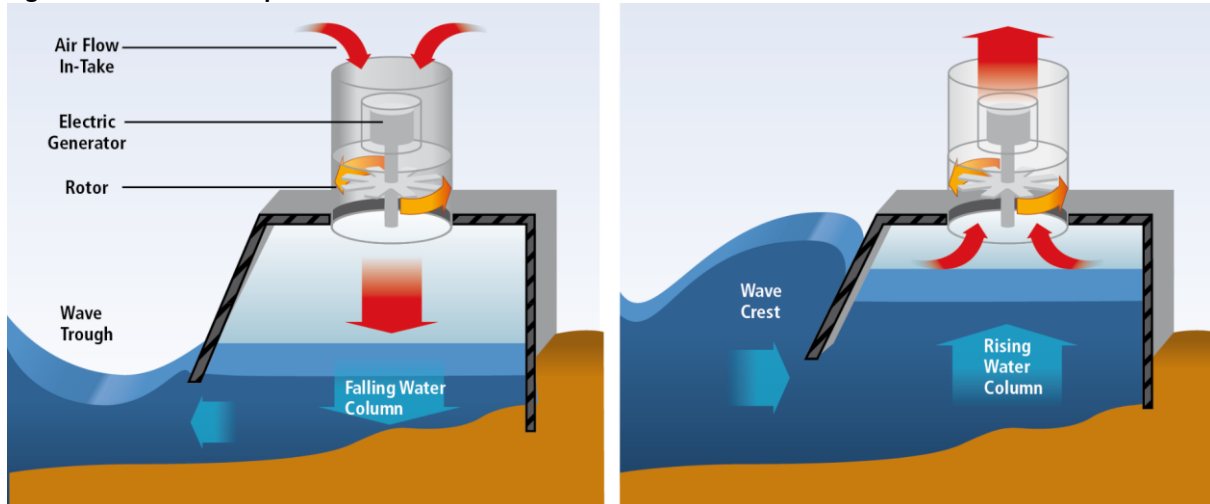
### iii. Oscillating Water Column

WECs based on the principal of Oscillating Water Column (OWC) have, also, been studied widely. The concept, in this case, is that an open-based hollow chamber is partially submerged into the sea. The coming waves are compressing the air inside the chamber, moving the trapped air-column to press a turbine, placed at the top of the chamber, forcing it to rotate and produce energy.

OWC converters can be placed either offshore or they can be land-based. Combination of OWC with breakwaters seems to enhance the performance of the OWC structures (Howe & Nader, 2017). A 2021 study on multi-chamber OWC-breakwater (Zhao et al., 2021) has shown that triple-chamber structures perform better than a single-chamber structure, “due to the hydrodynamic interactions of different water columns”. On a 2024 study, Ning et al. (Ning et al., 2024), came to the same conclusion for land-based OWCs.

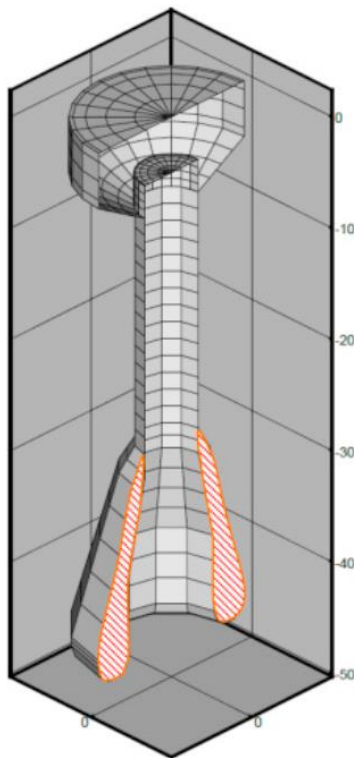
A schematic representation of a land-based OWC WEC is shown in Fig. 14, while Fig. 15.a and 15.b present the cross section and the scaled model of one of the simplest designs of floating OWCs; a spar-buoy type.

**Figure 14: Schematic representation of OWC**



Source: (Lewis et al., 2011)

**Figure 15: OWC spar buoy, tested in UK in 2012**



**a. Cross Section**



**b. Scaled Model**

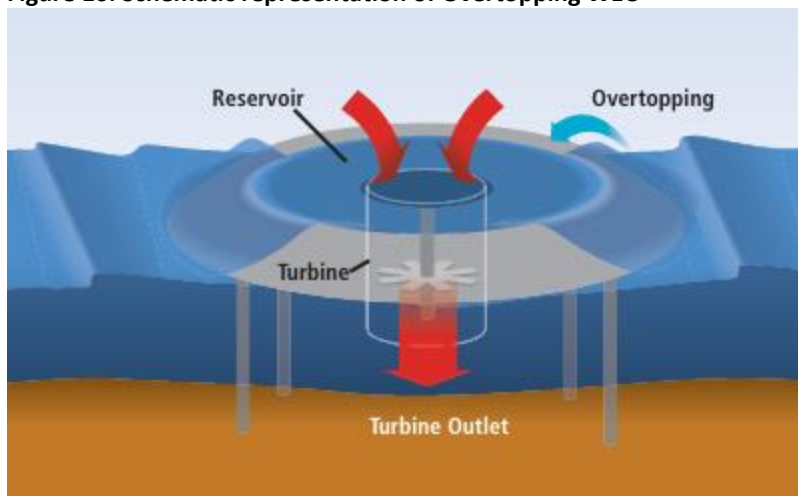
Source: (Falcão & Henriques, 2016)

#### iv. Overtopping

This type of WEC devices can be placed near the shore, and can be combined by breakwaters, or they can operate offshore. Their principal is to lead the incoming waves into a reservoir that is higher than the sea-level. Once water from waves is captured, it is drained back into the sea, passing through a turbine, generating power. Further studies have shown that the use of more than one reservoir can increase the average power output of the device (Kofoed et al., 2002, Kofoed & Osaland, 2005), with two to three reservoirs seem as the most reasonable options, based on cost criteria.

One of the most representative devices of overtopping WECs is that of Wave Dragon, which was connected to Danish grid in May 2003 (Kofoed et al., 2005). Schematic representation of overtopping WEC principal, a multiple-reservoir overtopping design and a 3D representation of Wave Dragon are presented in Fig 16, 17 and 18, respectively.

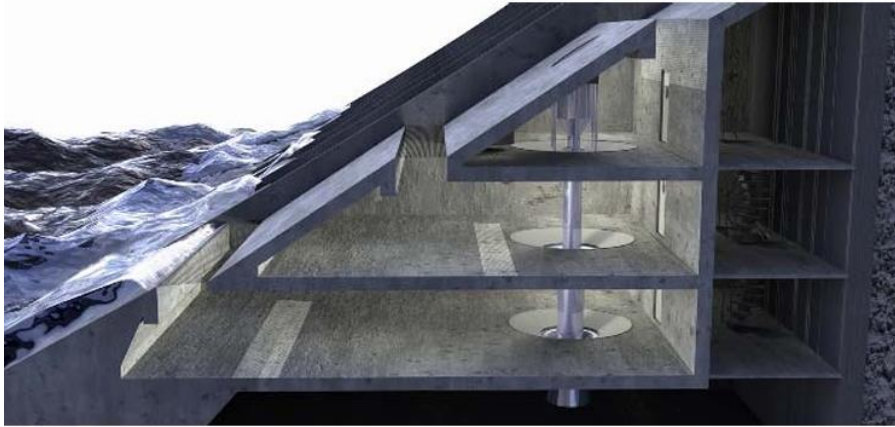
**Figure 16: Schematic representation of Overtopping WEC**



Source: (Lewis et al., 2011)

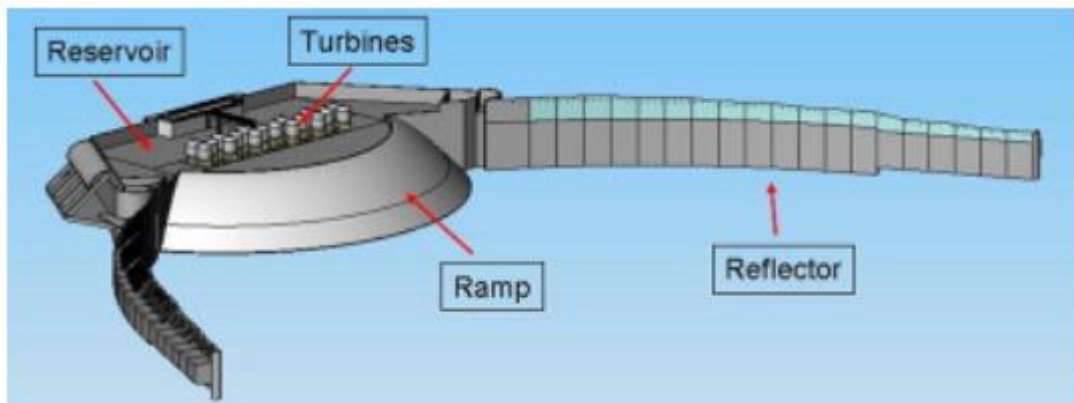


**Figure 17: Multiple-reservoir overtopping design**



Source: (Kofoed & Osaland, 2005)

**Figure 18: 3D representation of Wave Dragon**



Source: (Tedd & Kofoed, 2008)

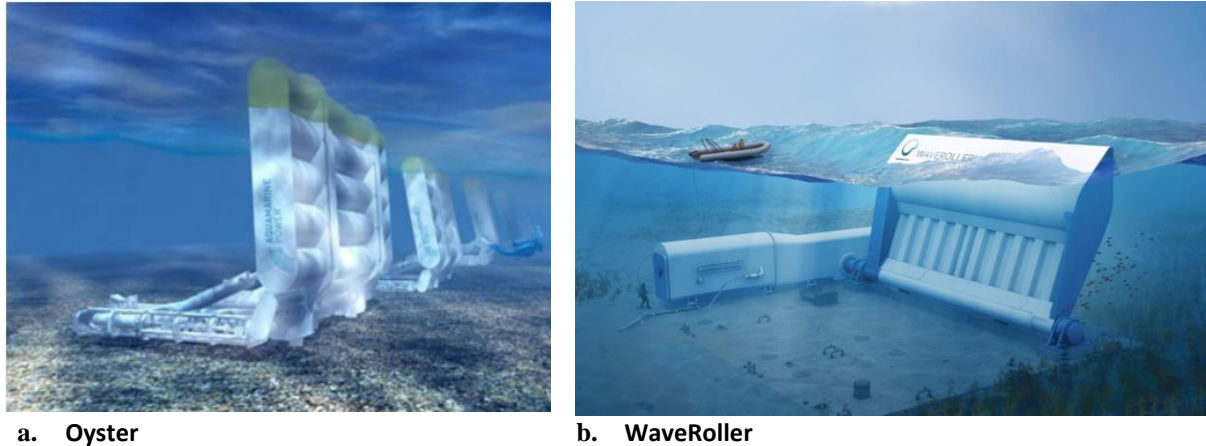
#### v. *Oscillating Wave Surge Converter*

Oscillating Wave Surge Converter (OWSC) has been studied extensively, due to its simplicity in structure. This converter usually comprises of a paddle or pendulum, vertical to the seabed, which is connected by a hinge or joint to a frame or base parallel to the seabed. The upper part of the paddle / pendulum is above the sea surface, forcing it to swing, due to the surge of the waves and, therefore, produce energy. OWSC's base can be fixed to the sea-bottom or it can be floating at a specific height above the seabed. In the past, OWSCs were commonly located near the shore and their base was attached to the seabed. However, as the floating technology evolves, new floating offshore structures have started being tested (Yu et al., 2015).

Fig. 19.a and 19.b present Oyster and Wave Roller, two typical OWSCs with their bottom frame attached to the seabed, while Fig. 20 presents the floating Reference Model (RM5), as analysed

by (Yu et al., 2015), on their technical report for the USA's National Renewable Energy Laboratory (NREL).

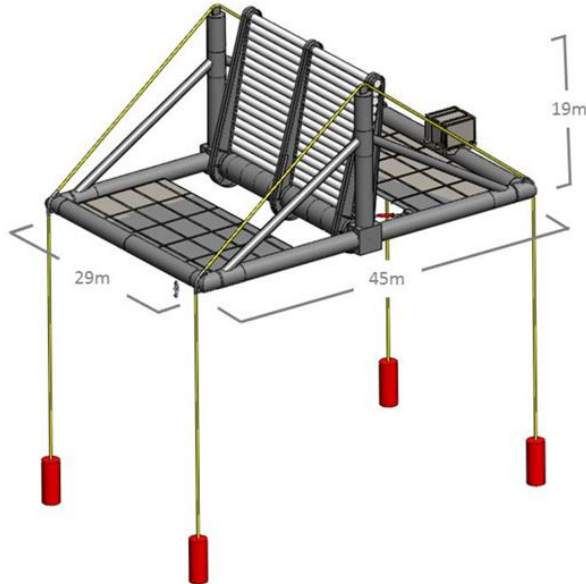
**Figure 19: OWSCs with their bottom frame attached to the seabed**



Source (a): (Oyster Wave Energy Converter, n.d.)

Source (b): (WaveRoller - AW-Energy, 2024)

**Figure 20: Floating Reference Model 5 (RM5)**



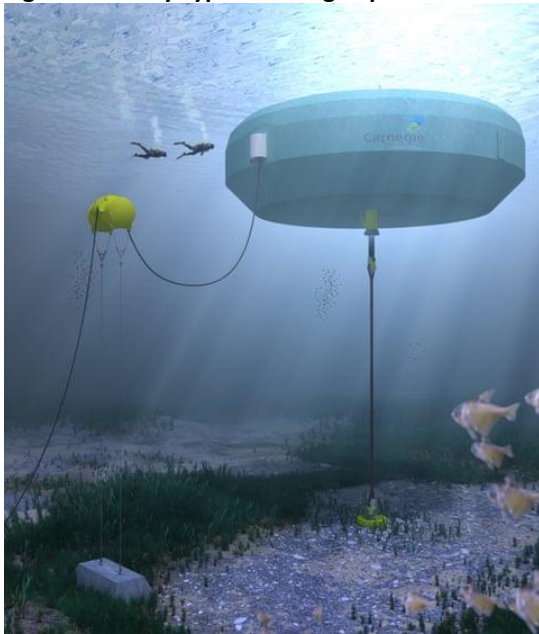
Source: (Yu et al., 2015)

#### vi. Submerged Pressure Differential WEC

Very similar to the design of the point absorbers are the submerged pressure differential devices for wave harvesting. These structures usually have a buoy, though in this case, the whole structure is located underwater, with the buoy submerged just below sea surface (Fig. 21). This

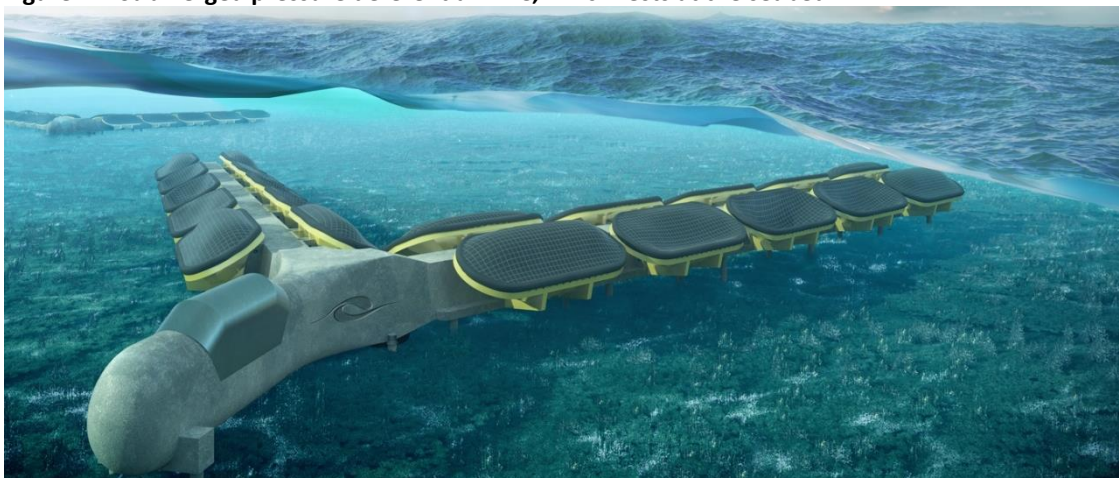
way the structure is protected from harsh weather conditions, while still producing energy through the movement of waves passing overhead. Submerged pressure differential devices can, also, be designed to rest at the seabed, using the pressure caused by the waves to produce energy (Fig. 22) or they can even alter their depth, in order to be protected from harsh weather conditions and strong sea waves (Fig. 23).

**Figure 21: Buoy-type submerged pressure differential WEC**



Source: (Parkinson, 2018)

**Figure 22: Submerged pressure differential WEC, which rests at the seabed**



Source: (Bombora Wave Power, 2020)



**Figure 23: Submerged pressure differential WEC, which can alter its depth below water**

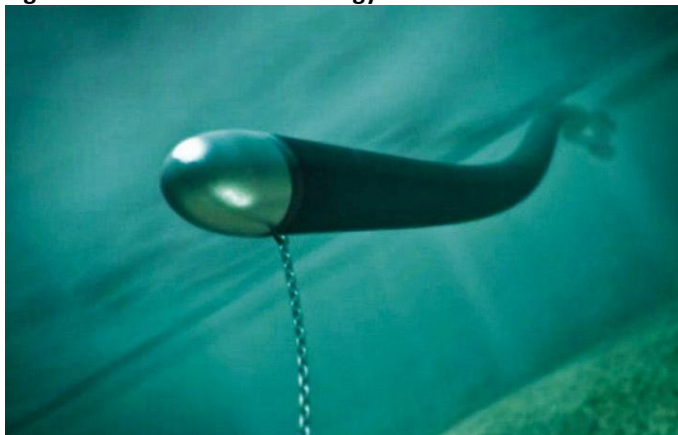


Source: (Projects – CalWave, n.d.)

#### vii. *Bulge Wave Energy Converter*

Usually located just below sea surface and anchored to the bottom of the sea, bulge wave energy converters are placed parallel to the predominant direction of the waves. They have a snake-like appearance, similar to that of attenuators, but without joints. They consist of a rubber tube filled with water, which is pressed by the force of passing-through waves, creating bulges that are travelling along the tube, generating power. The most well-known example of such a design was the Anaconda WEC (Fig. 24), licenced manufacturer of which was Checkmate SeaEnergy. Anaconda's model in scale was initially put into trial by the Southampton University in UK (Batten, 2012, Chaplin et al., 2012).

**Figure 24: Anaconda wave energy converter**

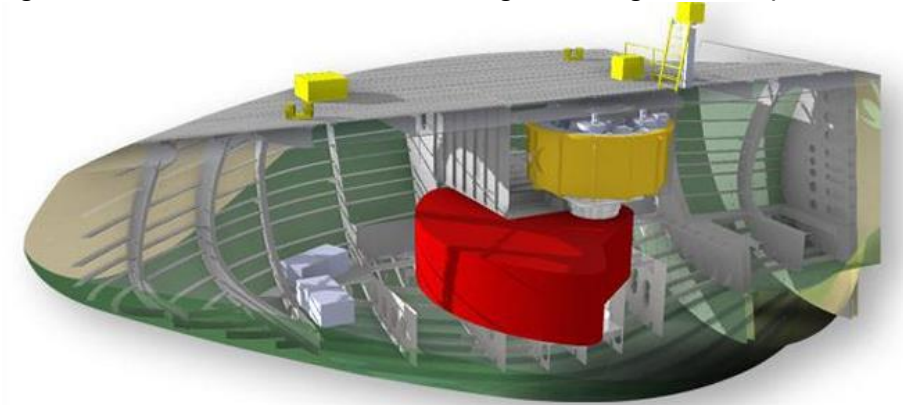


Source: (Checkmate UK Sea Energy, 2024)

### *viii. Rotating Mass WEC*

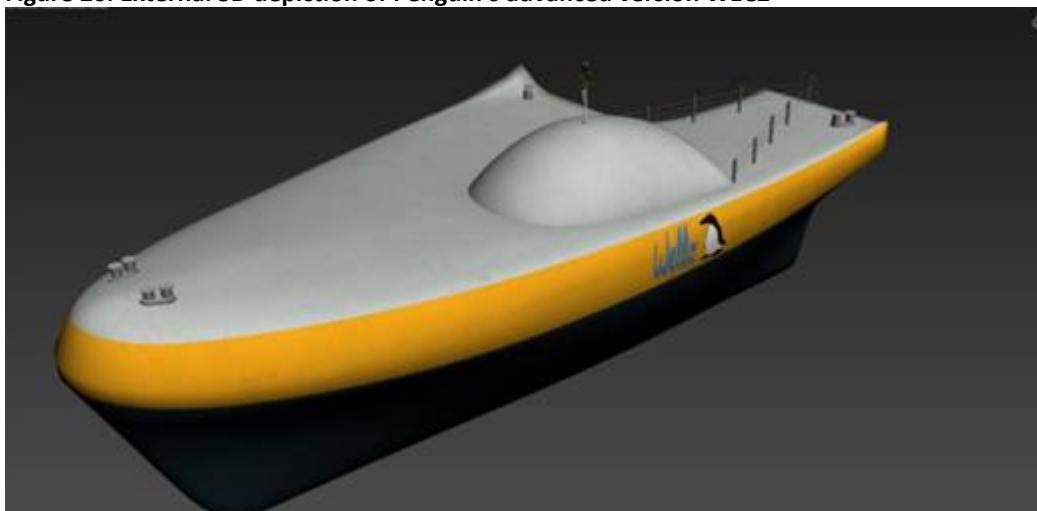
Rotating mass WECs are surficial devices, rotating eccentrically around their axis, exploiting the pitching and rolling of the sea waves. The movement of the waves are keeping the device in constant motion, forcing it to change their centre of gravity, producing this way a gyroscopic torque, which, in turn, is converted into energy. Full-scale models of Wello's Penguin rotating mass WECs have been tested at Orkney, Scotland and the Biscay Marine Energy Platform (BiMEP) test area in Northern Spain, not without problems though. The schematic cross section of Penguin rotating mass WEC is presented in Fig. 25, where rotating mass is coloured red, while Fig. 26 presents a 3D model of the external of the advanced version of Penguin.

**Figure 25: The schematic cross section of Penguin rotating mass WEC (in red: rotating mass)**



Source: (Wello - Wave Resource Assessment and Cost of Energy World Map | CMEMS, n.d.)

**Figure 26: External 3D depiction of Penguin's advanced version WEC2**



Source: (CEFOW -PENGUIN ARRAY Project Information Summary, 2018)

*ix. Other*

Other WECs do not fall under the above-mentioned categories and can be classified as other.

**2.1.2.4 Tidal Power – Tidal Energy Converters (TEC)**

As the name implies, tidal power refers to power produced from oceanic tides. It is considered more predictable form of energy than wind, solar or wave, it can produce energy during day or night and it is almost unaffected by the weather changes.

Tides derive from the centrifugal forces and gravitational attraction among the earth and the moon and -to a smaller extent- the sun and the relative motion among these three celestial bodies. The difference between the higher and the lower tide is known as tidal range.

The machines that convert tidal energy into electricity are known as tidal energy converters and the most common technologies behind these converters are tidal stream generators, tidal barrages and tidal lagoons.

*i. Tidal Stream Generator*

Tidal stream generators, also known as tidal current turbines, are transforming kinetic energy into electricity. They can be mounted to the seabed or float at a specific depth below water, or ever be attached underneath vessel-shaped floating structures. Their principals are similar to that of wind turbines and they usually bear blades. It is not uncommon for tidal stream generators to have more than one turbine, which can, also, be arrayed in different layouts. Water density, which is over 800 times higher than air density (Shetty & Priyam, 2021), can produce more energy, even when tidal stream generators' blades are moving with lower speeds than that of wind turbines.

Most common types of tidal stream generators are horizontal axis turbines, which rotate parallel to the flow of the current, and vertical axis turbines, the rotation of which is vertical to that of the water flow. The iconic, horizontal-axis, double-turbine tidal stream generator SEAGEN, in presented in Fig. 27. This generator was the first one to be connected to the grid and its operation initiated in 2008, in Northern Irland. By the summer of 2019 it was fully decommissioned.

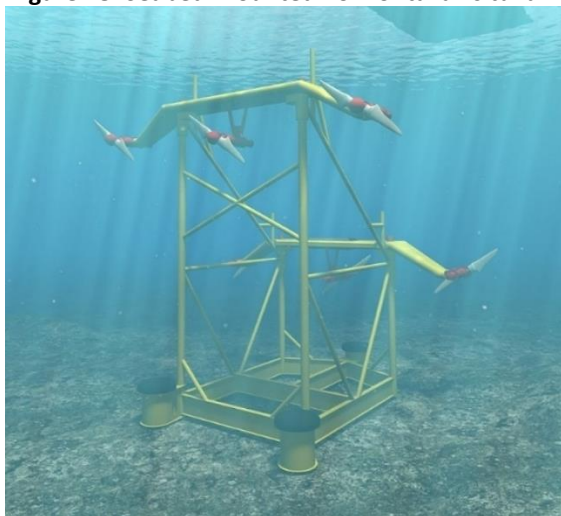
**Figure 27: SEAGEN tidal stream generator**



Source: Admin. (n.d.). *Marine Renewable Energy Services – CIMPINA*

Other, seabed-mounted horizontal axis turbines' tidal stream generators are presented below, as per Fig 28.a, 28.b, 28.c and 28.d.

**Figure 28: Seabed-mounted horizontal axis turbines' tidal stream generators**

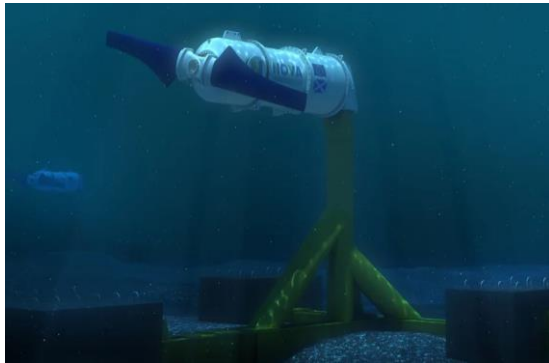


**a. HydroWing**



**b. MeyGen**





c. Nova Innovation's M100D turbine



d. Verdant Power's TriFrame

Source (a): (*HydroWing: Light Weight, Modular Platform*, n.d.)

Source (b): (Engineer, 2020)

Source (c): (*Nova Innovation | Tidal Energy and Turbine Developers*, n.d.)

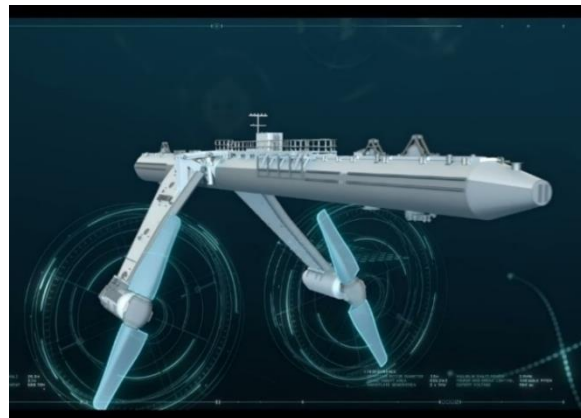
Source (d): (*RITE – Verdant Power*, n.d.)

Fig. 29.a, b, c and d present different structures of floating tidal stream generators with horizontal axis turbines.

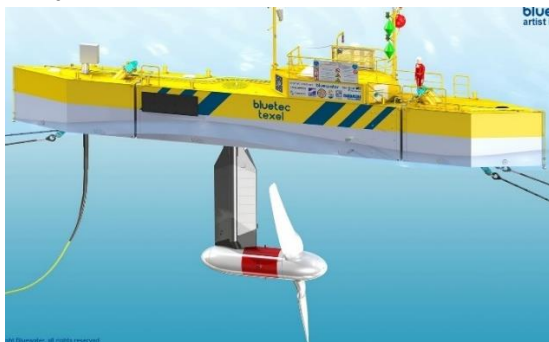
Figure 29: Floating tidal stream generators with horizontal axis turbines



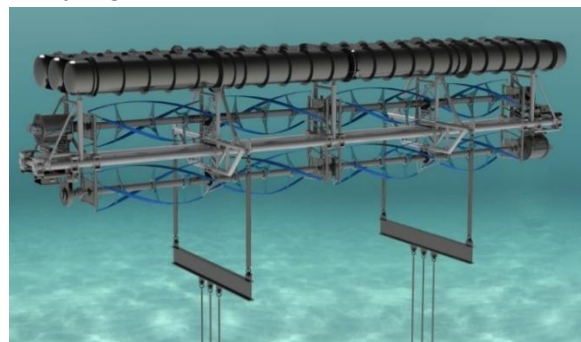
a. ATIR



b. O2



a. BlueTEC Texel Prototype



b. TidGen®8 Power System

Source (a): (*Magallanes Renovables | » Technology*, 2024)

Source (b): (Orbital Marine Power Ltd, 2021)

Source (c): (Bluewater Energy Services, 2019)

Source (d): (*Learn about ORPC - Netcapital*, n.d.)

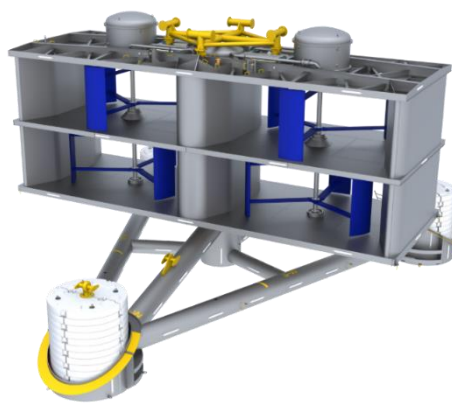


Apart from the, already mentioned, vertical axis generators (Fig. 30.a and 30.b), other types of tidal energy converters include: oscillating hydrofoils (Fig. 31.a), Venturi Effect devices (Fig. 31.b), tidal kites (Fig. 31.c), Archimedes screw (Fig. 31.d), and others.

**Figure 30: Tidal stream generators with vertical axis' turbines**



**a. HydroQuest's 2.5 MW TRL7**

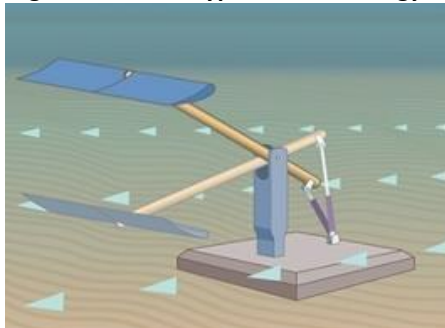


**b. OCEAN QUEST 1 MW prototype TRL6**

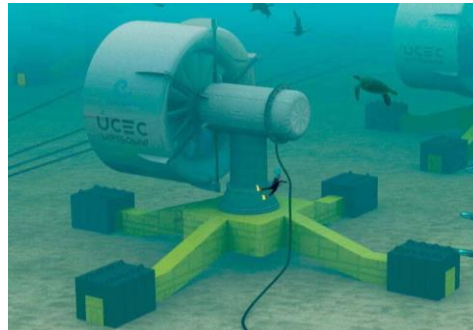
Source (a): (FloWatt - HydroQuest, 2024)

Source (b): (OceanQuest - HydroQuest, 2022)

**Figure 31: Other types of tidal energy converters**



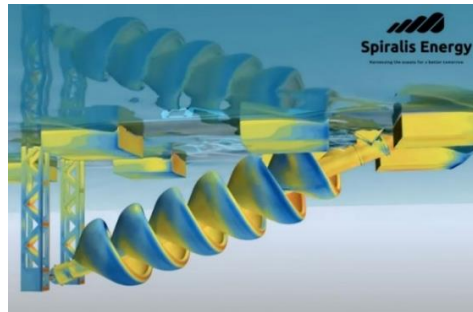
**a. Oscillating hydrofoil**



**b. Venturi effect device**



**a. Tidal kite, Minesto**



**b. Archimedes screw, Cape Horn Engineering & Spiralis Energy**

Source (a): (Thresher et al., 2012)

Source (b): (TIDALWATT, 2024)

Source (c): (BBC, *Tidal Kites: New Technology Harnessing Ocean Energy*, n.d.)

Source (d): (Cape Horn Engineering, 2024)

ii. *Tidal Barrage & Tidal Lagoon*

Tidal barrages, on the other hand, are types of barriers usually located across tidal rivers, estuaries or bays, forming a tidal basin. They take advantage of the tidal range and are able to generate electricity both during high and low tide, through the filling of the basin and the forceful releasing of the water during ebb. The largest barrages are that of Sihwa Lake's tidal power station in South Korea, operating since 2011, with electricity generation capacity of 254MW, and of Rance River estuary's tidal power plant in France, operating since 1966 with electricity generation capacity of 240MW. For energy production, tidal barrages require a tidal range of, at least, 5 meters (Shetty & Priyam, 2021). Due to the fact that there are not a lot of locations worldwide that fulfil this requirement, the potentials of such structures are limited. Same applies for the tidal lagoons, which are quite similar to barrages, but are built across coastlines (Pacific Northwest National Laboratory, 2021, *Tidal / Tethys*, n.d., U.S. Energy Information Administration, 2016).

The main disadvantages of tidal barrages are that their construction costs are very high, the production of energy might be far from consumption centres, they can impact navigation and they heavily disturb the aquatic life (*Tidal / Tethys*, n.d., U.S. Energy Information Administration, 2016, National Geographic, 2022, Shetty & Priyam, 2021). For tidal lagoons, the construction cost is lower than that of barrages, but remains still large in comparison to other RES (Waters & Aggidis, 2015), the production might be far from consumption centres, while there is controversy regarding the disturbance of aquatic life, with some advocating that disturbance is minimum (National Geographic, 2022) or acceptable (Waters & Aggidis, 2015), while other studies concluding that there may be a mismatch between the views of the projects' developers and that of the projects' influencing stakeholders regarding the environmental impacts (Elliott et al., 2017) or that the environmental impacts of lagoons are still posing a concern for the industry (Hinson, 2018, Hendry, 2016, Shetty & Priyam, 2021). However, with no operational tidal lagoons at present, these concerns cannot be verified by real-life data (Elliott et al., 2019). As tidal barrages and tidal lagoon technologies considered as nearshore energy harvesting systems, they will not be further elaborated, as they fall outside of current study's scope.

#### ***2.1.2.5 Ocean Thermal Power – Ocean Thermal Energy Conversion Technology***

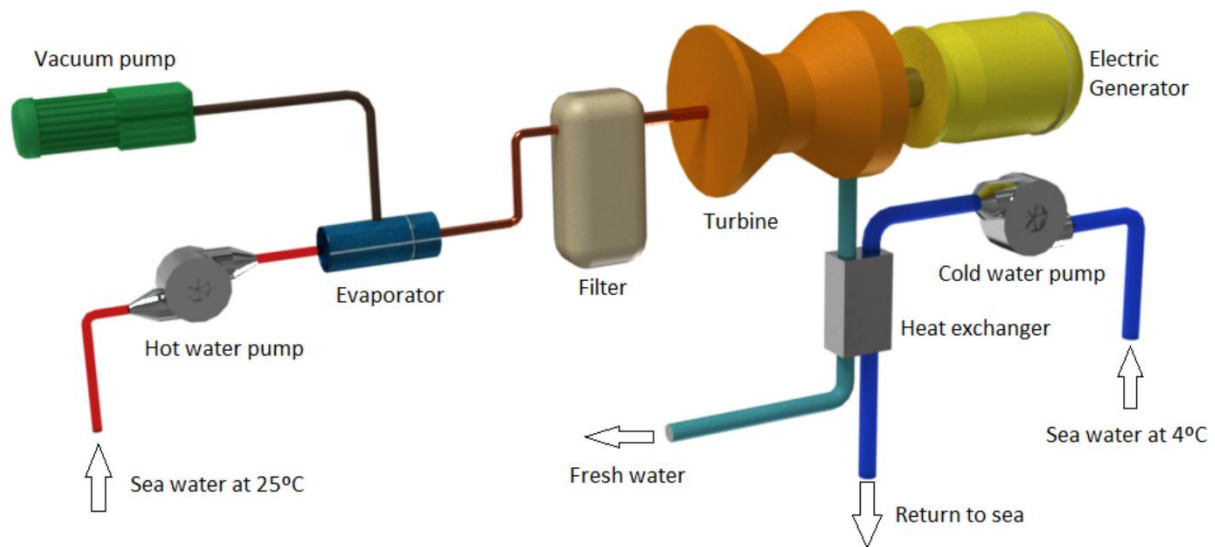
One of the most promising technologies for renewable energy harvesting is that of Ocean Thermal Energy Conversion (OTEC). Subject technology is using the temperature difference between the sea surface and that of deeper water to produce electricity. Seawater at depths of around 1000 meters has a temperature of about 2°C – 4°C. For OTEC technology to be efficient, a temperature difference of, at least, 20°C is needed (Adiputra et al., 2019). That means that surficial water temperature needs to be at about 22°C – 24°C or more. Also, in order for a OTEC power plant to be able to produce uninterrupted, temperature difference needs to remain at 20°C or more throughout the year. This is common in equatorial and tropical regions, between the latitudes of 30 degrees north and south of equator (Rau & Baird, 2018), where surficial water maintains a temperature difference of more than 20 degrees during the year. The volume of warm and cold water needed for such a plant throughout the day is huge and the need is constant, but due to the production stability, OTEC plants can be used to generate baseload electricity, i.e. the minimum level of electricity needed by the grid at any given time (NOAA *Ocean Thermal Energy Conversion (OTEC) Technology*, n.d.).

The main principle behind OTEC technology is that it uses a working fluid, which evaporates during the procedure, thus it expands, in order to spin a turbine, which, in turn, is transforming kinetic energy into electricity. This can be achieved through different types of OTECs. The main types are the open cycle, the closed cycle and the hybrid.

##### *i. Open Cycle OTEC*

Open cycle OTECs are using seawater, pumped from the sea surface, as the working fluid. In order for seawater to evaporate, it needs to reach its boiling point. This can be achieved through the use of a vacuum chamber, where the pressure is close to absolute zero (usually between 1% and 3% of atmospheric pressure). As the atmospheric pressure decreases, the boiling point of water also decreases; thus, water is reaching its boiling point and evaporates. The salt and all other components of seawater remain at the chamber, while the evaporated water is desalinated and can be used as fresh water. The vapour enters the turbine and the kinetic energy is transformed into electricity through an electric generator. Cold water, from deeper sea layers, is then used to condense the vapours back into their liquid state and return the fresh water back into the sea (Herrera et al., 2021). A schematic representation of open cycle OTEC is presented in Fig. 32.

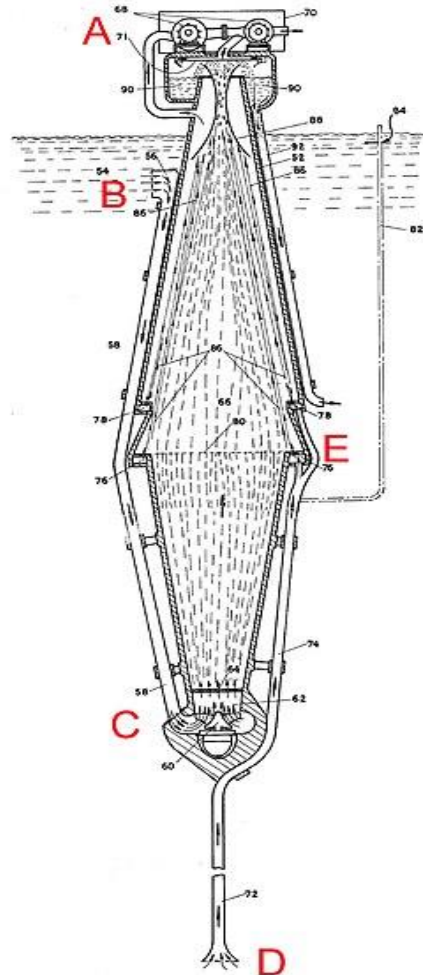
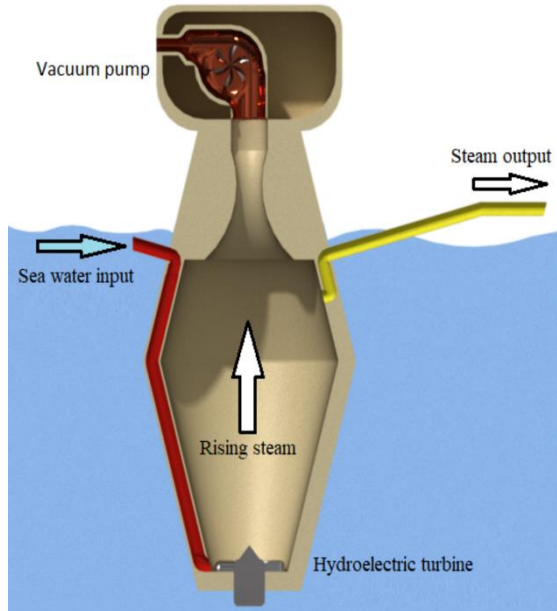
**Figure 32: Schematic representation of open cycle OTEC**



Source: (Herrera et al., 2021)

A modification of open cycle OTECs are the open cycle with mist lift. There are various designs for such OTECs. Below description is based on a vertical design, which includes a main chamber with three openings, one for warm water intake, a second one for cold water intake and a third opening for the return of water back into the sea. A large vertical tank of approximately 100 meters, usually made of concrete, is used. The larger part of that tank is submerged into the sea. From a submerged entry, close to the sea-level, the surficial warm water is entering the tank, falling from a height of about 100 meters, to a hydroelectric turbine, located at the bottom of the tank. This way, and due to gravitational force, the turbine turns and energy is produced. This water needs to return back into the sea, so that a new cycle can start again. In order for water to escape the tank, vacuum conditions – close to absolute zero – are created. The water is evaporating and, as it travels up through the tank, cold water from deeper sea is sprayed upwards into the chamber at a height of more than 20 meters. This process is creating, what is known in fluid mechanics as a multiphase steam (a fluid in two different phases: water vapour mixed with liquid water sprays), which has the ability to pull the steam up and out from the tank faster, based on fluid mechanics' "pneumatic transport" (Charwat & Ridgway, 1980, US patent 4441321A, 1984, Herrera et al., 2021). Below Fig. 33.a and 33.b are schematic representations of vertical submerged open cycle OTEC with mist lift, with the second being one of the drawings included into Ridgway's patent approval (US patent 4441321A).

Figure 33: Schematic representations of vertical, submerged, open cycle OTEC with mist lift



- A. Vacuum Pump which creates conditions close to absolute zero inside the chamber
- B. Warm surfacial water's entry opening
- C. Location of hydroelectric turbine
- D. Cold Water tube, reaching depth of 1000 meters below sea-level
- E. Cold water intake. From this level the cold water is sprayed upwards.

a. Cross-section of open cycle OTEC with mist lift

b. Drawing of open cycle OTEC with mist lift, as per US patent's number: 4441321A

Source (a): (Herrera et al., 2021)

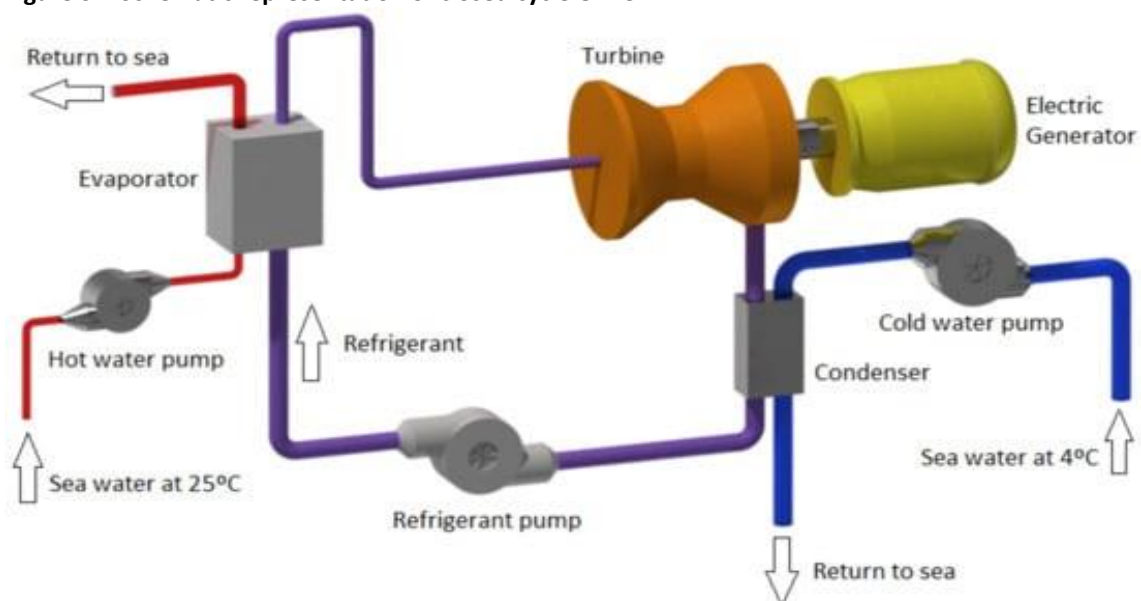
Source (b): (Wikipedia contributors | Mist lift, 2021)



## ii. Closed Cycle OTEC

In the closed cycle OTEC systems, the working fluid used is a refrigerant – most commonly ammonia – which has a low boiling point. The working fluid circulates within a closed loop. The warm, surficial, seawater – which is sufficient to evaporate the working fluid – is entering the system through an evaporator (a heat exchanger where the working fluid is circulating, too). Warm seawater's use is to evaporate the working fluid, and it will do that by transferring its heat. As the working fluid (e.g. ammonia) vaporises, it expands, reaching a turbine, which – in turn – is set into operation, producing kinetic energy. This energy is transformed into electricity through an electric generator. Cold water, from deeper sea-layers, entering the system through a condenser, is changing the state of the working fluid from vapor back into liquid. In order for both warm and cold seawater to be able to enter the system, water pumps are used to lift seawater up, as can be seen in the schematic presentation of closed cycle OTEC, in Fig. 34. Also, both evaporator and condenser are, actually, heat-exchanger systems. Although such systems carry lower costs and less technical challenges than that of open cycle, they lack the ability to produce desalinated water and, in many cases the working fluid used may be hazardous, toxic or easily flammable (Herrera et al., 2021, IRENA Innovation outlook: Ocean energy technologies, 2020, NOAA *Ocean Thermal Energy Conversion (OTEC) Technology*, n.d.).

**Figure 34: Schematic representation of closed cycle OTEC**



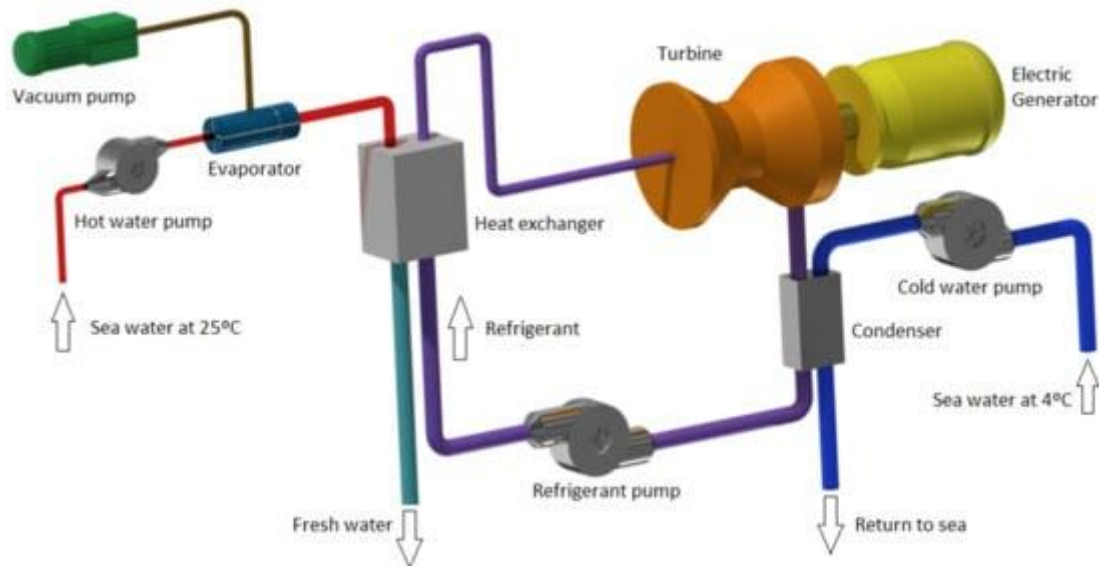
Source: (Herrera et al., 2021)



### iii. Hybrid OTEC

A combination of open and closed cycle OTEC technology is the hybrid OTEC system. This type of OTEC is working in two stages. During the first stage, warm surficial seawater is entering the system and is evaporating in a chamber, by the use of a vacuum pump. The vapours are travelling through a tube to reach a shared (between the open loop and the closed loop) heat exchanger. There, the working fluid (e.g. ammonia), which is also entering the shared heat exchanger, is evaporating too, while the evaporated water turns back into its liquid state, already desalinated. During the second stage, the working fluid in the closed loop is repeating the procedure described above for the closed cycle OTEC, turning the turbine and producing energy, before it is condensed back to its liquid phase, through the cold-water condenser (Herrera et al., 2021, IRENA Innovation outlook: Ocean energy technologies, 2020). A schematic presentation of this procedure is presented in Fig. 35.

**Figure 35: Schematic representation of hybrid OTEC**



**Source: (Herrera et al., 2021)**

Apart from solving the problem of drinking water in islands or districts where potable water is scarce, desalinated water can, also, be used for irrigation purposes or even production of green hydrogen. On the other hand, the cold seawater, which is pumped from deeper sea, instead of returning back to it, after being used as condensing liquid in OPEC cycle, it can be utilised in different fields. Its temperature after use is approximately 10°C and can be used as cooling fluid for air conditioning systems on-land. Also, deeper sea water is nutrient-rich and has been

proposed for aquacultural, as well as fishery fertilization purposes (Kobayashi et al., 2001, Ishaq & Dincer, 2019).

According to 2021 IRENA's publication of offshore renewables (IRENA Offshore renewables: An action agenda for deployment, 2021), 57.63% (or 44000 TWh/year) of the ocean energy recourse potentials, derive from OTEC technology. Wave potentials follow with 38.64% (or 29500TWh/year) and the salinity gradient and tidal follow with 2.16% (1650TWh/year) and 1.57% (1200 TWh/year) respectively.

Apart from the already active, there are miscellaneous OTEC power plants in the planning or development phase (Fig. 36), mainly for suppling power and provide desalinated water to islandic regions (IRENA Innovation outlook: Ocean energy technologies, 2020, EIA, 2016).

**Figure 36: Global map of active, projected and under construction OTEC power plants**



Source: (IRENA Innovation outlook: Ocean energy technologies, 2020)

#### ***2.1.2.6 Salinity Gradient Power (Osmotic Energy) – Main Technologies***

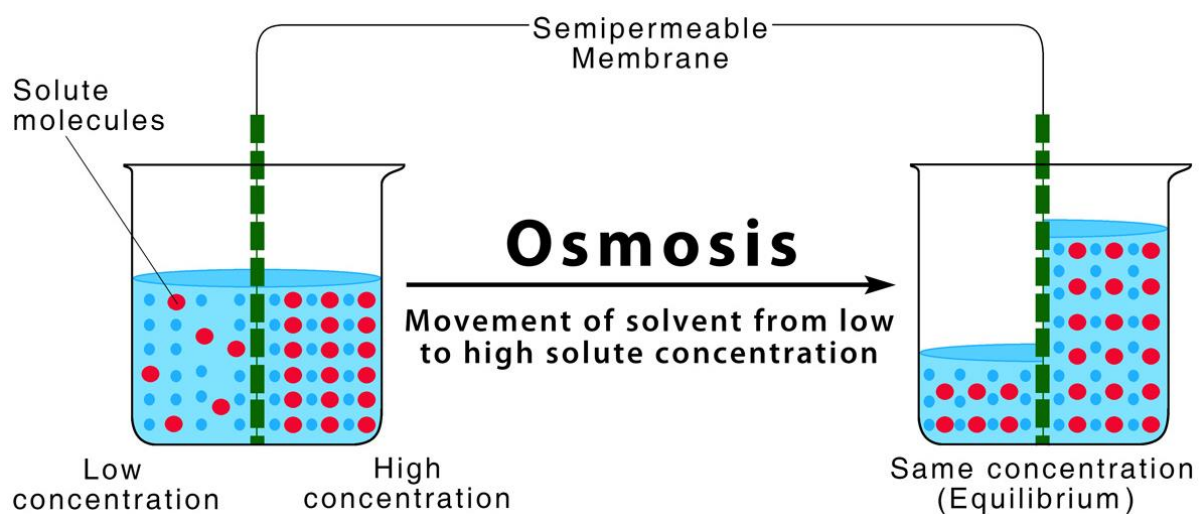
Another way to harness energy is through the difference in salinity concentration between two fluids, such as seawater and fresh water, when they mix. The mixing of seawater and fresh water is releasing energy as heat, which can be turned into electricity. The difference in salinity concentration between two fluids is known as salinity gradient. The two most studied methods in turning salinity gradient into electricity are the Pressure-Retarded Osmosis (PRO) and the

Reversed Electro Dialysis (RED). Both methods use membranes, but the type of membrane used in each case have different characteristics.

*i. Pressure-Retarded Osmosis (PRO) method*

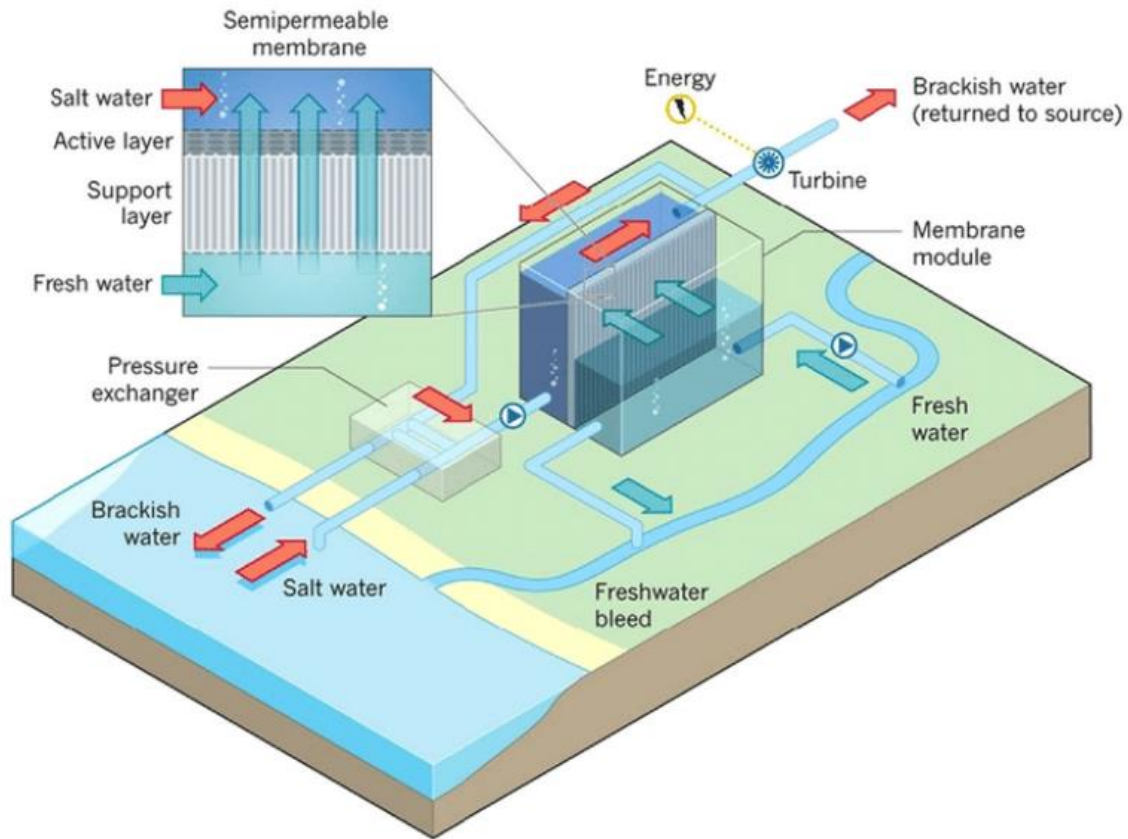
When two solutions with different concentrations are mixed, e.g. seawater and fresh water (different salt concentration), they are trying to reach an equilibrium in concentration. Thus, the final mixture will be less concentrated than seawater, but more concentrated than fresh water. If a semi-permeable membrane is used between these two solutions, which is allowing only the solvent (water, in this case) to pass through, in the effort of the two solutions to reach equilibrium, the fresh water will pass the membrane towards the seawater, as per Fig. 37. This phenomenon is known as osmosis. This is the principal used in the PRO method. As the column of seawater (right column in Fig. 37) rises, hydraulic pressure is created, which is, then, released through a tube, where a turbine is adjusted, as per Fig. 38. The turbine is turning, producing energy, before brackish water leaves the tube. This energy is known as osmotic energy. Generally, the energy produced is proportional to the difference in salinity concentration. Thus, brine, which has higher salinity concentration than seawater, will be able to produce more energy if combined with freshwater, leading to reduction in cost of energy production (Jung et al., 2022, Haddout et al., 2023).

**Figure 37: Osmosis**



Source: (Mukherjee, 2023)

**Figure 38: PRO method energy production**

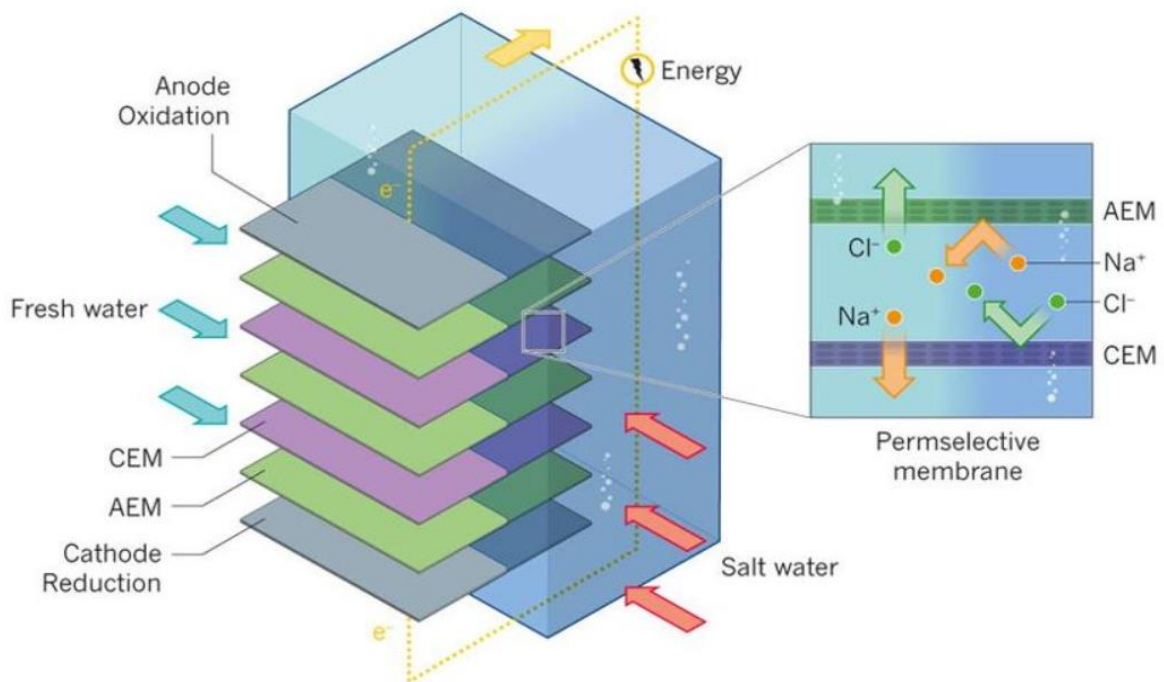


Source: (IRENA Renewable Energy Statistics Training, n.d.)

ii. *Reversed Electro Dialysis (RED) method*

In the case of RED method, a stack of two different types of membranes is used. Both types of membranes are permselective, meaning that they select what is permitted to pass through them. The first type of membrane used is Anion Exchange Membrane (AEM), meaning that it is permitting anions to pass through (excluding the pass of cations). The second type of membrane is Cation Exchange Membrane (CEM), allowing only cations to pass through it. As AEMs and CEMs are arrayed interchangeably, they create compartments of high and low salinity. In the endings of each stack there is an anode and a cathode, as per Fig. 39, creating a kind of battery. In this case, energy is produced without the need of a turbine.

**Figure 39: RED method energy production**



**Source: (Reverse Electrodialysis | Tethys Engineering, n.d.)**

For harvesting salinity gradient energy, locations where rivers meet the sea, like river deltas or fjords, are considered very good options, but there might be other alternatives for locating such plants, too. In his 2017 study, (Arias, 2017) described a salinity gradient process used, instead of pumps, for pulling water up to the sea surface for an OTEC plant's operation. The process was based in deliberate salinization of surficial seawater, in order for salinity difference to be created. Such combined structures could be located offshore, while the possibility of fresh water, produced from OTEC (e.g. fresh water as by-product in OTEC's open or hybrid cycle), instead of deliberately salinized seawater could be studied, alternatively. In such a case, a portion of the freshwater produced could be used as potable or for irrigation purposes, while the remaining portion could be used in osmosis procedure, as mean of salinity gradient-based form of pumping the water needed by the OTEC plant.

One of the most important advantages of salinity gradient is that power can be generated 24 hours a day, giving stability to the grid, by producing baseload, and acting complementary to other, more variable, forms of energy, such as wind and solar (*Salinity Gradient - Ocean Energy Europe*, 2023).



The capital cost, however, is higher than other RESs, mainly due to membranes' cost, which accounts for 50% - 80% of the total capital cost. Thus, further improvements in membranes' cost, as well as their technology, in regards to durability and power density, are expected to be significant factors in bringing this technology closer to commercial use (IRENA Salinity gradient energy, n.d.).

#### **2.1.2.7 Green Hydrogen**

Hydrogen (H), with chemical formula  $H_2$ , is a highly flammable, colourless, odourless, non-toxic chemical element. It is abundant on earth and this is one of the main reasons it is gaining popularity in the renewable energy sector in recent years. Another reason is that it carries high specific energy density, meaning that it contains more energy per unit of weight compared to other energy sources. In comparison to petrol or diesel, its energy density is about three times greater, since a kilo of hydrogen contains 33.33 kWh, while a kilo of petrol or diesel contains 12 kWh, but storing hydrogen requires greater volume (Yue et al., 2021).

Hydrogen, almost always, is found as part of another compound, such as water ( $H_2O$ ), from which it needs to be separated, in order to be used. For it to be classified as green, both the compound which hydrogen derives from, as well as the energy source used for the separation of hydrogen from its compounds need not to be pollutant emitters. The most common compound used for hydrogen production is water and the most common procedure for such a separation is an electrochemical reaction, called electrolysis. Electrolysis is using electrical current to break-down water molecules into its elements: oxygen and hydrogen (Queensland State, 2024). The apparatus by which electrolysis is performed is called electrolyser.

In the case of water-based hydrogen production with use of renewables as source of energy for electrolysis, the only by-product is water vapor. Thus, zero GHGs are emitted during this process. The produced hydrogen, in this case, is called green or clean or renewable hydrogen. For the production of 1 kilogram of green hydrogen, about 10 Liters of clean water are needed (Mueller & Dittmeyer, 2023), while the life-cycle of an electrolyser is about 7 to 10 years (*The Rise of Offshore Hydrogen Production at Scale - Ramboll Group*, n.d.).

Four types of electrolyzers for use in green hydrogen production have been developed or are currently at development stage:

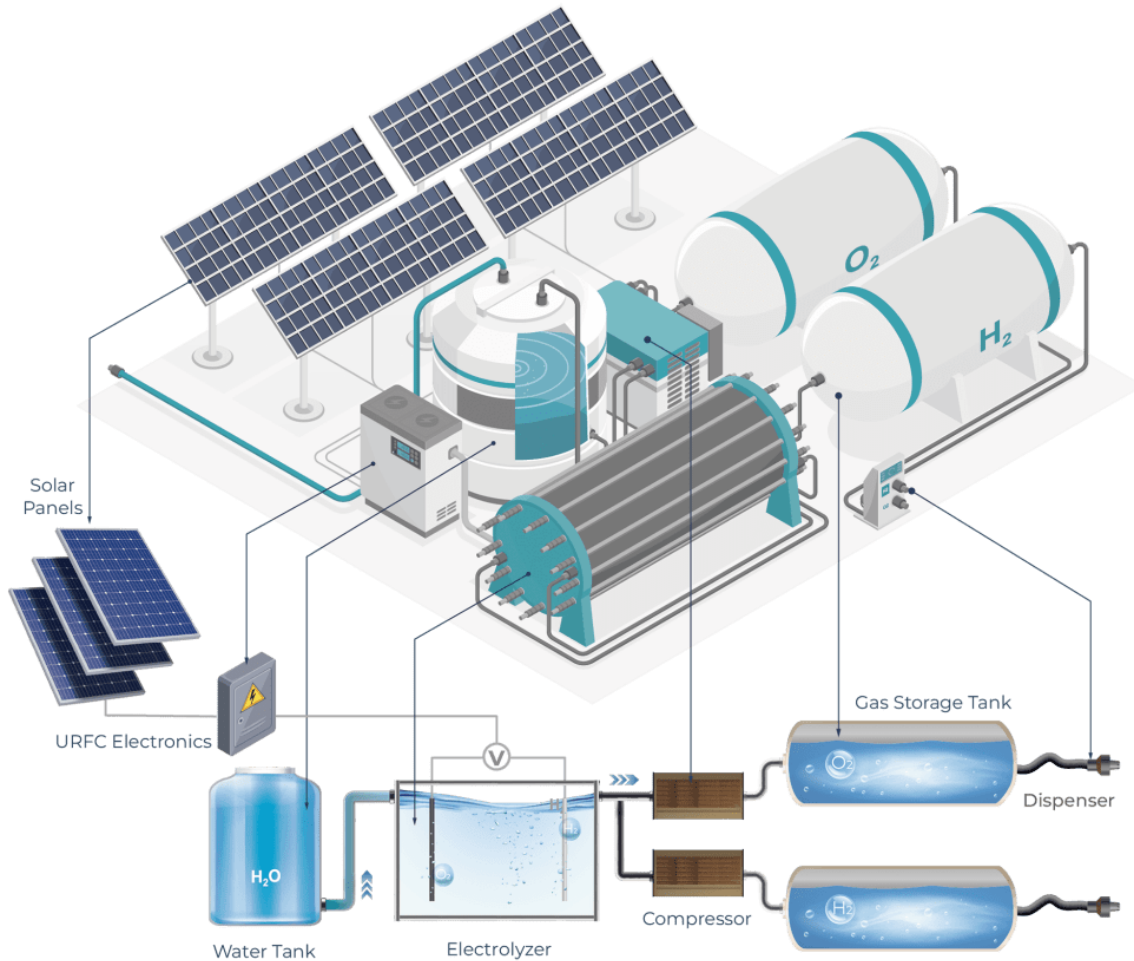


- i. *Alkaline electrolyzers.* These electrolyzers use a liquid alkaline electrolyte, usually potassium hydroxide, and, economically, they are the most competitive type today, due to their low-cost materials, the simplicity in design, their life span and because they do not require ultrapure water. They are the most matured technologically and the broader used globally. Their main disadvantages are their relatively low efficiency and their late start / stop response, which is creating difficulties in coupling them with variable renewables (Brynolf et al., 2018, *Hydrogen Production by Water Electrolysis - Jennings Anodes*, 2024, IRENA Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5°C, 2020).
- ii. *Proton Exchange Membrane (PEM) Electrolyzers.* They carry the second most established technology after alkaline electrolyzers and they are considered safer, due to the absence of caustic electrolytes (*Jennings Anodes*, 2024), since the electrolyte used in this case is a solid polymer membrane. The water fed must be ultrapure, but they respond fast to rapid load changes, rendering them a suitable choice in coupling with variable renewables. One of their main disadvantages, though, is high cost (Brynolf et al., 2018, Mueller & Dittmeyer, 2023, Herold, 2024, Pellegrino et al., 2024).
- iii. *Anionic Exchange Membrane (AEM) Electrolyzers.* This is an emerging and very promising new technology. AEM electrolyzers use an alkane electrolyte and an anion exchange membrane and they can be easily coupled with variable renewables, since they can respond fast to rapid load changes, but the cost of the materials is still high – although lower than that of PEM electrolyzers (Pellegrino et al., 2024).
- iv. *Solid Oxide Electrolysis Cells (SOECs).* Another new, but very promising technology, not commercially available yet, though. SOECs use solid ion-conducting ceramics as electrolytes (Pellegrino et al., 2024), as well as water in the form of steam (*Jennings Anodes*, 2024), and can produce highly pure hydrogen (Pellegrino et al., 2024). The materials used are inexpensive, SOECs present increased energy efficiency, but the temperatures needed for their operation – typically ranging between 650°C to 1000°C – are significantly higher than that of other electrolyzers' operating temperatures, which range

between 40°C to 90°C (Pellegrino et al., 2024, IRENA Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C, 2020). SOECs are suitably coupled with high temperature / high heat sources, but they seem unsuitable for coupling with variable renewables, due to their limited long-term stability. Since they are still at development stage the costs cannot be determined yet, thus, only estimations are available (Brynolf et al., 2018).

A special reference must be made to hydrogen's storage options, due to the challenges they present, stemming from hydrogen's gaseous nature and its light weight. Two of the most common ways for storage of hydrogen is under high pressure (compressed hydrogen), or under low temperature (liquified hydrogen). In both cases, cylindrical vessels are most commonly used for storage, but in the second case a percentage of 1.5%-3% is estimated that it evaporates from the tank per day. A combination of high pressure and low temperature can be used, as an alternative way of storage (Cryo-compression). Other ways include chemical interaction with metals (metal hydrides and complex metal hydrides), physical adsorption and liquid organic hydrogen carriers (LOHC) (Usman, 2022). LOHCs have liquid form and, through chemical reactions, they can absorb hydrogen or release it back. They are used as storage means for hydrogen, since both storage and transportation of LOHCs is simpler than that of hydrogen, because LOHCs can be handled at ambient conditions (Carvalho et al., 2021). Fig. 40 presents a hydrogen production system, coupled with solar panels, where electrolyser and storage tanks are included.

**Figure 40: Hydrogen production system, coupled with solar panels**

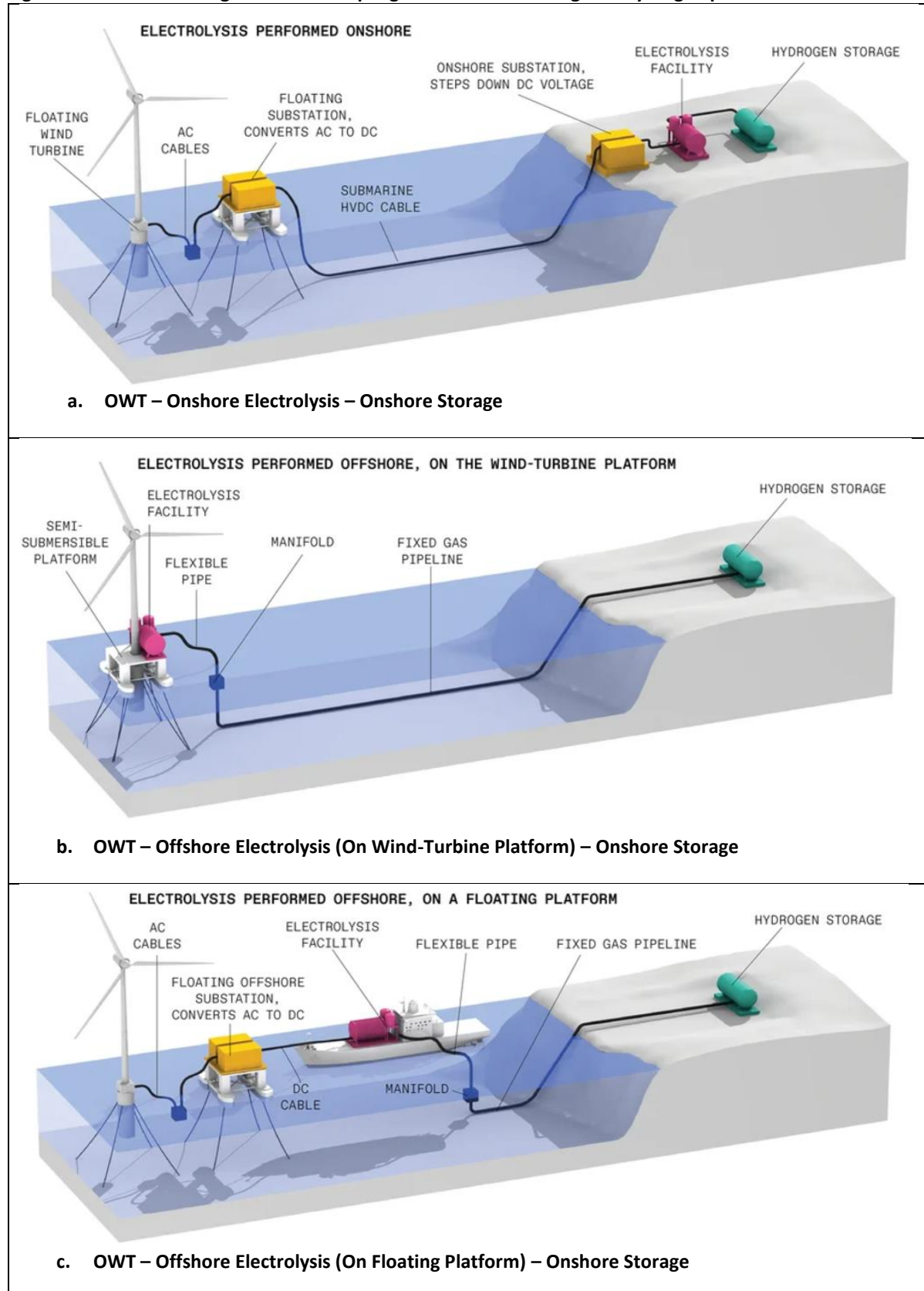


**Source: (Jennings Anodes, 2024)**

For green hydrogen production, most common couplings offshore are those including wind or solar, due to higher maturity of subject technologies. However, green hydrogen production can, also, be coupled with tidal, wave, OTEC, salinity gradient or biogas energy systems (Pellegrino et al., 2024, Awad et al., 2023, Ishaq & Dincer, 2019).

Another factor which plays vital role in the green hydrogen production offshore, in regards to energy coupling, is the configuration. Many studies have assessed different scenarios in the positioning of electrolyzers, substations – AC / DC converters and storage facilities, as well as RESs' clustering options, inclusion of more than one RESs to the system and the dilemma of connection to the grid or not. Fig. 41.a, 41.b and 41.c present different configurations in coupling an OWT with a green hydrogen production system.

**Figure 41: Different configurations in coupling offshore wind with green hydrogen production**



Source (a, b, c): (Mueller & Dittmeyer, 2023)

Different variations of such couplings between offshore wind and hydrogen production configurations have been included in a 2022 study (Ibrahim et al., 2022), where the selection of different materials and technologies regarding electrolyser, desalination, wind platform, cables and pipelines have been explored. In this case, the different scenarios referred to a dedicated floating offshore wind to hydrogen platform. (Yan et al., 2021) assessed 5 different scenarios, also coupling offshore wind with hydrogen production and storage / distribution system. In their study, they analysed the hydrogen price for the different scenarios and concluded that distance from shore plays a vital role in the configuration selection, since for production of hydrogen offshore, in case of mid-distances from the shore, a pipeline is a better option, while for hydrogen production offshore and longer distances, ship tankers are preferable. This study referred, also, to the supplementary physis of energy produced from wind and hydrogen and included an idea of energy balancing into this coupling, by the production of hydrogen during wind power surplus (e.g. during the night) and re-use of hydrogen during wind power deficit (e.g. during days with no wind). Similar scenarios were studied by (Jang et al., 2022) and (Ramakrishnan et al., 2024), while (Queensland State, 2024), also referred to production of hydrogen from the curtailed wind and solar energy, i.e. the excess RESs energy not being able to be absorbed by the grid.

Other papers assess scenarios where more than one OWTs are clustered with an electrolyser (IRENA Offshore renewables: An action agenda for deployment, 2021) or scenarios incorporating more than one ORESs into the system, such as both wind and solar, as well as batteries (*Grid-Integrated Offshore Power-To-Gas*, n.d.), or even the use of decommissioned gas pipelines for further reduction of capital cost of such systems (Yan et al., 2021). In this case, the energy loss from the transportation of hydrogen onshore via pipelines is significantly less, compared to that of electric cables transporting energy from ORESs (Ibrahim et al., 2022). Use of decommissioned O&G platforms can further reduce cost and promote efficiency. Currently the biggest projects, coupling offshore wind with hydrogen production are AquaVentus (Fig. 42) and BrintØ Green Hydrogen Island, with a capacity of 10 GW each, both in North Sea.



**Figure 42: AquaVentus project (3D presentation) coupling offshore wind with hydrogen production**



Source: (AquaVentus, 2024)

One of the most important challenges in hydrogen production is the high price of the final product (IRENA Offshore renewables: An action agenda for deployment, 2021). And although coupling with ORESs carries the advantage of not using land, which can be left free for other uses, the unavoidable use of seawater entails additional desalination and brine management costs (*Grid-Integrated Offshore Power-To-Gas*, n.d.). Furthermore, in order for economies of scale to be achieved, electrolyzers need to become more efficient and carry greater power (*The Rise of Offshore Hydrogen Production at Scale - Ramboll Group*, n.d.). Energy production variability, following most RESs – wind turbines included – poses an additional challenge in efficiency and cost-competitiveness of coupled hydrogen production with ORESs (Ibrahim et al., 2022).

Biomass and marine biomass can, also, be used for production of green hydrogen, through biochemical conversion (Obiora et al., 2024, Show et al., 2018), while reforming of biogas to hydrogen is an alternative option (European Commission, 2020). And as per water-based hydrogen production, if coupled with renewables, no GHG emissions are produced in this case, either (Queensland State, 2024).

The importance of green hydrogen in decarbonisation is that it can fuel industries and heavy vehicles that are hard-to-decarbonise. Use in transport sector, and especially shipping, aviation, heavy vehicles, trains and public transports is of paramount significance. Vehicles using hydrogen can be refuelled fast and, due to hydrogen's high energy density, they need less refuelling per distance. Furthermore, hydrogen can contribute to the high energy needs of heavy



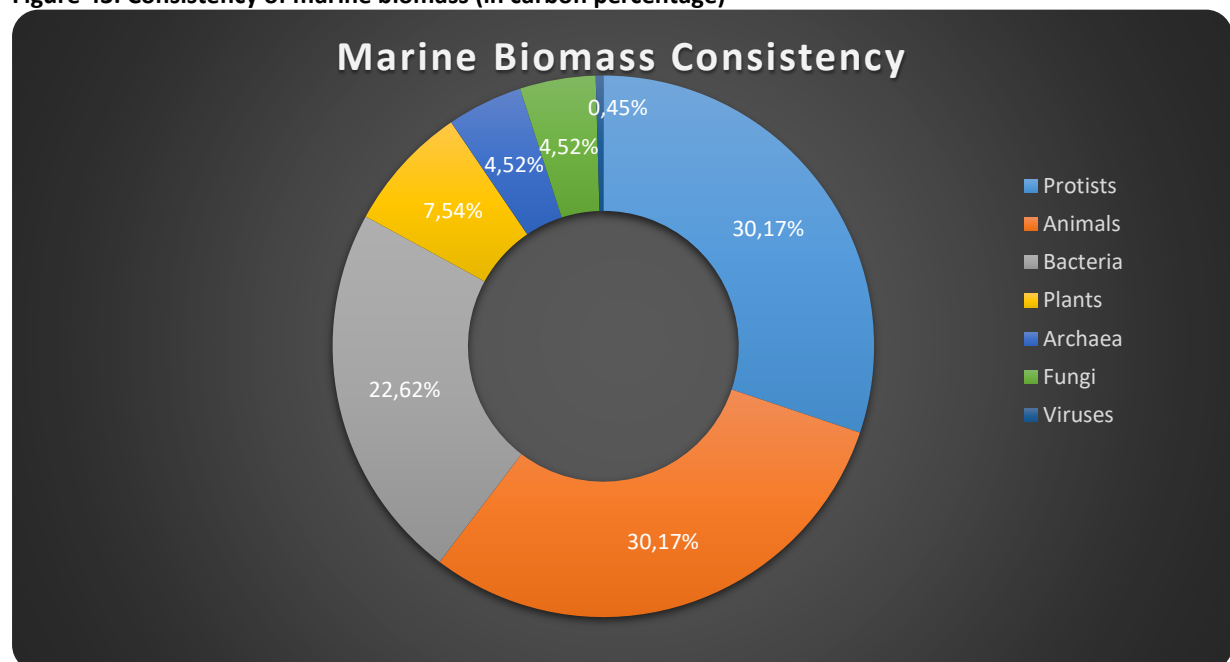
industries, such as manufacturing and steel. In the chemical industry it can be used for the production of methanol and ammonia, while ammonia can be further processed for fertilisers' production. Hydrogen can, also, be used in the food industry for hydrogenation of food (HOPE, 2024) and in heating systems, although relative technology is currently immature, bearing high costs (*Hydrogen Overview* / *MINISTRY OF NEW AND RENEWABLE ENERGY* / *India*, n.d.).

#### 2.1.2.8 Bioenergy – Marine Biomass and 3<sup>rd</sup> Generation Biofuels

Marine biomass, which has received higher attention in recent years, can be used to produce various forms of energy, biofuels being one of them. Marine biomass constitutes a subcategory of biomass, which includes living or recently deceased organisms, like plants or animals, and their byproducts (Environmental and Energy Study Institute (EESI), n.d.). One of its main characteristics is that -unlike coal, oil and natural gas- it can be replenished (Padder et al., 2024).

Marine biomass mainly includes marine animals, plants, protists and bacteria, as well as other organisms in lower portions and one of its main advantages is that it can be produced throughout the year. The consistency of marine biomass is depicted at Fig. 43, below.

**Figure 43: Consistency of marine biomass (in carbon percentage)**



Source: (Bar-On & Milo, 2019) | processed data

Algae are considered a third-generation base for biofuels, while genetically modified algae are paving the street for the fourth-generation biofuels. Edible energy crops, including sugar-based, oil-based and starch-based crops, such as oils from palm and corn, starch for wheat, sugar from sugarcane and other vegetables were the feedstock of first-generation biofuels, creating problems of food security, deforestation, water availability and competition for land-use (Padder et al., 2024, Siddiki et al., 2021). The second-generation biofuels were non-edible based, minimizing food security issues, but still competing for water and land-use. Third and fourth-generation biofuels are both algae-based and, although not posing issues regarding food security, water and land-use, they bear higher CAPEX and OPEX costs (Siddiki et al., 2021).

Biofuels can be in solid, liquid or gaseous form. The most common 3<sup>rd</sup> generation biofuels are biodiesel (also known as Fatty Acid Methyl Ester or FAME), bio-butanol, bio-ethanol and bio-propanol, while the most common 4<sup>th</sup> generation biofuels are bio-butanol, bio-hydrogen and bio-methane (Narayanan, 2024). Among the methods used to convert marine biomass to biofuels are fermentation, anaerobic digestion, thermal combustion, direct combustion, pyrolysis, chemical conversion, acid hydrolysis, gasification. And, although these methods are eco-friendlier and more cost-effective than those used in the past, 3<sup>rd</sup> and 4<sup>th</sup> generation biofuels need significantly large volumes of water during the conversion process (Vaishnavi et al., 2019).

Generally, biofuels are not Zero GHGs emitters. The CO<sub>2</sub> emitted by such fuels depends on miscellaneous factors, from cultivation to method used for transforming it or even the feedstock itself, but they emit lower GHGs than conventional fuels. Pure biodiesel, for example, reduces CO<sub>2</sub> emissions by 75%-78% compared to petroleum diesel (NREL Biodiesel basics, 2024, Narayanan, 2024).

In addition, biofuels carry another significant advantage. In most cases, they can be used in existing combustion engines with minimal need for modification of the engines, if at all. They can, also, be mixed with fossil fuels, while the existing distribution and refuelling infrastructures of fossil fuels can be used by biofuels to a large extent. Thus, they can be used as transitional means towards net zero emissions' era.

Biofuels are used mainly in transport and especially by those sectors hard to decarbonise, such as aviation, maritime and heavy-duty transport.

### **2.1.2.9 Rain Power – Rainwater Harvesting Systems**

One source of energy that has not received the proper attention until now is that of rain harvesting. Raindrops can produce both kinetic, as well as electrostatic energy, through friction. Techniques such as piezoelectric energy harvesting (PEH), which can capture noise, motion and vibration and transform it into electricity, are some of the most commonly used in this case.

In 2016 (Tang et al., 2016) made reference to an all-weather solar cell. They presented a flexible cell, which could harness energy, both from the sun and raindrops. This subject was, further, studied by (Liu et al., 2018), where a triboelectric nanogenerator (TENG) device<sup>1</sup> was integrated into a conventional solar panel, in order for both solar and raindrops energy to be able to be harnessed. (Li et al., 2023) proposed bridge array generators (BAGs), change of thickness of cells and independence between cells, as means of more efficient energy harnessing of raindrops, and they concluded that “when the area of the raindrop energy harvesting device is  $15 \times 15 \text{ cm}^2$ , the peak power output of BAGs reached  $200 \text{ W/m}^2$ ”.

The electricity produced from raindrop energy harvesting systems is low, compared to other RESs, but these systems can power devices with small electricity needs, such as LEDs, sensors and microelectromechanical systems and can be used complementary to other RESs. The simple design, the small number of components and the easy fabrication of raindrop harvesting systems are advantageous in this respect (Wong et al., 2014). It can be easily understood that locations with heavy rains are more suitable for such technologies to be deployed (Ilyas & Swingler, 2015). Such systems can support solar systems, especially in the case of single cells which could perform both under sunny and rainy conditions.

### **2.1.2.10 Energy Production Under Dark Conditions**

One of the main disadvantages of photovoltaic systems is that, as a lot of other renewables, energy harvesting is volatile and difficult to be predicted in the long term, due to the inherent characteristic of such systems’ reliance on weather conditions. In their effort to eliminate this

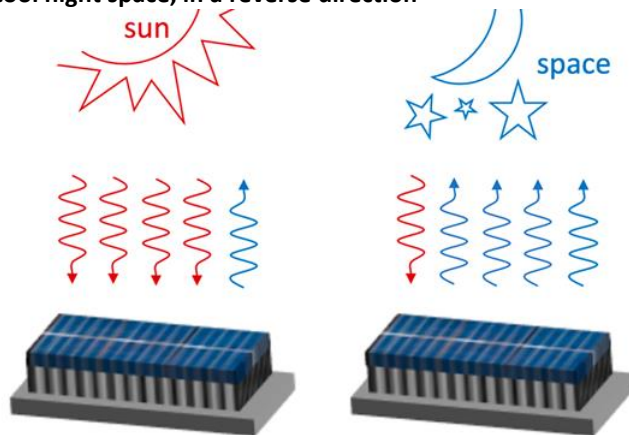
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<sup>1</sup> Triboelectric nanogenerator (TENG): A device, relatively new technologically (first demonstration on 2012), able to convert mechanical energy into electricity.

disadvantage, researchers are recently focusing on studies for energy harnessing under dark conditions, i.e. during cloudy days or at night.

In their 2017 study, (Tang et al., 2017) explored the potential of dye-sensitized solar cells, in their effort to generate electricity under dark and cloudy conditions and referred to the importance of such characteristics' incorporation to a single solar cell device. The nighttime photovoltaics' idea was further boosted by a 2019 study (Deppe & Munday, 2019), which elaborated on the notion of radioactive cooling and reverse direction energy harvesting compared to that of photovoltaics energy harvesting during sunny days, as per Fig. 44. Subject idea is based on the temperature gradient between the warm earth surface and the cool night sky and the fact that such solar panels radiate throughout the night, releasing heat back in the air, through the emittance of infrared radiation. Their findings were further validated by (Omair et al., 2022), who modified an existing PV panel by incorporating a thermoelectric generator (TEG) – that is, a device used to convert the temperature gradient into electricity. (Alajlan et al., 2024) further integrated a water-passive cooling system, into a similar hybrid energy-harvesting system to increase its efficiency throughout a 24hour day.

**Figure 44: PVs absorb sun-light to generate electricity during sunny days, while cells release heat back to the cool night space, in a reverse direction**



Source: (Deppe & Munday, 2019)

And although such studies are still far from commercial use, they contribute towards the idea of reduction of volatility in energy-harvesting from sources such as the sun.

### **3. Additional Tools Towards Sustainability and Circular Economy in Offshore Sector**

#### **3.1 Sea Water Air Conditioning (SWAC)**

Global warming, increase of global population and a rise in the living standards of developing countries create higher demand for buildings' cooling (Hunt et al., 2020). This demand is expected to increase rapidly within the following years, leading to increased demand for energy. Cooling of buildings consumes 20% of the total electricity globally, while electricity consumption for same purpose is expected to triple by 2050 (*The Future of Cooling – Analysis - IEA*, 2018). Energy for cooling purposes is even higher in locations where the need for space cooling is present throughout the year. In tropical and subtropical climates, for example, energy consumption for cooling purposes, in some cases, may reach or exceed 50% of a building's demand for energy (Katili et al., 2015).

A, relatively new, space cooling technology which is very effective, sustainable and green is that of SWAC systems. Subject technology is a non-intermittent renewable thermal energy, which can be used directly, without any transformation (Sanjivy et al., 2023) for cooling near-shore large buildings and neighbourhoods (Lucas & Kanhan Sanjivy, 2024). It uses deep-sea water as mean of cooling, replacing the conventional AC systems (SWAC – *SeaWater Air Conditioning / Makai Ocean Engineering*, n.d.).

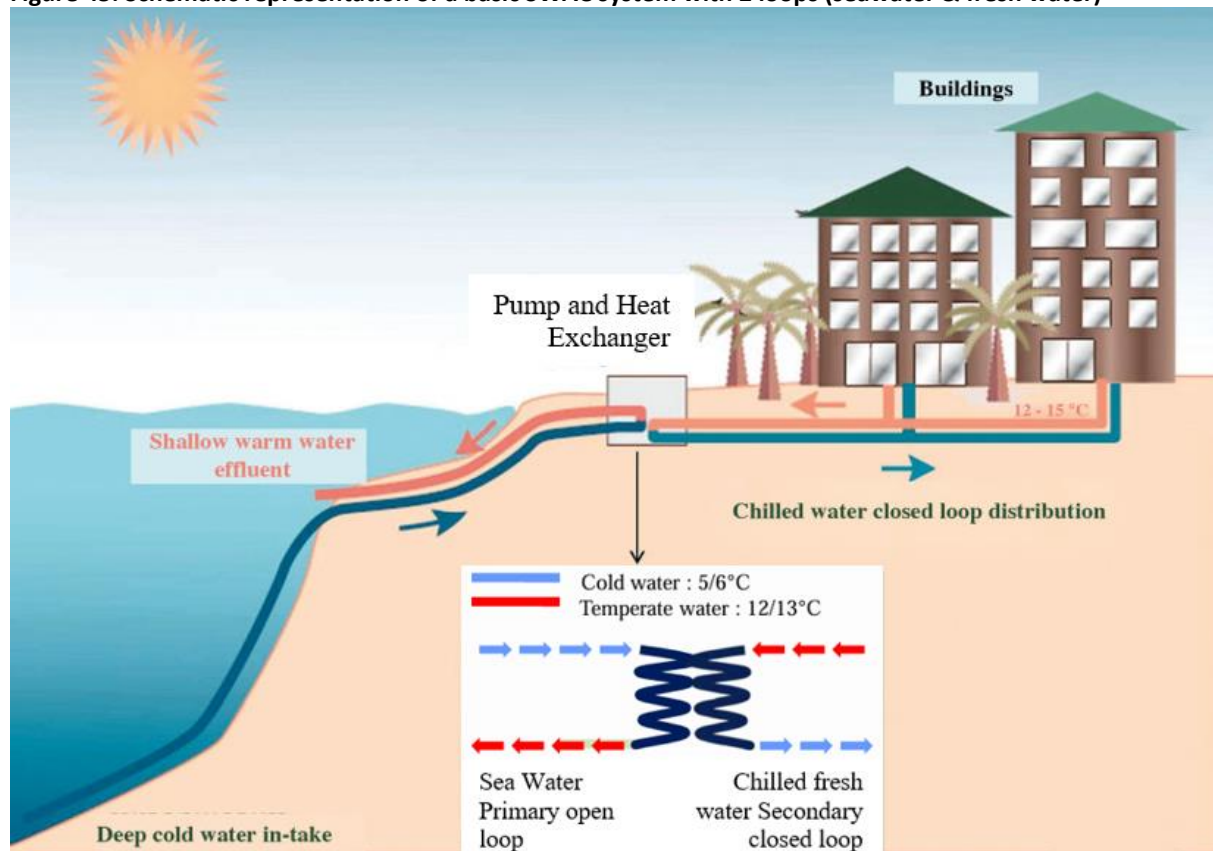
In its most common form, SWAC comprises of two loops. The first -or primary- loop, is the seawater open loop. It consists of two pipelines: an intake and an outlet pipeline. In this loop, cool seawater, with approximate temperature of 5°C - 7°C, is pumped from sea depth of about 1000 meters or more to a heat exchanger, before released back into the sea. Temperature of sea water, when released back is about 11°C - 13 °C (Sanjivy et al., 2023) and the depth released is estimated, so that water outlet temperature equals the sea temperature, in order for the impact to the marine environment to be minimum (Lucas & Kanhan Sanjivy, 2024, Hunt et al., 2020).

The second -or secondary- loop, is the chilled water closed loop. This loop is using fresh water, which is circulating among the system's buildings, while passing through the heat exchanger



(Hernández-Romero et al., 2019, Sanjiv et al., 2023, Hunt et al., 2020). As the freshwater passes through the heat exchanger, it meets the cold seawater. The two liquids' temperatures are reaching an equilibrium, thus fresh water cools down, before being distributed back to the buildings (War, 2011). Temperature inlet for chilled water is about 12°C - 13°C and outlet is about 7°C - 8°C (Sanjiv et al., 2023, Hunt et al., 2020). A schematic representation of a SWAC system's basic design is presented in Fig. 45.

**Figure 45: Schematic representation of a basic SWAC system with 2 loops (seawater & fresh water)**



Source: (Resinex, 2021 | Modified)

The use of cold fresh water intake, e.g. water from lakes or rivers can, alternatively, be used by the system (War, 2011), but the temperature of water intake, also needs to be at about 5°C to 7°C, as in the seawater case. However, in this case there is no need for a heat exchanger or a secondary loop and the water can be directly distributed to the network. The heat exchanger is used in the case of seawater, because salty water is highly corrosive, thus entering into the distribution network must be avoided (Lucas & Kanhan Sanjiv, 2024).

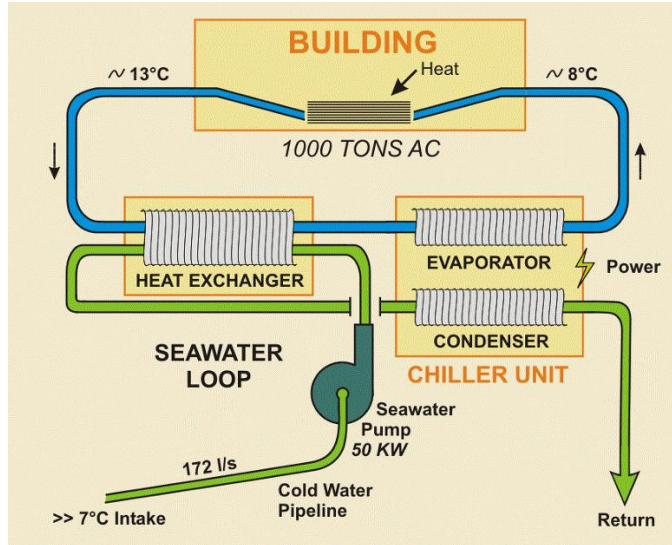
The advantages of SWAC system are that no chemical refrigerants are used, since the secondary loop's operation is based on fresh water (War, 2011), it reduces the emittance of CO<sub>2</sub> by 3 to 4 times in comparison to conventional cooling systems (Sanjivy et al., 2023), it can save energy of about 75%-90% (Lilley et al., 2015, Looney & Oney, 2007), the conventional systems can be easily modified to SWAC technology and the use of fossil fuels can be eliminated (War, 2011).

SWAC technology is most suitable for inter-tropical regions, where there is a higher need for cooling throughout the year, and especially in islands, where distance from coast is short, the bathymetry and temperature of the sea aligns with the system's requirements and the cost of fossil fuels is higher, due to transportation (Hunt et al., 2020). The CAPEX for such projects is high and it is heavily affected by the length of the intake pipeline (Hunt et al., 2020), but the return on capital investment is short, ranging from 6 to 11 years (War, 2011, IRENA Renewable energy opportunities for island tourism, 2014). In order for economies of scale to be achieved, such projects should be large, as the size of the project is connected to its viability (Development Bank of Latin America, 2015).

Buildings that could use SWAC technology include facilities with high demands for cooling, which are relatively close to each other and to the shore, since fragmented demand for district-cooling results to higher costs, due to longer pipelines and complexity of such networks. Such buildings could include hotels and resorts, airports, malls and large stores, large offices, universities, museums, military facilities and governmental buildings, data centres, industrial facilities etc. (Hunt et al., 2020).

Variations of SWAC systems are the assisted SWAC and the Sea Water Heat Pump (SWHP). Assisted SWAC systems include a chiller unit, as per Fig. 46, which is used for the reduction of intake water's temperature, in cases where temperature is higher than required (e.g. seawater pumped from shallow waters). SWHPs, on the other hand, include a heat pump and are used in cases where there is a need for buildings' heating (Lucas & Kanhan Sanjivy, 2024). Combination of cooling and heating systems can further reduce CAPEX costs, through the exploitation of a common distribution network.

**Figure 46: Schematic representation of SWAC system with chiller unit**



Source: (MAKAI OCEAN ENGINEERING Seawater Air Conditioning: A Basic Understanding, n.d.)

Operational costs can be reduced by the use of thermal energy storage tanks. These tanks can store cold water for short periods of time, e.g. a week, or freeze water for longer periods, e.g. a month. This stored water can be used when cooling needs are high, e.g. during hot weeks or months, respectively (Hunt et al., 2020).

Due to common requirements regarding bathymetry and water temperatures, SWAC systems can be easily coupled with OTEC systems, enabling them to share the high CAPEXs, which both systems are subject to and which are considered the main reason of scarcity of such systems (Sanjivy et al., 2023). Desalination can further be added to such couplings (Osorio et al., 2016). SWAC can, also, serve industries such as aquaculture, pharmacology and cosmetology, which can use the highly-nutrient deep-sea water (Lucas & Kanhan Sanjivy, 2024).

### 3.2 Desalination

Two billion people globally do not have access to safe drinking water. That is about ¼ of the earth's population (UNESCO, 2023). And the problem is expecting to rise, due to global warming and population growth (United Nations, 2022). Apart from drinking, fresh water is needed, among others, for sanitation, irrigation, industrial purposes and production of green

hydrogen. In most cases, countries facing water scarcity are located close to the sea, thus, they could benefit from desalination projects.

Desalination is the process of removing the salt and other substances, usually from seawater, although brackish and wastewater can also be treated. The methods of treatment used fall under two main categories: thermal process and membrane process, as well as hybrids of these two categories. The core idea of thermal process is for seawater to reach its boiling point and evaporate, leaving behind salt, minerals and other substances. Water vapours are then condensed back into their liquid phase. Membrane process, on the other hand, uses semi-permeable membranes -with small pores, which allow water, but not salt or other substances to pass through- to separate fresh from salty water. Under these two categories fall different technologies of desalination, as listed in table 1.

**Table 1: Main categories of desalination methods and the technologies used in each category**

<b>Thermal Process</b>	<b>Membrane Process</b>	<b>Hybrid Process</b>
Multi-Effect Distillation (MED)	Micro Filtration (MF)	RO - MSF
Multi-Stage Flash Distillation (MSF)	Ultra Filtration (UF)	RO - MED
Mechanical Vapour Compression (MVC)	Nano Filtration (NF)	FO - NF
Thermal Vapour Compression (TVC)	Membrane Bioreactor (MB)	ED - RO
	Membrane distillation (MD)	RO - MD
	Electro Dialysis (ED)	FO - ED
	Reverse Osmosis (RO)	RO - ED
	Electrical Dialysis Reversal (EDR)	
	Forward Osmosis (FO)	
	Capacitive Deionization (CDI)	

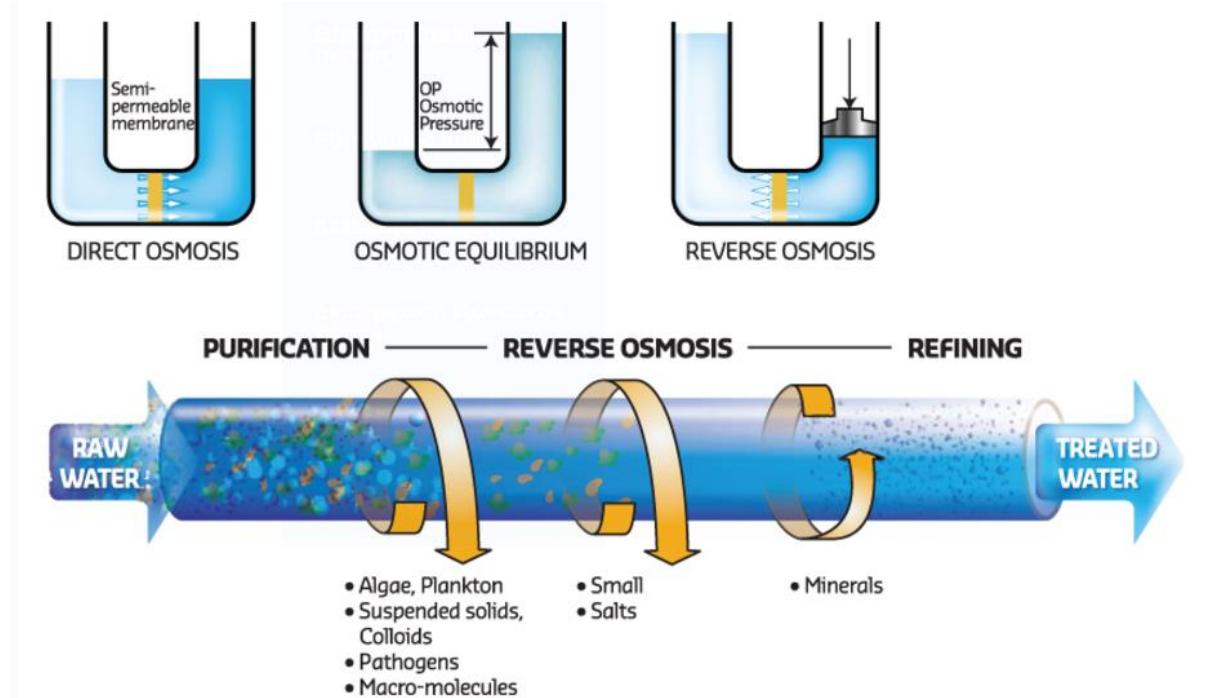
Source: (Thi et al., 2021, Curto et al., 2021, Manesh et al., 2020)

And, although a lot of these technologies are still under study, most desalination plants today are using RO, MSF or MED for seawater treatment (Thi et al., 2021, Eke et al., 2020).

RO has gained popularity in recent years, due to a reduction in costs of such systems, driven mainly by cost-reduction in membranes used. Cost-reduction of membranes, in turn, was driven by maturity of subject technology, as new, more affordable materials, of higher technology and durability emerged. The technology is based on the principles of osmosis, which has already been described, but in this case, pressure is applied to the higher water-column (right column in Fig. 47), leaving back the brine solution, while the treated water is accumulated to the other

part of the tank (left column in Fig. 47), after passing the semi-permeable membrane, which selectively allows the solvent (water), but not salt or other impurities to pass through.

**Figure 47: Schematic representation of direct and RO**



Source: (Ro-diagram - Clear Water, n.d.)

RO technology is more energy-efficient, compared to other desalination technologies, although costs are still considered high. One of its main advantages is its scalability and its flexibility. It can be easily coupled with RESs and operate offshore. Biofouling, though, poses a challenge, while the quality of treated freshwater is lower than that of MSF and MED technologies (Curto et al., 2021).

Both MSF and MED technologies use thermal process to evaporate seawater. The procedure in both cases is done in stages, where different chambers are used to evaporate water, with the assistance of steam-heat and pressure, and then condense it back into its liquid phase, leaving brine behind. However, the methods of evaporation and heat-transfer differ. MSF uses higher temperatures and energy consumption than MED (Thi et al., 2021), but MED systems are prone to scale and fouling and present constraints during cleaning procedures, as the system needs to be turned down, when such procedures take place (Waterman Engineers Australia, 2023). MEF plants, also need to stop operations in case of maintenance, though. The main advantage for



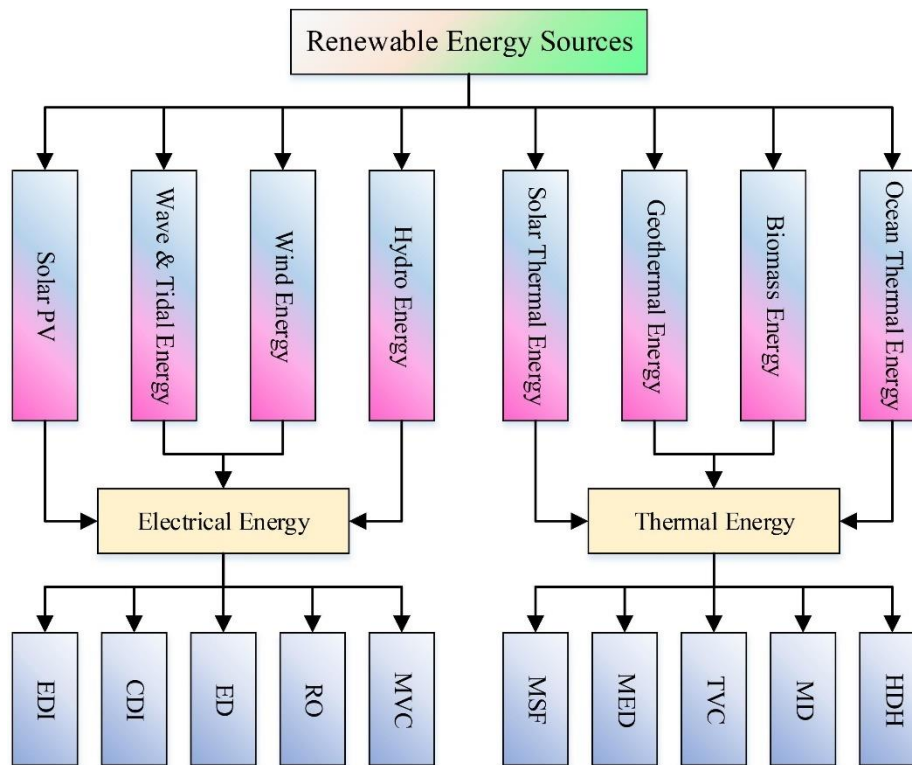
both MEF and MED technologies is that the treated water is of high quality. Furthermore, they can treat effectively water with high levels of salinity (Curto et al., 2021).

Generally, high cost of desalination is mainly linked to the energy-intensive nature of such operations. High energy consumption, which is heavily powered by fossil fuels, is leading to high CO<sub>2</sub> emissions. This issue, however, can be mitigated by coupling desalination technologies with RESs. The most common couplings offshore are with wave, tidal, solar PV, solar thermal and wind technologies (Thi et al., 2021, Alkaisi et al., 2017, Esmaeilion et al., 2021), as well as combination of different RESs coupled with desalination plants, e.g. hybrids solar PV and wind powering desalination operations (Kalogirou, 2005). However, the variability in energy production of some RESs poses challenges. Thus, batteries can play significant role in such couplings. Other RESs, such as biomass, biofuels and fuel cells, could also be coupled with desalination projects, mainly for smaller plants (Esmaeilion, 2020, Esmaeilion et al., 2021).

The selection of RESs, which are most suitable to be coupled with desalination projects depends on many factors, such as the desalination technology used, the size of desalination plant, the location of the plant, the type and location of RESs and their energy potentials at the specific location (Kalogirou, 2005).

Generally, though, the best suited couplings for the membrane-based desalination technologies are considered the RESs that produce electricity and for the thermal-based technologies, the thermal RESs. In more detail, RO plants are best integrated with solar PV, wind and wave/tidal energy, while MSF and MED plants are best coupled with solar thermal, ocean thermal and biomass energy (Alawad et al., 2023, Esmaeilion, 2020, Alkaisi et al., 2017), as per diagram in Fig. 48.

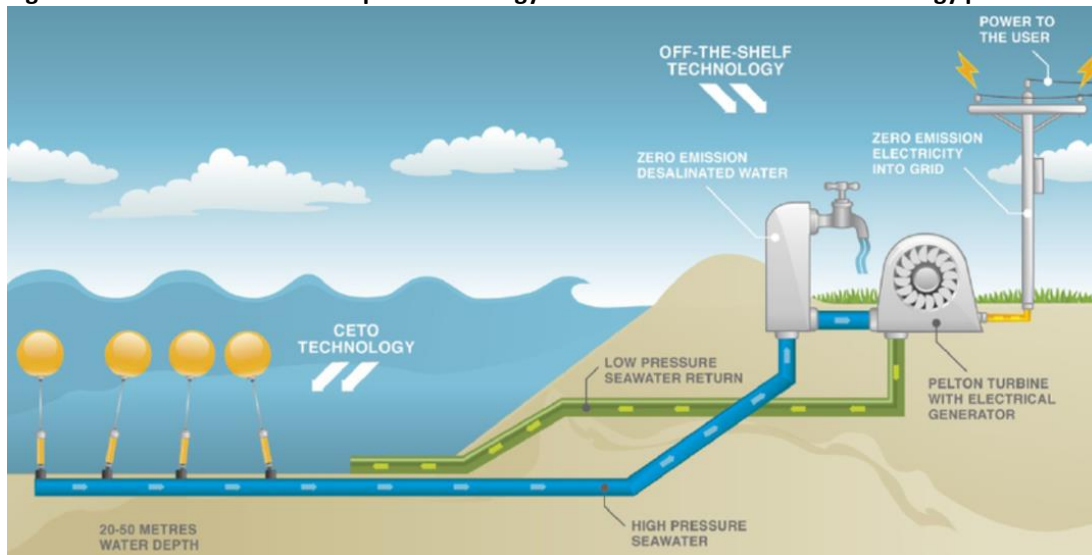
**Figure 48: Possible couplings between desalination plants and RESs**



Source: (Alawad et al., 2023)

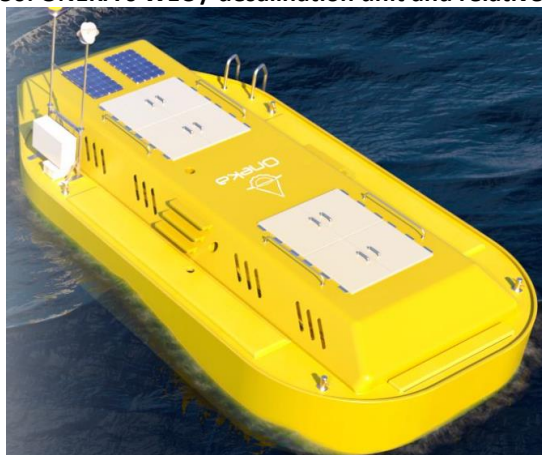
In the case of waves, instead of electricity, mechanical energy, produced by WECs, can be used directly, without conversion, for RO desalination (Foteinis & Tsoutsos, 2016). Such couplings are more efficient, since no intermediate energy conversion is needed. In fact, most of these WECs can both produce power and desalinate. Desalination WECs, which have already been tested include CETO submerged buoys, the first WECs used commercially for desalination purposes at Garden Island, Australia in 2014 (*CETO 5 – Perth (WA) - Carnegie*, 2022) and the more sophisticated Oneka's units, which incorporate filters and RO membranes and can perform desalination onboard (Oneka Technologies, 2024). The freshwater is then pipelined onshore, using energy produced by the waves (*Desalination: What Is It and How Can It Help Tackle Water Scarcity?*, 2024). Both WECs seen in Fig. 49 & 50 respectively.

**Figure 49: CARNEGIE's CETO coupled technology for seawater desalination and energy production**

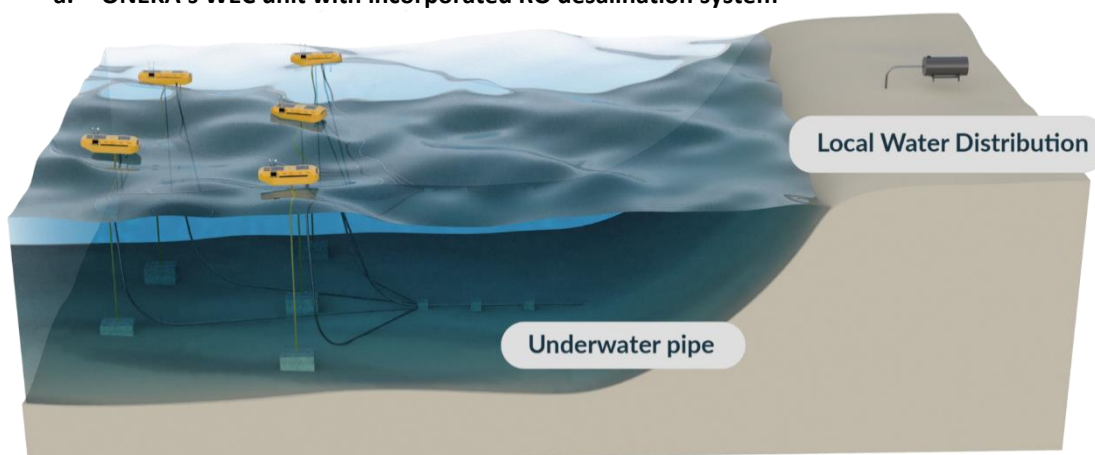


Source: (Wu et al., 2016)

**Figure 50: ONEKA's WEC / desalination unit and relative offshore buoy array**



**a. ONEKA's WEC unit with incorporated RO desalination system**



**b. Offshore Buoy Array**

Source: (Oneka Technologies, 2024)

And, of course, OTEC technology cannot be omitted from desalination sector, since, as already described, variations of this technology (open cycle and hybrid) are able to produce desalinated water, without any adjustments needed. In this case, instead of energy use for re-condensation, this process is done by the use of deep-sea cold water (Osorio et al., 2016). (Dyer and Ragan, 2012), also, proposed a closed cycle OTEC desalination system using RO technology.

Desalination, however, faces some challenges, probably the most important of them being brine management. Different approaches of brine management are used currently. The location of the plant plays important role in such decisions. In offshore locations it is common for brine to be disposed into the sea. If this is the case, brine's concentration in salt and metals should be taken into account, since it can threaten the marine ecosystem. Some of the most environmental-friendly methods used today are the treatment of brine into salt and its other components for commercial use (*Desalination: What Is It and How Can It Help Tackle Water Scarcity?*, 2024) or low-salt-concentration disposal of brine into the sea, so it can be dispersed faster to the seawater, without changing its PH or its salinity levels (Oneka Technologies, 2024b).

### 3.3 Offshore Aquaculture

The ever-increasing need for seafood is pushing the global fishing industry to expand -mainly through aquaculture, rather than increase in captured fisheries- in order to meet demand. Aquaculture, which is one of the fastest growing industries, currently accounts for about half of the total world production of the sector (FAO, 2022), while by 2030 62% of the total seafood consumed is expected to be raised in aquatic farms (Clemente et al., 2021). The Asian countries are those with the higher seafood production (Clemente et al., 2021), with China being the leader (FAO, 2022). However, factors such as limited coastal space, competition for sea-space with other shore activities, pollution, better quality of open-sea water etc. are leading aquaculture industry to move from coastal areas to offshore districts.

In their 2017 study, Froehlich et al. (Froehlich et al., 2017) pointed out that the definition of offshore aquaculture still remains vague, with sea-depth and distance from shore generally perceived as the main criteria for defining aquaculture as an offshore industry. They

furthermore, highlighted the fact that currently the term “offshore” in regards to aquaculture, may include sites which are closer than 3nm to shore and as deep as 30 meters or less. Wave exposure and jurisdiction boundaries had, also, been identified by Gentry et al. (Gentry et al., 2016) as criteria for the determination of offshore aquaculture.

Generally, aquaculture includes cultivation of different organisms, mainly finfish (salmon, milkfish, seabream, seabass etc.), shellfish (mussels, oysters, scallops etc.), algae and seaweeds (Japanese kelp, *Eucheuma* seaweed, nori etc.), as well as crustaceans (crab, prawn, lobster etc.). The use of aquaculture products varies from human consumption to animal feed, soil enrichers, raw materials for cosmetics and pharmaceutical and feedstock for biofuels. The cultivating method depends on the species. Finfish are usually cultivated in floating or submersible sea cages and net pens anchored to the sea-bed, while mussels (shellfish) and sugar kelps (algae) are mainly cultivated in floating long-lines. Other shellfish can be bottom-laid or cultivated in suspended bags (*Exploring Opportunities for Marine Renewable Energy in Maritime Markets*, 2019).

Multitrophic offshore aquaculture is, also, under development. According to this method, cultivation of species from different trophic levels, such as finfish, shellfish and algae, are cultivated together (polyculture) and the by-products/waste produced from higher trophic level species are used for feeding/fertilizing the immediate lower trophic level, promoting a circular economy approach (*Exploring Opportunities for Marine Renewable Energy in Maritime Markets*, 2019, Lee et al., 2022).

Regardless of the species cultivated or the method used, aquaculture needs power for its facilities. The power needs are determined by the type of aquaculture. Finfish aquaculture has substantially more needs than shellfish and algae cultivation, although energy needs for algae cultivation are expected to grow significantly in the future, since large-scale algae growing for CO<sub>2</sub> sequestration and biofuels’ production are under study. The most common energy needs of such facilities include automatic fish feeders, navigation lights, monitoring equipment, refrigeration and ice production machines, marine pumps for production of compressed air, marine sensors etc. (*Exploring Opportunities for Marine Renewable Energy in Maritime Markets*, 2019). Thus, offshore aquaculture can be benefited from co-location with ORESs, as it can use the energy produced by such systems, reducing its dependence from diesel generators, which are, currently, the main source of energy used by the sector.



In their 2022 study for the International Energy Association (IEA), Freeman et al. (Freeman et al., 2022) listed aquaculture cultivation in 14 countries, each country's cultivated type of species, the existence of offshore aquaculture facilities or the countries' plans to move offshore and the ORESs those countries intended to couple with offshore aquaculture. In the case of expansion of facilities offshore, the site seemed to play significant role in the determination of the specific ORES to be used. Wave and currents energy were the most favoured options, followed by wind, solar photovoltaic and ocean thermal energy.

However, the contribution of offshore wind and, mainly, solar PVs is expected to rise significantly in the following years, as offshore floating structures have recently been developed and are moving fast towards full maturity, assisted by the relative on-shore technological maturity and cost reductions. For coupling offshore aquaculture with ORESs, energy requirements of each cultivated species play important role and must be determined during the early stages of a project. Technology and practices used at each farm are affecting their energy requirements, too, while the need for storage devices, such as batteries, should not be neglected in such systems.

A sample of combination of ORES and polyculture aquacultural approach was presented in Dol et al.'s study (Dol et al., 2021). In subject study the researchers concluded to a platform design which included wave, wind and solar power generators, while it also introduced a polyculture approach. According to it, plants could be grown on the facility and used for fish-feeding, while wastes from fish could be used as fertilizers for the plants.

Ocean Farm 1, which was designed and build in China, before being towed to its final location, in Norgay, is considered the first offshore farm (Freeman et al., 2022). While the first functional Multi-Use Offshore Platform (MUOP) with aquaculture facilities is considered to be the Guoneng Sharing project, both built and located in China, coupling wind and solar with aquaculture (Manolache & Andrei, 2024). At the end of 2023 the "Guoneng Sharing" platform was launched and towed into place and in June 2024 it was set into full operation (Xin, 2024, *The World's First Floating Wind-Fishery Integration Project "Guoneng Sharing" Takes to the Water*, 2023). Figures 51.a and 51.b present Ocean Farm 1 and Guoneng Sharing project respectively.

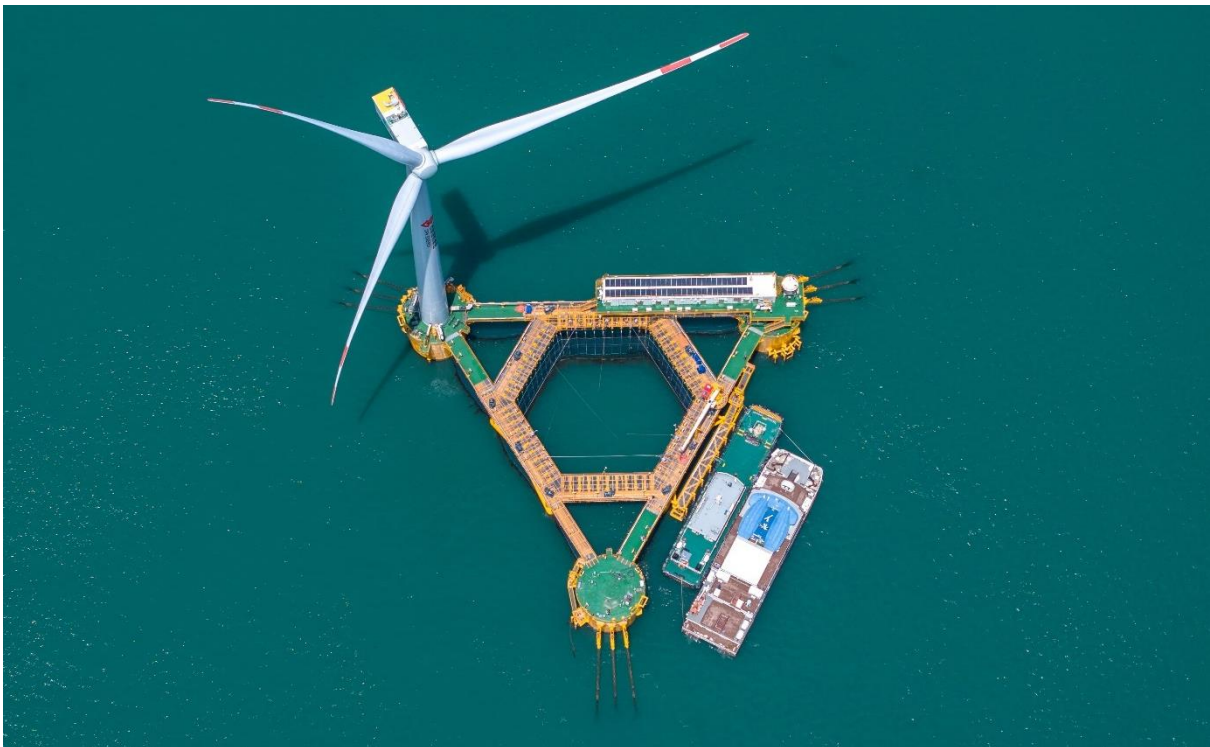
In their 2024 study, Manolache & Andrei (Manolache & Andrei, 2024) listed the most important offshore aquaculture facilities, which are coupled to one or more offshore

renewables. According to subject study, all four currently operational MUOP are located in China, while other significant MUOP projects coupled with aquaculture, are either at test or at concept stage.

**Figure 51: Offshore aquaculture platforms**



**a. Ocean Farm 1**



**b. Guoneng Sharing project**

Source (a): (*Re-inventing Fishery* - KONGSBERG, 2015)

Source (b): (Holo Fujian, 2024)

### 3.4 Carbon Capture and Storage (CCS)

Alone the transition from fossil fuels to more sustainable energy production alternatives will not be enough for Paris Agreement goals to be reached. In the 2024 report of the Intergovernmental Panel on Climate Change Expert Meeting on carbon dioxide removal, capture, utilisation and storage (IPCC, 2024), the role of carbon dioxide's sequestration as a mean towards net zero target was pinpointed. However, it must be taken into consideration that this is an energy intensive procedure.

Carbon sequestration includes both carbon removal and carbon capture. Carbon removal refers to CO<sub>2</sub> removal directly from the atmosphere, while carbon capture focuses on reduction of CO<sub>2</sub> emissions coming from large CO<sub>2</sub> emitters, such as industrial activity (mainly refineries, steel and cement industries) and energy generation (e.g. burn of fossil fuels at power plants). For carbon capture, various CCS procedures are currently examined. According to the most common, also known as geo-sequestration, CO<sub>2</sub> is separated from other gases, compressed to reach a liquid/dense phase, and then transported via pipelines, tank trucks or vessels and injected into underground geological formulations or cavities, which are then sealed (*System Integration Concepts — North Sea Energy*, n.d.).

For carbon dioxide's safe storage, the depth of such cavities should exceed 1000m and apart from saline aquifers they can, also, include depleted oil or gas reservoirs. The procedures from CO<sub>2</sub> capturing to safely storing it are costly, but the use of decommissioned offshore O&G platforms, wells and the repurposing of O&G pipelines for transportation of the compressed CO<sub>2</sub> can reduce costs and extend O&G assets' life, delaying their decommissioning.

However, since repurposed O&G pipelines may present higher failure risks, monitoring and detection systems for CO<sub>2</sub> leaks should be set into place and procedures for quick response in case of emergency should apply. Large leakage of CO<sub>2</sub> can lead to decrease of oxygen and acidification of water, severely impacting marine flora and fauna. Asphyxiation risk is an important danger for humans, too. More recent pipelines, though, present lower failure risks, due to their design and stricter safety regulations in regards to older facilities (Mahmoud & Dodds, 2022).

### 3.5 Carbon Capture and Utilization (CCU) – Algae and Their Role in CO<sub>2</sub> Absorption

CCU emerges as better option in comparison to CCS. The concept behind this notion is that instead of storing it, the excess CO<sub>2</sub> could be directed to alternative uses, promoting carbon circularity through more environmental-friendly options. In this case, CO<sub>2</sub> emissions from the alternative uses should be smaller than those absorbed during process (*Three Carbon Utilization Methods*, n.d.).

One of CCU options is carbon dioxide's use for Enhanced Oil Recovery (EOR) in oil fields. According to this method, captured CO<sub>2</sub> is injected into mature oil fields which are reaching their depleted phase. CO<sub>2</sub> has the ability to change the chemical properties of the crude oil, dissolving it and reducing its viscosity. This way, the mobility of the oil is increased, enabling its recovery (El-Hoshoudy & Desouky, 2018). For carbon dioxide's permanent underground storage, in this case, a closed loop procedure must be established, according to which CO<sub>2</sub> is separated from recovered oil and reinjected back into the field (*Can CO<sub>2</sub>-EOR Really Provide Carbon-negative Oil? – Analysis - IEA*, 2019). CO<sub>2</sub>-EOR can extend the oil-fields' life by several decades (*Commercial Carbon Dioxide Uses: Carbon Dioxide Enhanced Oil Recovery*, n.d.). However, this method does not decrease CO<sub>2</sub>, which remains stored underground, while at the same time, the extension of the oil-fields' operational life is prolonging the transitional phase towards net zero target.

Apart for EOR, CO<sub>2</sub> can, also, be used for the production of fertilizers, chemicals and plastics, medicines and cosmetics, fire extinguishers, refrigerants, carbonated drinks, DVDs, optical lenses, synthetic fuels, etc (Bobeck et al., 2019, *Three Carbon Utilization Methods*, n.d., Center for Climate and Energy Solutions, 2020). For the production of green CO<sub>2</sub>-based fuels and chemicals, however, large quantities of green H<sub>2</sub> are needed, the cost of which is currently high (IEA, 2019). Other uses of CO<sub>2</sub> include water treatment, while in the construction industry its main usage is for hardening concrete, aggregates and other building materials (Bobeck et al., 2019, *Three Carbon Utilization Methods*, n.d.).

CO<sub>2</sub> could further be utilised for algae cultivation. Algae require substantially larger quantities than plants for photosynthesis. The advantage in this case is that CO<sub>2</sub> used for algae growth doesn't need to be highly-pure, since sulphur and nitrogen oxides act as nutrients in most algae

species (Iglina et al., 2022). Algae, in turn, can be the feedstock for the production of biofuels, biofertilizers or they can be used as food for fish farming, shellfish, livestock farming (Bobeck et al., 2019) or even for human consumption (e.g. omega 3) (Bobeck et al., 2019).

In their 2022 study on algae and CO<sub>2</sub> capture, (Iglina et al., 2022) referred to the acceleration in growth rate of microalgae cultures through the absorption of greenhouse gases. They further discussed the consideration of algae as feedstock for biofuels, due to their rapid growth, their ability in storing lipids and their advantages of being biodegradable and sulphur-free and concluded that from the studied species, *Chlorella* sp. performed best in CO<sub>2</sub> capturing.

And although according to IEA's 2019 report on the issue (IEA, 2019), the estimated annual use of CO<sub>2</sub> was 230 million tonnes (Mt), this number reflected only “approximately 1% of the annual global energy-related carbon emissions” (Ismail & Gaganis, 2023).

### **3.6 Modularity and Standardization**

The notion of modularity is closely connected to flexibility and adaptability, characteristics that are much needed in the fast-paced offshore renewables field. The changes in the field are continuous and their infrastructure should be able to follow such changes. In fact, modularity is a designing approach based on the notion of breaking a system into smaller parts or modules of self-sufficient components, which they (the modules) could be recombined into multiple structures, based on a set of rules, defined by the system's architecture (Schank et al., 2011, Erikstad, 2019, Xylia et al., 2023). Thus, a structure can be broken into modules and reconstructed differently, according to the needs. Modules can be added or extracted, in order for new structure to meet these needs.

The concept of modularity includes a vast number of different items or components. Containerization is probably the most common form of modularity. In the field of offshore energy platforms, container modules, broadly known as Portable Accommodation Modules (PAMs), are used by O&G sector, either complementary to the permanent structure or as full module-based structures.

Apart from sleeping compartments, these modules may serve as control rooms, Remotely Operated Vehicles (ROV) cabins, interconnected galley and diner rooms, offices or meetings rooms, laundry, gym, locker / change rooms, recreation rooms, workshops, storage areas etc.



Depending on their use, units are built and certified to meet the high requirements of offshore harsh and / or hazardous environments and the safety standards set by International Organizations or national authorities. Some of their main advantages are that they are standardized, easy to be transported by truck and that they can be linked together or stacked.

There is, also, the option for a set of modules to be linked together at the factory and framed by a metallic frame. These units are known as single-lift modules. They can be transported by truck to port and by vessel to the installation, where a single crane is used to lift them into place.

In the energy sector, two of the most significant containerized modules are the electrical equipment houses or Electrical Houses (E-Houses) and the Battery Energy Storage Systems (BESS). The former are prefabricated, self-contained modules, servicing as power distribution centres, while the latter are, in short, containerized types of batteries. Both carry the advantages of portability, expandability, scalability, customization and they are stackable and easily installed. There are types of both above mentioned units which are specially designed for offshore harsh environments. Apart from energy storage, BESSs can assist in integrating RESs into the grid. They can, further, manage energy demand, by storing energy during off-peak hours, in case they are connected to a grid, and supply the stored energy during peak hours, stabilizing the grid (Stenclik et al., 2017, Rabanal et al., 2024) and preventing black-outs, or even serve as energy back-up units. Storage of excess energy is of paramount importance in the renewables sector, due to the volatility in power production, which is affected by the intermittency of the sources.

And, although the technological maturity of batteries for cargo vessels is still inadequate, a future option for zero-emission-built vessels could be to lift the BESSs from a RES offshore platform and place them onboard, while returning their empty BESSs to the platform. This way, an offshore platform could operate based on the same logic as a gas station, fuelling vessels with batteries instead of gas, while at the same time, vessels wouldn't have to wait for batteries to be charged, since they would have been charged already and they would, just, be traded. In this context, decommissioned O&G platforms could further be used as BESSs' and E-houses' storage facilities.

Apart from the already mentioned advantages of the modular structures, containerised modules can be customized, bought or rented and refurbished, to be used for the purpose which were originally built or be redesigned for repurposed use, leading to extension of their life cycle.

Transportation, replacement or decommissioning of these modules is easy, thus structures using modules bear greater adaptability and versatility in meeting the volatile needs of ORESs sector. Time from order to installation, as well as time on-site are reduced, as modules are pre-fabricated and are based on a plug-and-play architecture. In addition, there is reduction in the designing time and cost, especially for the items that customization is not needed, since they are designed only once, but they can be used to multiple structures.

Modularity, however, is a very broad notion, thus it does not include only the concept of containerization. Concepts of Modular structures, Floating Modular Platforms (Lagasco et al., 2019) or, even, Modular Islands (Tamis et al., 2021) can be spotted to academic research in recent years. European Union's (EU) MERMAID (Rasenberg, 2013, MERMAID Project, 2012), TROPOS (Gutiérrez et al., 2012, TROPOS, 2014) and Space@Sea (Flikkema & Waals, 2019) projects include different variations of modularity into their architecture. MERMAID is incorporating a narrower notion of modular components, while TROPOS includes the broader notion of a modular MUOP. Space@Sea project, which is, probably, the project with the higher embracement of the notion of modularity, goes even further. It includes modularity in the development of a floating island. The concept of standardization is, also, included in this project, as one of the components that, in coordination with modularization, will reduce production cost and make islandic structures more flexible (Flikkema, et al., 2021). Standardization, in this case, however, mainly focuses on the location of the connectors between the floaters, that is, between the individual pieces / modules from which the island will be comprised. The final idea is for floaters, regardless of their size and shape, to be able to be added or extracted, expanding or decreasing the islandic platform, as per the needs of the geographical area, the future challenges etc.

Modularity, standardization, versatility and flexibility should be the core ideas of the entire planning of offshore renewable energy systems. From components and pieces to interchangeable parts, ORES systems' orientation should include the probability of incorporation of more ORESs into the system. Apart from re-purposing and re-using such parts, these concepts can, further, enable decommissioning phase, e.g. containerized modules of an O&G platform can be used in ORES platforms. More extensive insight into decommissioning phase will be discussed in due course. Future uncertainty of technological advancements, however, is making planning challenging.

## 4. Multi-Use Platforms – Hybrid Systems, Co-location and Synergies

There are many different reasons for offshore production of RE. Initially, the seas and oceans provide some unique opportunities for RE harvesting, such as waves and tides. Also, there are cases where the conditions offshore are more favourable than those onshore, such as higher winds, which enhance the production of wind-turbines or cooler environment, which assists solar panels' efficiency. Another reason for offshore production is that RE structures need more space to produce the same amount of energy compared to non-RESs, due to their lower power densities (van Zalk & Behrens, 2018). The land needed by solar and wind RESs is 10 times larger compared to coal or natural gas-fired power plants, per unit of power produced (Gross, 2020, Gomstyn, 2024). In the case of Europe, the estimated land needed for covering full electricity requirements by wind and solar is 2% of the total land (Tröndle, 2020). This land-space could be used for other purposes, such as agriculture. In addition, RESs have a visual impact, which can be mitigated -to an extent- offshore, while at the same time, property values are significantly high or increasing, as the global population is growing, leading to increased costs for such installations.

And, although sea is significantly larger than land, use of space and maritime spatial planning plays important role in this case, too, as sea-space for current and future uses should be considered. Operations and activities at sea-space are expected to increase in the future and competition over same sea-space are expected to rise (Bocci et al., 2019). Under this realm, the cost efficiencies that may arise from synergies and the need for mitigation of environmental impact underscores the necessity of multi-use or multi-purpose offshore platforms.

Such platforms can be fixed to the seabed -mainly in shallower waters- or floating, usually anchored to the sea-floor -when at deeper waters. They can share space, structure, timeframe (operations taking place at the same time), infrastructure and services. Different terms are used, commonly interchangeably, to describe such structures. Generally, though, they can be categorised to (Schupp et al., 2019, *SHORT SUMMARY 1.20.004 Multi-Purpose Offshore/High Energy Platforms: Concepts and Applications the CHALLENGE*, n.d., Pérez-Collazo et al., 2015, Clemente et al., 2021):

- Symbiotic: sharing space, timeframe and services -such as monitoring data or crew transport- and their relative costs.
- Co-location or Co-existence structures: mainly sharing space, timeframe, grid connection, operation & maintenance and logistics
- Integrated or Hybrid: they are sharing space and time, but they also incorporate different systems (e.g. solar and wind) into a single structure.
- Energy Islands: Larger platforms, which can be either built as artificial islands or as floating structures and they can include different energy harvesting means and technologies, energy-storage facilities, harbours etc.
- Re-purposing or Sub-sequent use: they lack timeframe connection. These are platforms initially constructed for different use, that have been re-purposed, mainly for cost-reduction reasons.

Apart from the apparent benefits of shared assets -such as structures, grid infrastructures etc.- and operational costs -such as logistics and maintenance- additional expected benefits of such synergies include increased energy production with less variability, better use of resources, as well as benefits such as shadow effects (shielding). For example, arrangements of overtopping WECs (such as Wave Dragon) around a set of wind turbines, could reduce the mean wave high, reducing -in turn- the turbines' fatigue (Pérez-Collazo et al., 2015) and increasing their lifespan. On the other hand, different levels of technological maturity among ORESs and co-operation of different actors may hinder the development of MUOP.

#### **4.1 Synergies Among Sustainable Sources & General Considerations to be taken Into Account**

Open seas and oceans are harsh environments. And, although this may carry some advantages regarding to energy production, such as stronger winds, it can also impose barriers, due to increased need for protection of equipment from typhoons, high waves, corrosion and biofouling. An additional factor, leading to extra costs in offshore environments, is that energy

production has to be supported by a network of cables and pipelines, in order for produced energy to be transported onshore. Thus, the decision of moving energy production offshore needs to align with relative benefits. Synergies can lower the costs of such endeavours through cost-sharing, leading to reduction of LCOE per source.

One of the main factors affecting the decision of moving energy production offshore is the level of the source's technological maturity. Wind and solar are considered the most technologically matured ORESs. Wind energy has been tested in offshore conditions for almost 35 years, since Vindeby, the first fixed-bottom offshore wind farm, was placed in Denmark in 1991. It was not until 2007, though, that floating wind turbines have started to be employed. A delay which mainly stemmed from stability and buoyancy challenges connected to such structures. But since shallow waters are unable to cover global energy needs, as they constitute a small fraction of the total sea-space, floating structures need to be incorporated into the energy systems.

The maturity in technology of photovoltaic panels, on the other hand, though high for land installations, it delayed in marine environments. First modules of floating offshore solar farms were installed in Dutch North Sea in November 2019, although floating panels for water reservoirs, lakes and dams had already been employed. Solar PV's technology, however, is growing at a fast pace, as China (Reuters, 2024), Japan (Zerina, 2024), Taiwan (Jowett, 2024) and EU (mainly at North Sea) (Zerina, 2024b), have already installed offshore solar panels for commercial use, while Brazil is entering into a pilot project for membrane-based offshore floating PVs in 2025 (Zerina, 2024c). Offshore solar panels can be deployed among wind turbines, without the need of extra space occupancy and they can act complementary to wind energy, since solar production is higher during summer season, while wind energy during winter.

Tidal and wave energy follow wind and solar PV's level of technological maturity (IRENA *Fostering a blue economy: Offshore renewable energy*, 2020). Technological maturity and geographical potentials around the world are main factors taken into consideration when synergetic ORES are studied. Tidal, salinity gradient and ocean-thermal energy are less studied, due to location restrictions. Wind, wave and solar or a mixture of these seem to be the most studied alternatives.

In their 2024 study, Khurshid et al. (Khurshid et al., 2024) collected 143 articles, published between 2000 and 2023, which included wind, wave and solar hybrid ORESs technologies. As



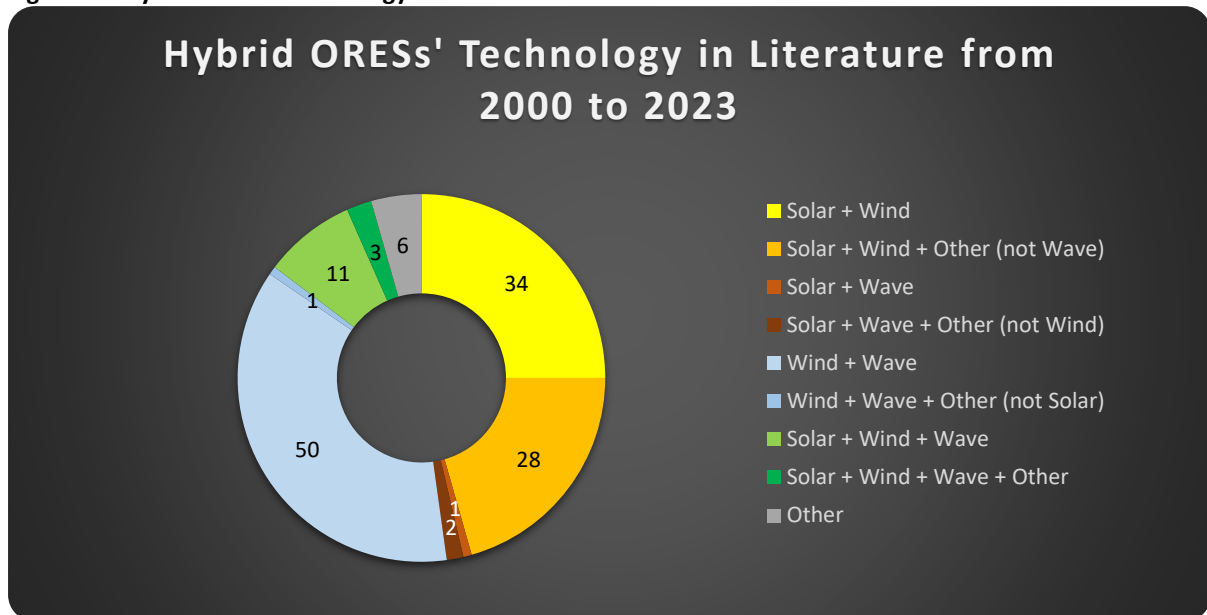
per Table 2 and figure 52, which derive from processed data based on subject study, wind-wave hybrids are the most studied, followed by solar-wind hybrids. In the case of hybrids including two or more sources, solar-wind and solar-wind-other (not including wave) are collectively the most studied cases. Figure 53 is presenting the yearly evolution in hybrid ORESs' studies from 2000 to 2023. Between 2000 and 2006 no studies on subject synergies have been identified. From 2019 a significant increase in studies is obvious, with a 67% increase in 2023 (35 studies), compared to the previous year (21 studies).

**Table 2: Hybrid ORESs' technology in literature from 2000 to 2023**

Hybrid Technology	Number of Studies
Solar + Wind	34
Solar + Wind + Other (not Wave)	28
Solar + Wave	1
Solar + Wave + Other (not Wind)	2
Wind + Wave	50
Wind + Wave + Other (not Solar)	1
Solar + Wind + Wave	11
Solar + Wind + Wave + Other	3
Other	6
Total	136

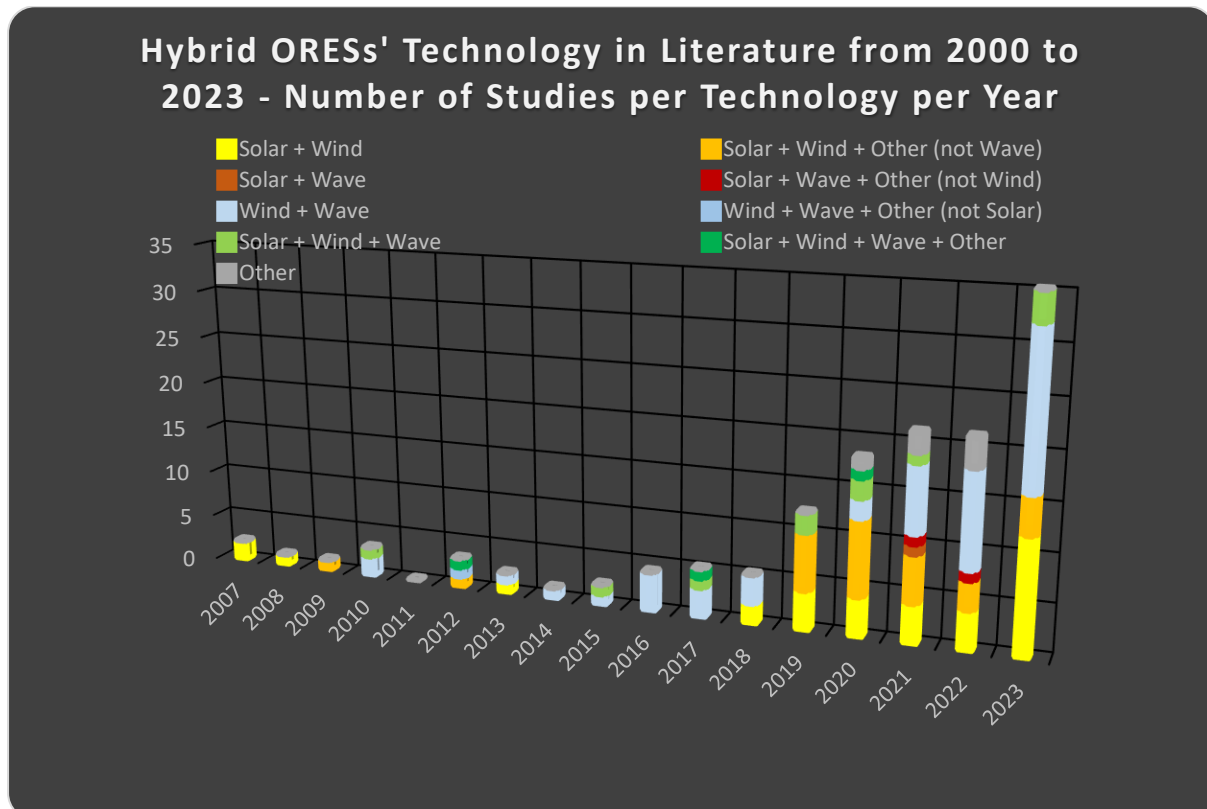
Source: (Khurshid et al., 2024) | processed data

Figure 52: Hybrid ORESS' technology in literature from 2000 to 2023



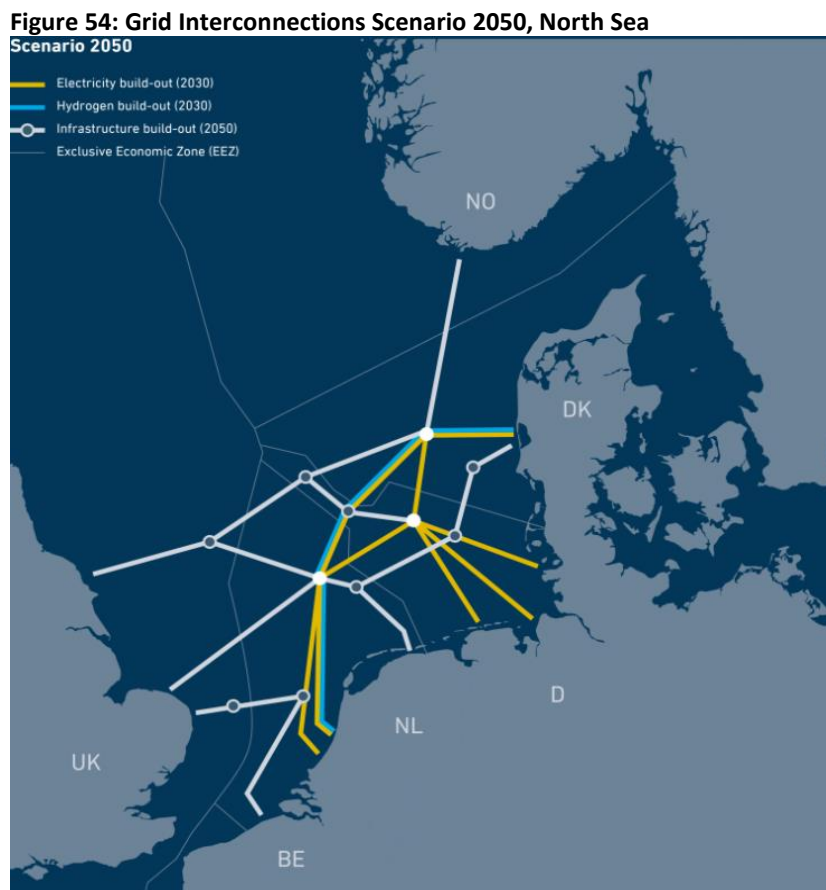
Source: (Khurshid et al., 2024) | processed data

Figure 53: Hybrid ORESS' Technology in Literature from 2000 to 2023 - Number of studies per Technology per Year



Source: (Khurshid et al., 2024) | processed data

Generally, in previous years and as the production of energy was moving offshore the alternatives on site-selection were more limited. The selection of the site was heavily based on the most favourable conditions for energy production. But as technology evolves and becomes more efficient it is expected that there will be a shift from optimal location to that which serves the needs of the local communities and/or the national grid. In a more advanced level, exchange of energy among different national grids (grid interconnections) through sea is expected. These interconnections have the ability to further stabilize the grid, by sharing power with other countries, in the case of excess production, limiting the need for this power to be stored. Figure 54 presents a grid interconnections' scenario for the North Sea by 2050, as depicted by North Sea Wind Power Hub program, where UK, Norway, Denmark, Germany, the Netherlands and Belgium are grid interconnected, for both electricity and hydrogen.



Source: (A Blueprint for the New Energy Highways, 2022)

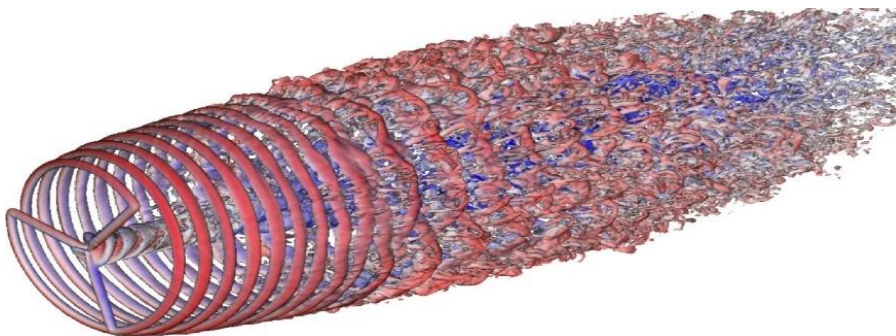
Other parameters that should be taken into consideration during the designing phase of synergistic ORESSs' systems is sea-use for other activities, military areas/uses, navigation corridors, Natura protected areas etc., but, also, air and fluids mechanics and the changes that

may inflict. One of the most important factors in changing of dynamics, either above sea surface or below water is wake-effect. According to it, the flow of air or water changes, as it passes through a turbine. Such a change alters the air-flow / waterbody flow patterns, and, apart from reducing the power production of the turbines in vicinity, it can, also, lead to sediment displacement, the same way a helicopter displaces sand, when landing in a desert (Kelly et al., 2009). This effect can be observed mainly in wind, tidal and current turbines, and generally in devices bearing blades or creating spinning turbulence of air or water, changing the flux of their mass. Fig. 55.a, 55.b, 55.c and 55.d, present wake effect in wind and tidal turbines.

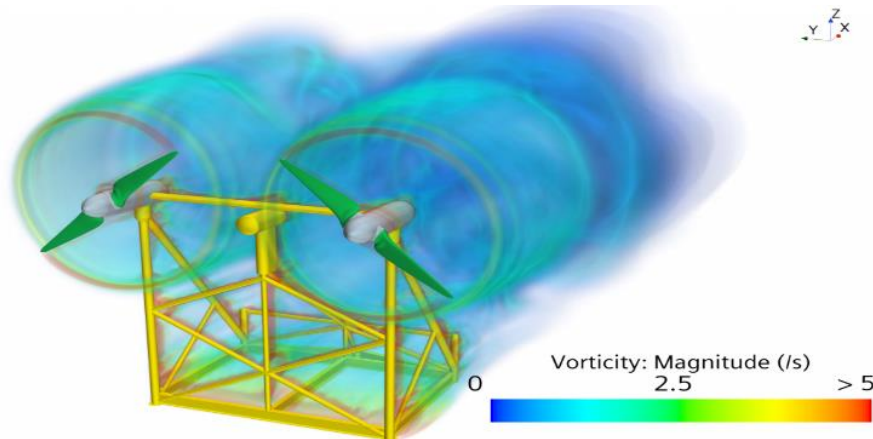
**Figure 55: Air and water turbulence, caused by wake affect in wind and tidal turbines**



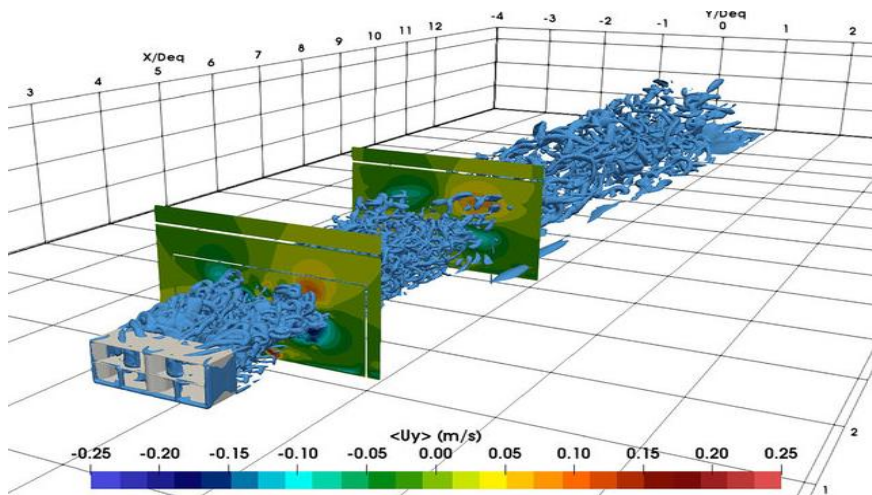
**a. Wake effect in an offshore wind farm**



**b. Simulation of a wind-turbine wake effect**



c. Simulation of vertical axis tidal wake effect



d. Simulation of vertical axis tidal wake effect

Source (a): (Sanderson, 2024)

Source (b): (Benard et al., 2018)

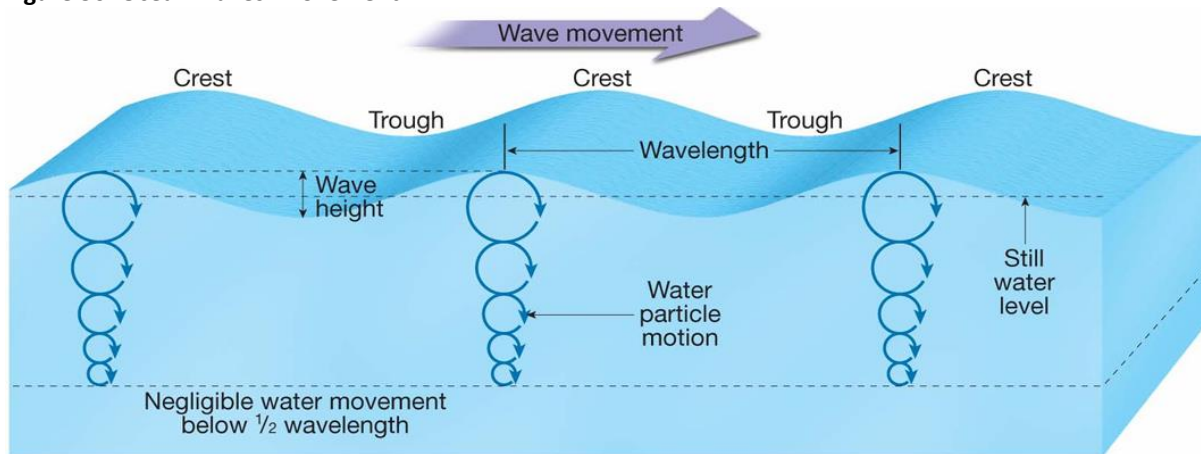
Source (c): (ARCHIE-WeSt, 2020)

Source (d): (Neill et al., 2021)

Another parameter to be taken into account when designing ORESs systems, operating in harsh environments, is their protection from the forces of nature and the corrosive effect of seawater. Devices' protection from wind and waves can be achieved through controlled submergence, since water movement is neglectable half a wavelength below sea level, as per Figure 56. Incorporation of devices within other structures, such as General Electric's integration proposal of hydrogen production unit within wind turbine pile, as per Figure 57, can protect them from corrosive effects.



**Figure 56: Ocean waves' movement**



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Source: (What Happens Underwater during a Hurricane, 2012)

**Figure 57: General Electric's integration concept of Hydrogen production unit within OWT pile**



Source: (Luo et al., 2021)

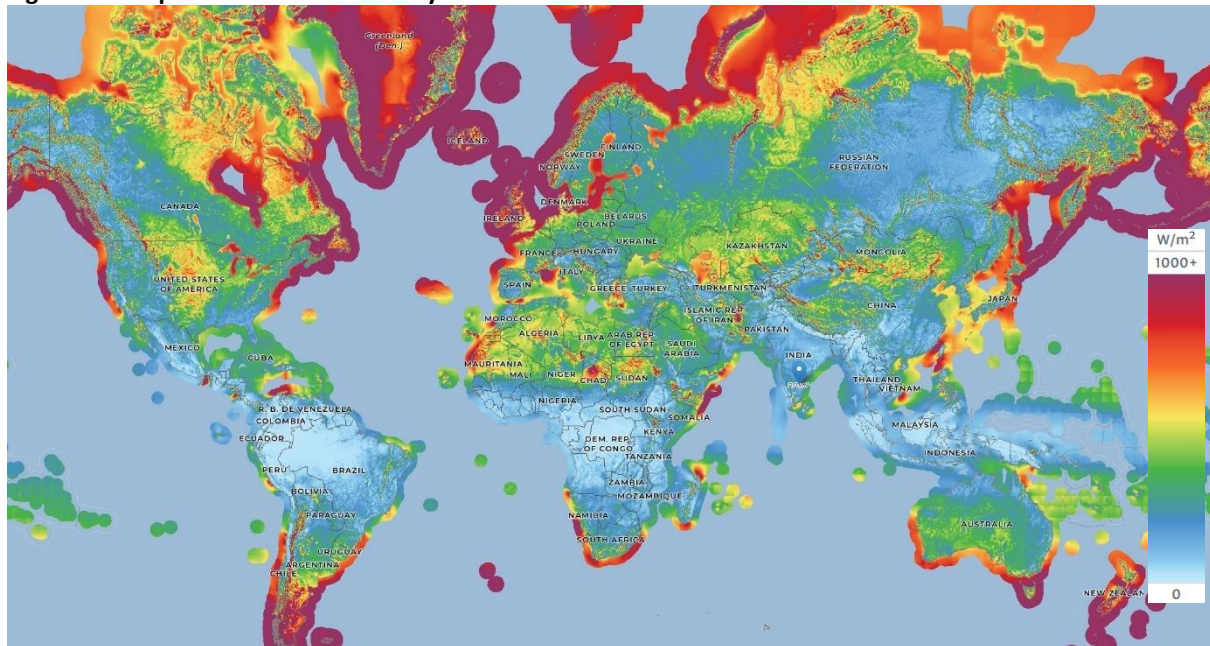
In their 2018 study, Przedzimirska et al. (Przedzimirska et al., 2018) explored the possible synergies between ORESs and other offshore sources, including the parameter of time and created a matrix, presenting which couplings were currently feasible, which were expected to be possible in the near future and for which the coupling was not expected to happen soon. According to it, offshore wind could already be coupled with wave, hydrogen production, desalination, cultivation of seaweed and shells, floating shipping terminal, environmental monitoring and protection and it was expected that its coupling with finfish aquaculture could be possible in the near future. Commercial fisheries, on the other hand, presented difficulties in coupling with wave, hydrogen, desalination and aquaculture in the near future. Offshore solar PVs were not included, though, since the concept of employing them offshore, was just emerging (Slinn, 2020), although some studies on the subject had already been done in the past.

#### 4.1.1 Global and Mediterranean Sea Potentials

In the case of co-located or hybrid Offshore Renewable Energy (ORE) systems, different maps (e.g. wind power density, solar capacity, tidal range, ocean thermal gradient, salinity gradient) must be co-examined for the determination of the optimal location of such a system.

From a global spectrum, offshore mean wind power density is lower in the equator and higher towards the poles (Figure 58). North Sea presents high potentials in regards to offshore wind and this was among the reasons the area was chosen for the installation of the first OWTs.

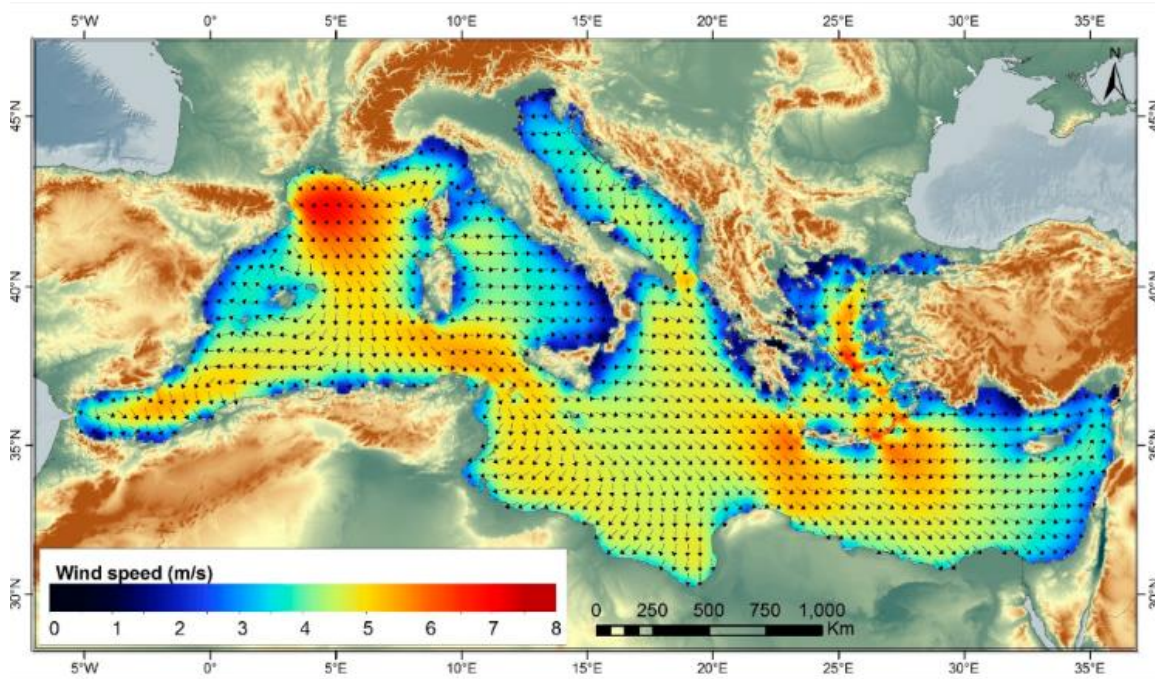
**Figure 58: Map of Mean Power Density of Wind**



Source: (Global Wind Atlas, n.d.)

In the Mediterranean basin, wind speed and power density present variability among the different locations. The highest mean annual speeds are located in the Gulf of Lion, the central Aegean Sea, between Greek islands Kasos and Rhodes and east and west of Crete, as per Figure 59.

**Figure 59: Mean Annual wind speed in the Mediterranean basin**



Source: (Soukissian et al., 2017)

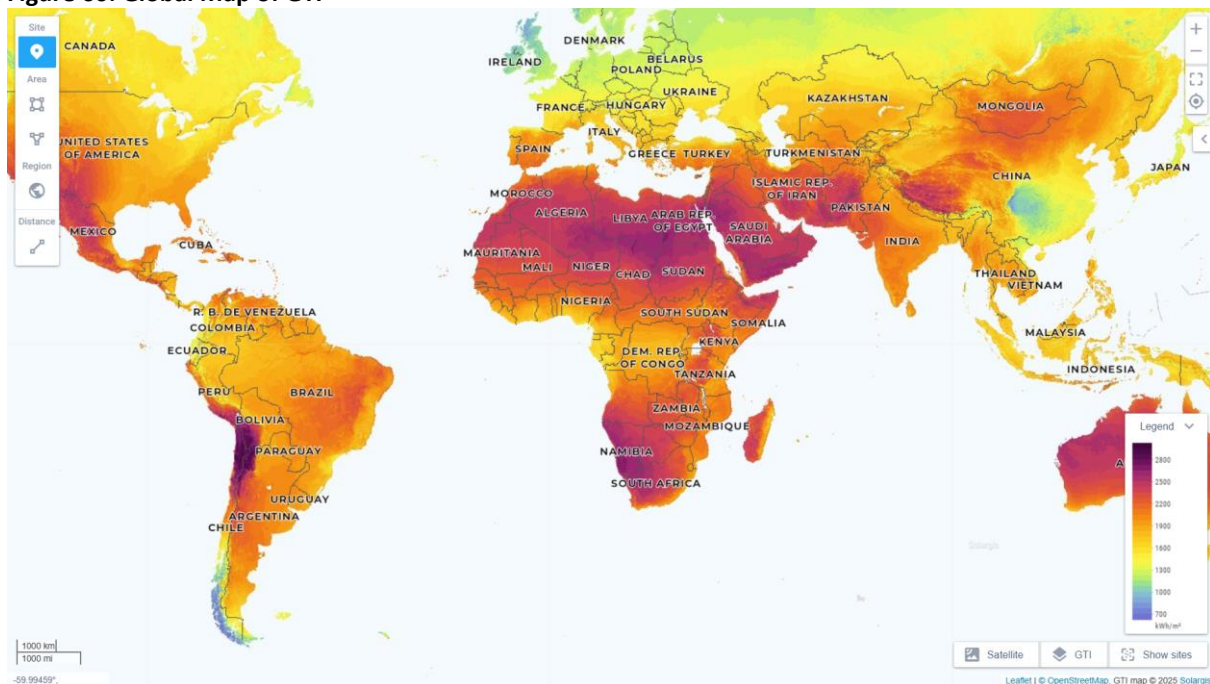
In their 2020 study (ESMAP, 2020), the World Bank and Energy Sector Management Assistance Program estimated the photovoltaic power potential by country, taking into account various parameters, such as irradiance, air temperature at 2 meters, seasonality, but also terrain slope, land cover, tree cover density, protected areas, population density, LCOE etc. and concluded to three different levels of potentiality. The theoretical, the practical (technical) and the economic PV power potential. Monofacial fixed mounted modules of PVs were considered for their assessment, thus this is a more conservative assessment compared to bifacial options or other, more advanced technologies.

For the theoretical PV power potential estimation, the main parameters used were: the Global Tilted Irradiation (GTI) -which derives from Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI)-, the temperature of air at 2m. and seasonality. The practical PV power potential estimation took into account parameters such as: terrain complexity, large water bodies (excluding the sea, 1km further from the coastline), forests, uninhabited remote areas and very dense urban districts. For the economic PV power potential, the main parameters used were: the LCOE (without subsidiaries) and socioeconomic criteria such as Human Development Index (HDI), access to electricity, electricity power consumption etc.



The map (Solargis, GTI, 2025), as per Figure 60, is providing a quick view of the GTI worldwide, while the study ranks Republic of Yemen, Namibia, Sudan, Oman and Niger in the first five places, based on the average GHI theoretical potential. Generally, countries of Middle East, the Saharan region, South-West African countries, and West South-American countries are among those with the highest potentials.

**Figure 60: Global Map of GTI**



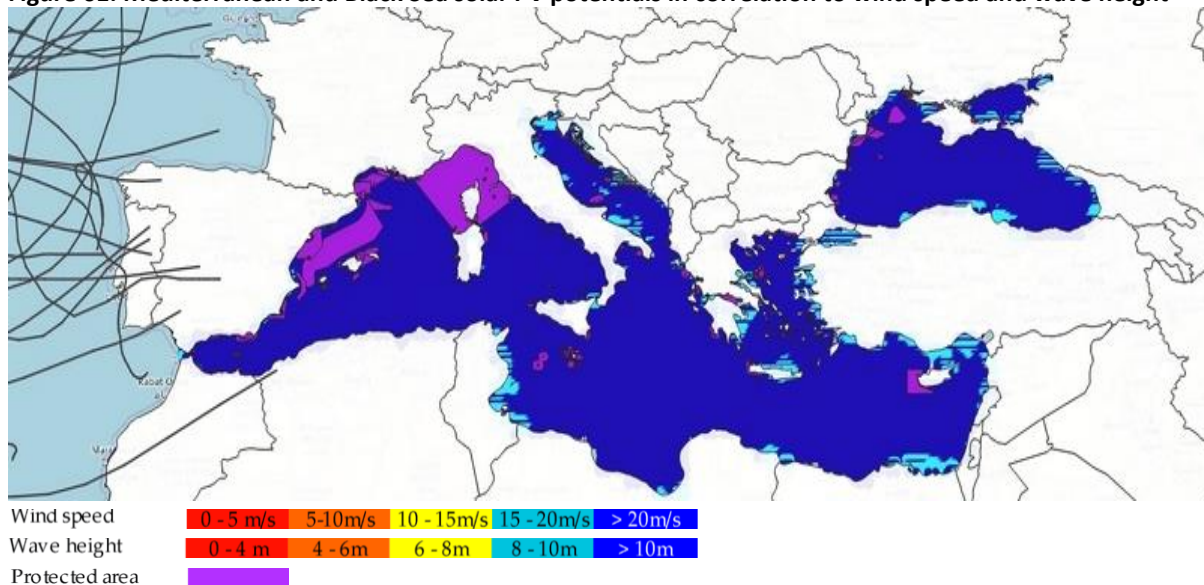
**Source: (Solargis, GTI, 2025)**

In the Mediterranean basin the higher ranked countries are: Egypt (9<sup>th</sup> in the global ranking), Libya (11<sup>th</sup> in the global ranking), Algeria, Israel and West Bank & Gaza. Mediterranean basin countries that are ranked low are Montenegro, Croatia, Bosnia – Herzegovina, France and Slovenia, which are the northern countries bordering with Mediterranean basin. However, additional studies, including the sea-space, need to be done, since they could provide more accurate assessments of Mediterranean countries' potentials, which could be used in the designing phase of multi-use ORESs platforms.

In their 2023 study, Silalahi & Blakers (Silalahi & Blakers, 2023) analysed data of maximum wind speed and wave heights globally in order to determine the optimal offshore locations for solar PV floating systems. For the Mediterranean and Black Sea collectively, they concluded to an estimated potential energy production of 29,000 TWh per annum. According to same

study, the feasibility of the employment would depend on the structures' efficiency to withstand wind speed up to 2m/s and wave height up to 10m. Their combined map of wind speeds, wave heights and protected areas is presented in Figure 61. Subject study did not take into account the option of submersible PV panels. This alternative, however, is very important for the Mediterranean basin projects, since it can both protect PV systems from high wind and waves, but mainly it can boost their efficiency, which is compromised due to high summer temperatures. The optimal option would be a structure with the ability to stand above sea-level (e.g. when temperature is  $\leq 25^{\circ}\text{C}$ ) or be able to submerge at different sea-column depths in a mechanically controlled way (e.g. 10cm below sea-level when surficial temperature is  $>25^{\circ}\text{C}$ , in order to take advantage of the cooling effect of the sea or lower when waves are high). Controlled submersion devices are more versatile and reduce the cost of cleaning, but their CAPEX is higher.

**Figure 61: Mediterranean and Black Sea solar PV potentials in correlation to wind speed and wave height**

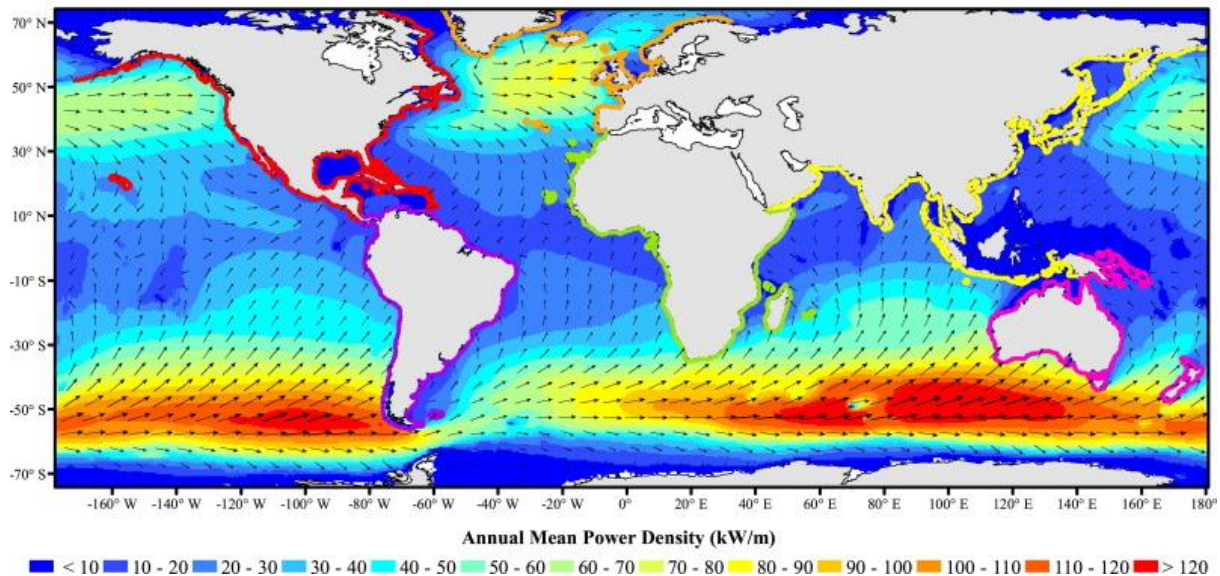


**Source: (Silalahi & Blakers, 2023)**

Regarding wave energy density, as seen from global spectrum, it is accumulated close to the poles, at latitudes between  $40^{\circ}$  to  $60^{\circ}$  north and  $40^{\circ}$  to  $60^{\circ}$  south, as per Figure 62. Highest wave energy density can be detected at southern hemisphere (Gunn & Stock-Williams, 2012). Australia, New Zealand, Chile and southern countries of Africa seem to carry great potentials on wave energy. Other countries with high potentials include US and Canada -both east and west-, UK, Ireland, Norway and Eastern Russia.



**Figure 62: Annual mean wave power density | Data for 2005–2011 from the WaveWatch III global model run by NOAA**

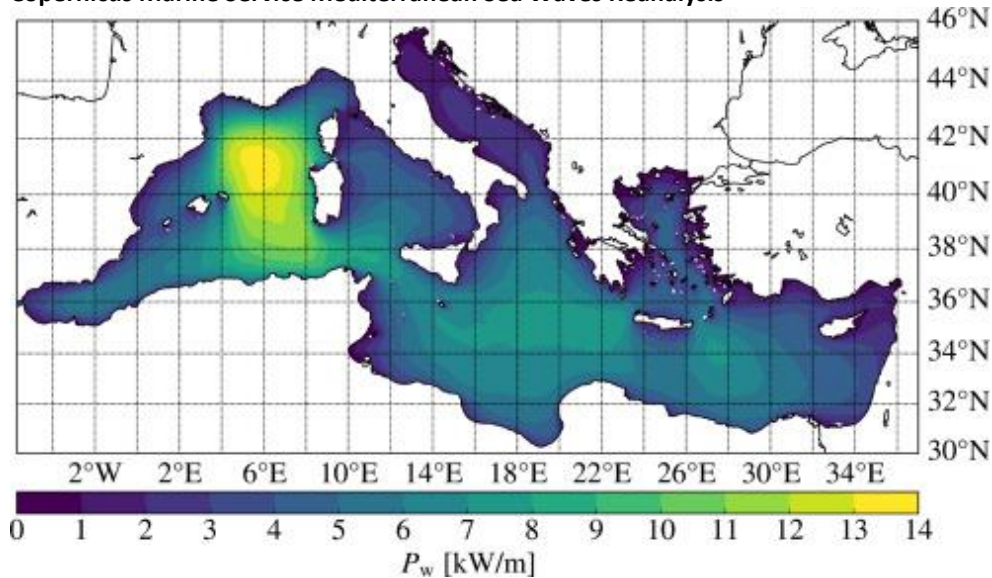


Source: (Gunn & Stock-Williams, 2012)

The Mediterranean basin, on the other hand, presents high water depths and relatively low wave resources. Metrics between the studies of Oikonomou et al. (Oikonomou et al., 2024) and Liberti et al. (Liberti et al., 2012) regarding wave power distribution in the region coincide. According to them, the highest mean wave power is detected in north-west basin, offshore south France and east Spain, extending to the sea-space north of Algeria, as per Figure 63. Peak wave energy at northwest Mediterranean can reach 24 kW/m during winter season (December – February), while mean annual wave energy at subject district ranges between 12 and 14 kW/m. The specific district, however, is presenting relatively high seasonal variability (Figure 64), due to winter high cyclogenetic activity, which poses challenges regarding wave energy integration to the grid.

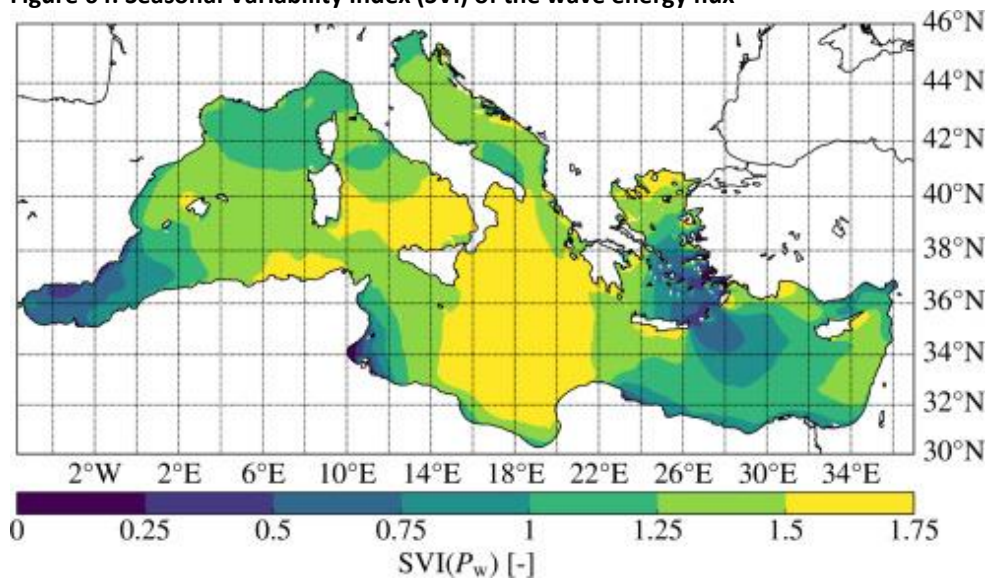
According to the same two studies, at the sea-space west southwest of Sicily the mean wave energy was estimated at about 9kW/m, while south Ionian Sea and the district southeast of Crete presented mean wave energy of about 8kW/m. Aegean Sea's mean wave energy was significantly lower, at 4-5kW/m., while Adriatic Sea exhibited some of the lowest means at 3kW/m. Southeast Aegean Sea, along with the Gulf of Gabès and Alboran Sea where among the districts with the lower wave energy seasonal variability, while the highest seasonal variability was detected in central Mediterranean -in the sea-district between west Greece, south Italy, Malta and north Libya- and between south Italy and Sardinia.

**Figure 63: Mean wave energy flux based on the 30-year long reanalysis. January 1993 to December 2022 | Copernicus Marine Service Mediterranean Sea Waves Reanalysis**



Source: (Oikonomou et al., 2024)

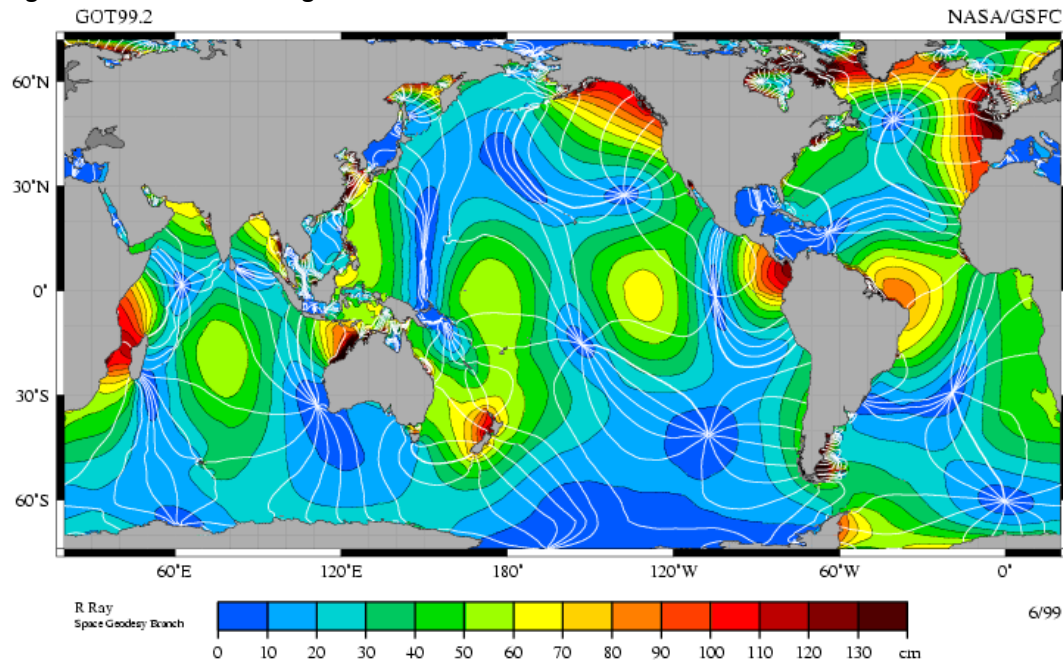
**Figure 64: Seasonal Variability Index (SVI) of the wave energy flux**



Source: (Oikonomou et al., 2024)

Tides, as the periodical oscillation of sea-level stemming from the centrifugal forces of the earth and the gravitational forces between the earth and other celestial bodies -mainly the moon- can be highly predictable and the measure used to describe them is the tidal range, i.e. the difference between higher and lower tide. Such tides can be observed at specific location worldwide. Figure 65 presents NASA's global map, where tidal range is depicted (SVS Archived Story: [/Svs/Db/Stories/Topex/tides.html](https://svs.gsfc.nasa.gov/Content/Db/Stories/Topex/tides.html), n.d.). The locations with the highest tidal range are coloured in deeper red.

**Figure 65: Global Tidal Range**



Source: (SVS Archived Story: /Svs/Db/Stories/Topex/tides.html, n.d., NASA).

The 12 areas with the higher mean tidal range are listed in below table 3. (NOAA Tides & Currents, n.d.). Other locations with high mean tidal range include Argentina, France, Chile, Russia and Australia (Time, 2024).

**Table 3: The 12 districts with the higher mean tidal range**

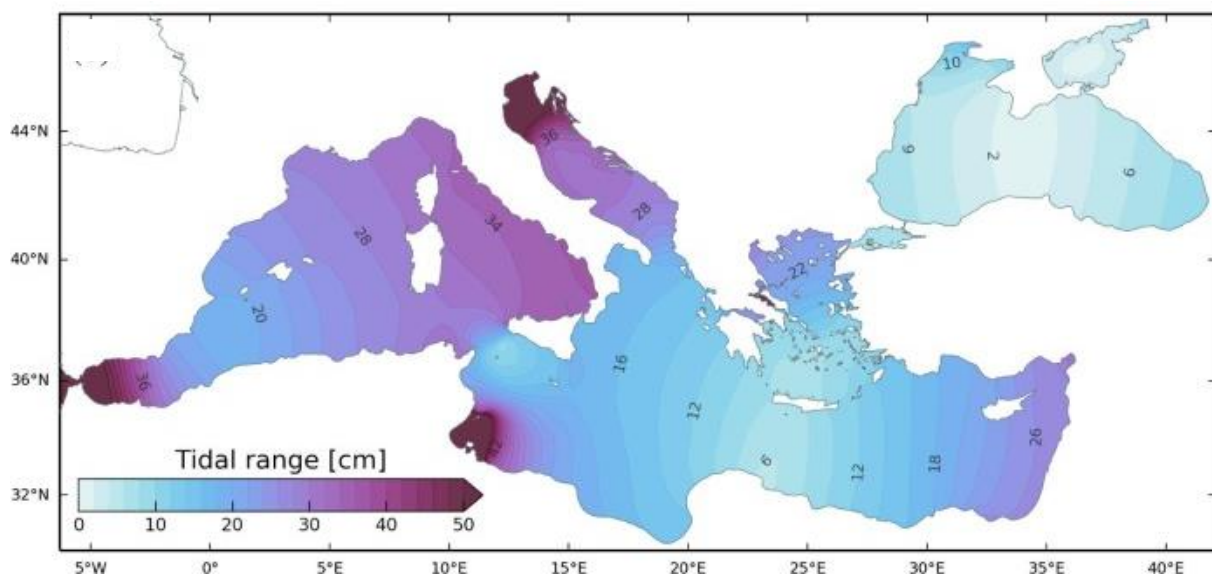
District / Location	Country	Mean Tidal Range in meters
Burntcoat Head, Minas Basin, Bay of Fundy, Nova Scotia	Canada	11.7m
Horton Bluff, Avon River, Minas Basin, Bay of Fundy, Nova Scotia	Canada	11.6m
Amherst Point, Cumberland Basin, Bay of Fundy, Nova Scotia	Canada	10.8m
Parrsboro (Partridge Island), Minas Basin, Bay of Fundy, Nova Scotia	Canada	10.5m
Hopewell Cape, Petitcodiac River, Bay of Fundy, New Brunswick	Canada	10.1m
Joggins, Bay of Fundy, Nova Scotia	Canada	10.1m
Leaf Lake, Ungava Bay, Quebec	Canada	9.7m
Port of Bristol (Avonmouth)	UK	9.6m
Grindstone Island, Petitcodiac River, Bay of Fundy, New Brunswick	Canada	9.5m
Spencer Island, Bay of Fundy, Nova Scotia	Canada	9.3m
Newport, Bristol Channel, United Kingdom	UK	9.2m
Sunrise, Turnagain Arm, Cook Inlet, Alaska	USA	9.2m

Source: (NOAA Tides & Currents, n.d.).



In the Mediterranean basin tidal range is low and apart from the gravitational forces, it is, also, affected by the entrance of water masses from the Atlantic Ocean, through Gibraltar Strait (Tsimplis et al., 1995). Figure 66 presents the mean tidal range in centimetres for the Mediterranean basin and Black Sea, as depicted in Ferrarin et al.'s study (Ferrarin et al., 2018). Gulf of Gabès in Tunisia presents the higher maximum tidal range, which can reach 1.5m, followed by north Adriatic Sea and Alboran Sea at Gibraltar Strait, the maximum tidal range of which can reach about 1m. and 60cm., respectively (Ferrarin et al., 2018).

**Figure 66: Mean tidal range in centimetres for the Mediterranean basin and Black Sea**



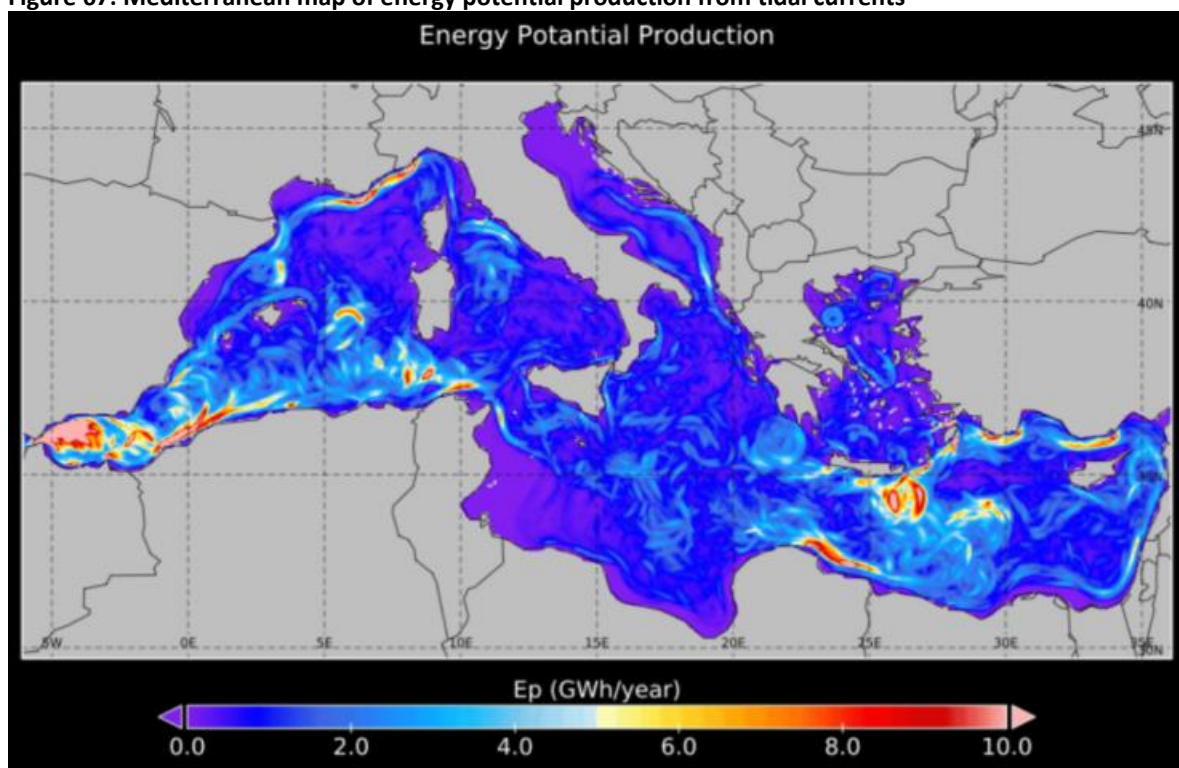
**Source: (Ferrarin et al., 2018)**

However, apart from tidal range, the velocity of sea currents can be used for harnessing tidal energy. Velocity of currents is measured in cm/s or m/s and it describes the speed per time-unit that water masses are moving from one place to another. Such currents may be found at surficial waters or at any depth within the sea water-column. For the effective operation of a tidal turbine a stream speed of 1.5–2 m/s must be reached (Soukissian et al., 2017, Gucel & Sakalli, 2024).

The Strait of Messina has already been proven to carry the highest sea current potentials in the Mediterranean basin, with maximum stream velocity reaching more than 3 m/s (Gucel & Sakalli, 2024, Soukissian et al., 2017), followed by the entrance of Gibraltar Strait with maximum current reaching 2.7 m/s in the period between March to May 2018 (Gucel & Sakalli, 2024) and average flux above 1.8 kW/m (Soukissian et al., 2017). Alboran Sea, the entrance of Ibiza Strait, and the sea district close to Balearic Islands, as well as the Tyrrhenian Sea and Sicily Channel, all have shown good potentials (Gucel & Sakalli, 2024, Poulain et al., 2018).

Gucel & Sakalli (Gucel & Sakalli, 2024), after analysing Copernicus' data on Mediterranean Sea currents -both per year and per season- between 2016 and 2018, concluded to the map of Figure 67 and a list of alternative potential locations for tidal currents' energy harvesting. Highest potentials among them are attributed to the sea districts south of Derna and Tobruk, in Libya. Also, at specific districts in the sea-space between south of Toulon and Genoa and off the coasts of Algeria and Tunisia. Other possible sites could be the sea district between Cyprus and Turkey and sea areas close to Greek islands of Rhodes and Crete.

**Figure 67: Mediterranean map of energy potential production from tidal currents**



Source: (Gucel & Sakalli, 2024).

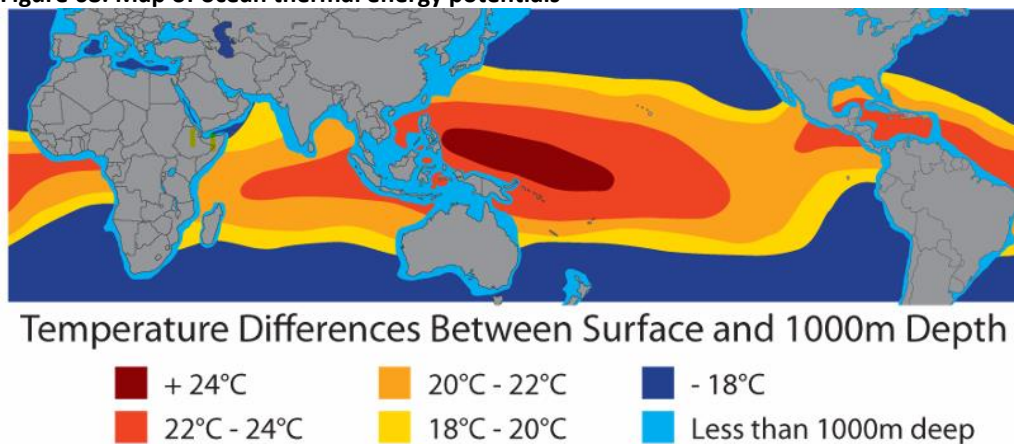
In case, though, that TECs are part of a synergic system, their employment could be economically viable even in areas with lower current stream speeds, due to lower CAPEX, OPEX and LCOE, stemming from structure & cables sharing and less O&M costs. Routes that are followed by marine organisms during e.g. migration, which might coincide with tidal currents, however, should be assessed before TECs' implementation.

As ocean thermal energy needs a water temperature difference of 20°C or more between the surface and deep sea, the potentials of this form of energy are concentrated in equatorial and tropical areas, as per Figure 68. Due to subject restrictions of temperature difference, stemming



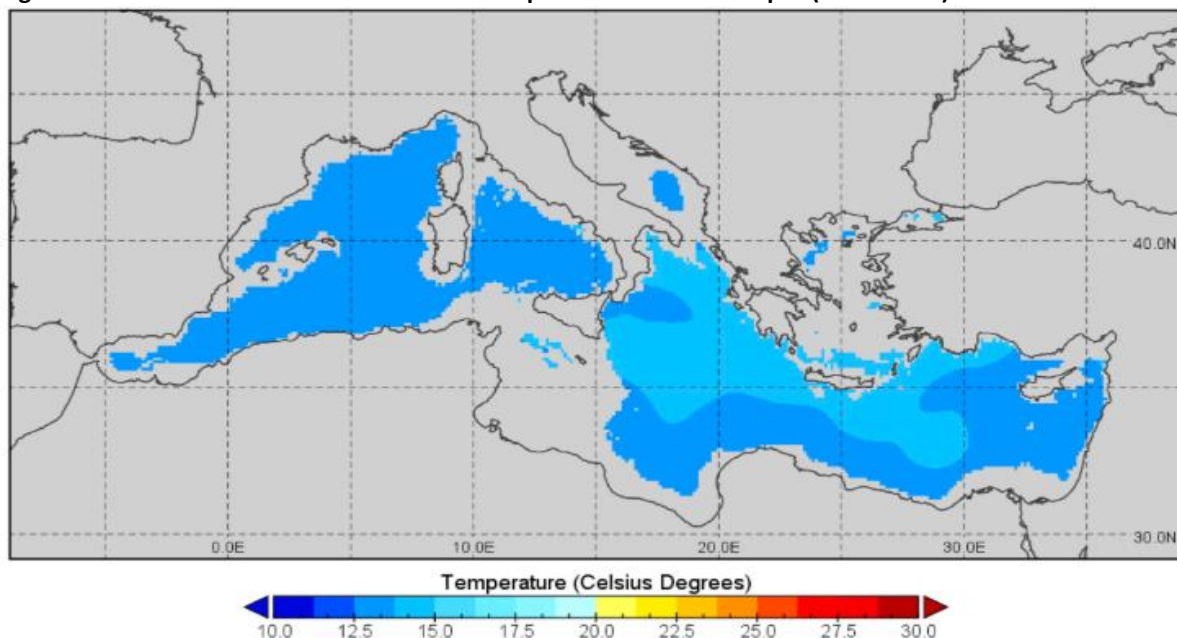
from current technology, OTECs cannot be efficiently deployed in the Mediterranean region, where the mean temperature at 1000m depth ranges between 12.7°C and 13.6°C (Figure 69), while the highest mean surficial temperature is 20–22 °C (southeast Mediterranean) (Soukissian et al., 2017). However, alternative OTEC technologies have been proposed for the Mediterranean region, as the temperature difference between deep-sea water and ambient air (Georgiou et al., 2012).

**Figure 68: Map of ocean thermal energy potentials**



Source: (Hillhouse, 2021)

**Figure 69: Mediterranean mean annual sea temperature at 1000m depth (2000–2015)**



Source: (Soukissian et al., 2017)

Salinity gradient energy is concentrated in river deltas and estuaries, where fresh water meets seawater. Alvarez-Silva et al. in their study on salinity gradient potential (Alvarez-Silva et al., 2016) listed the rivers with the higher extractable energy. According to their study, rivers Congo (Democratic Republic of the Congo), Orinoco (Venezuela), Mississippi (US), Parana (Argentina) and Amur (Russia) are those with the highest extractable energy worldwide. In the Mediterranean basin the highest extractable energy is attributed to rivers Rhone (France), Po (Italy) and Nile (Egypt). However, it must be taken into account that most Mediterranean river deltas constitute environmentally protected areas (Soukissian et al., 2017).

Regarding Green Hydrogen, since its production does not present location constraints, it can be done worldwide, as long as there are adequate available renewable resources. For the location of such construction, factors such as vicinity to markets, supply chain, benefits from co-location of installations and environmental impacts in case of accident should be taken into account, during site selection.

## **4.2 Synergies Between Sustainable Sources and O&G Sector**

As the world is moving from fossil fuels to renewable energy and during the transitional phase, the focus of research should not only be drawn to renewable sources and the increase of their share into the energy mix, but also to the O&G industry and how it can currently reduce its GHG emissions, with the assistance of RESs.

Offshore O&G platforms are heavily energy intensive. They need energy for heating of oil, in order for it to be easily extracted. Furthermore, they need energy for pumps, compressors, and other machines, as well as for the control room and the daily activities of the employees on the platform. In order to meet these needs, platforms currently mainly use gas turbines or diesel generators, which fuel them from part of the extracted product. However, if some of this energy was supplied by ORESs, the O&G CO<sub>2</sub> emissions could be reduced.

The first step was done in 2022, when Hywind Tampen, a floating offshore wind farm dedicated in providing energy to offshore O&G fields Gullfaks and Snorre, in Norway, was set into operation. Both fields, as well as Hywind Tampen are owned and operated by Equinor, the Norwegian state-owned company. According to Equinor's projections, the farm is expected to

reduce the fields' CO<sub>2</sub> emissions by 200,000 tonnes per year and to cover about 35% of their annual energy needs (Cuthrell, 2023).

For the same geographical area, Oliveira-Pinto et al. (Oliveira-Pinto et al., 2019) had studied the possibility of energy supply from WECs to offshore O&G platforms. In that study, the researchers assessed 7 different types of WECs, scaled to the needs of the specific location, and concluded to the feasibility of use of some of the studied WEC types for the electrification of O&G offshore platforms in this area.

However, such facilities should be examined in a broader context. For example, Gullfaks platforms A, B and C are gravity based (*Gullfaks Gas Export*, 2020), while Snorre platform A is a tension leg platform (TLP) and platform B is a semi-submersible type platform (*Snorre*, n.d.). After decommissioning phase, such platforms could be repurposed for accommodating equipment for H<sub>2</sub> production and desalination facilities, which are essential for H<sub>2</sub> production. The gravity-based platforms, which are fixed to the seabed, would be a better option for higher-risk activities, such as H<sub>2</sub> production, due to its flammability, that can cause fires and explosions. They could, also, accommodate personnel or energy storage and energy management systems and be used supportively for aquamarine operations or as storage areas. Structures, such as helidecks, which already exist on these platforms, could further enable the maintenance services.

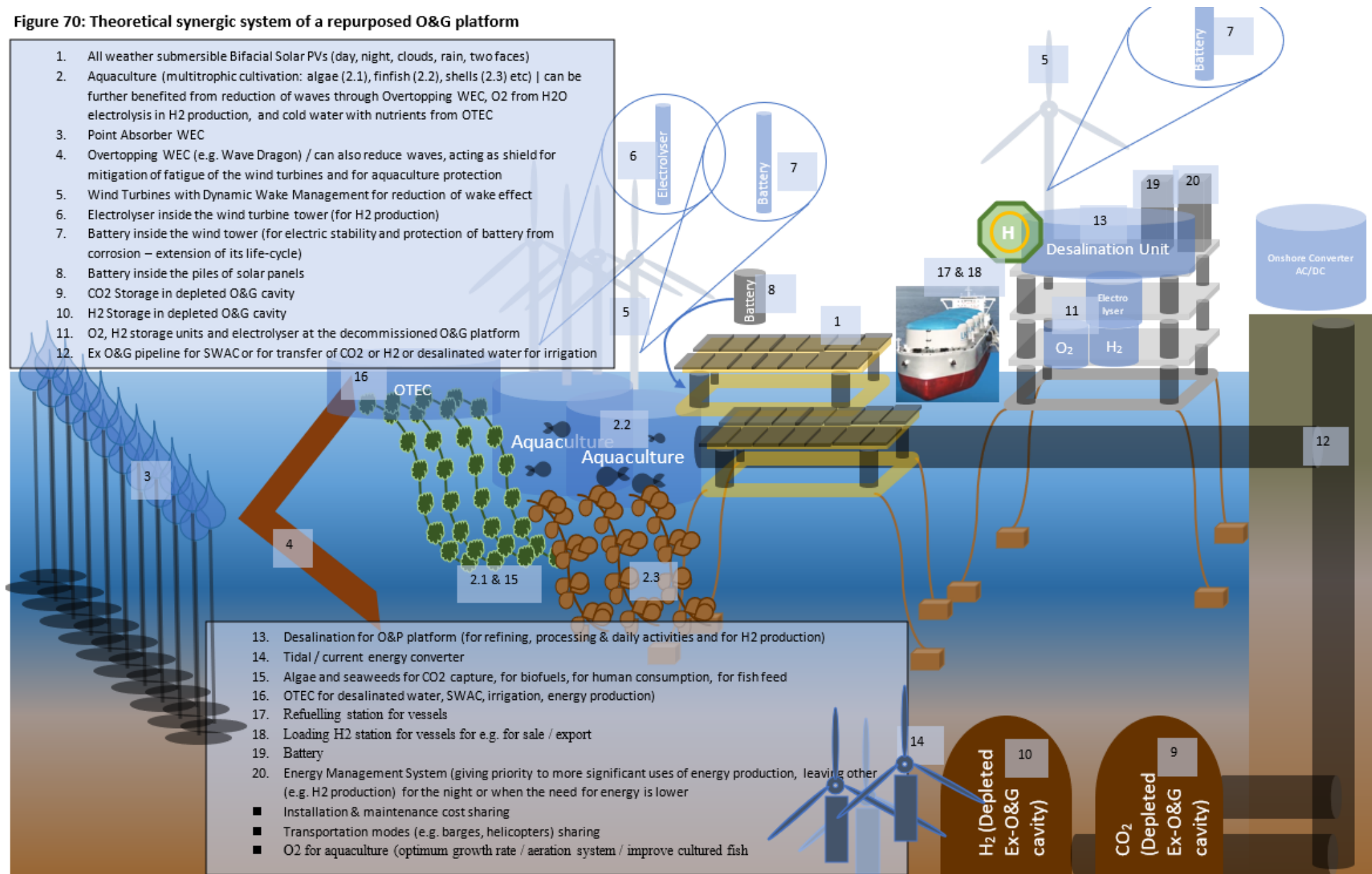
In addition, the undersea cavities from the extracted O&G could act as storage fields for H<sub>2</sub> or sequestered CO<sub>2</sub> (Kumar et al., 2023, Mahmoud & Dodds, 2022). Platforms could, also, accommodate batteries, while the current network of pipelines could be repurposed to transfer H<sub>2</sub> onshore. Transportation of H<sub>2</sub> through pipelines is considered better option than electricity transmission through cables, due to its smaller energy losses and its lower costs when transported over long distances (Kumar et al., 2023). This option is still under study, though, due to higher risk of pipelines failures, caused by acceleration of degradation when H<sub>2</sub> is transferred. This impact is caused by the chemical traits of hydrogen and it is leading to material embrittlement (Mahmoud & Dodds, 2022). Decommissioned submarine pipelines could, also, be used for CCS (Mahmoud & Dodds, 2022). Also, they could transfer seawater for SWAC systems onshore, fresh water, biofuels or even fish feed (Robinson et al. 2021).

The repurpose of such facilities could prolong their life-cycle and save the financial and ecological cost of decommissioning, which is substantial. According to North Sea Transition

Authority's 2022 report on UK Continental Shelf, the estimated total decommissioning cost (for all UK Continental Shelf platforms in 2022) was GBP 44.5 billion (about USD 55 billion), a 25% decrease from GBP 59.7 billion since 2017 (*UKCS Decommissioning Cost Estimate 2022*, 2022). The cost of decommissioning of a typical platform at 80m water-depth operating at North Sea was estimated to GBP 800 million (about USD 989 million) (Carpenter, 2015).

In figure 70 a theoretical synergic system of a repurposed O&G platform has been included.

**Figure 70: Theoretical synergic system of a repurposed O&G platform**





## 5. PESTEL Analysis

For a better understanding of the environment in which offshore renewables and interactions among them affect the entire system, a PESTEL analysis is conducted. PESTEL analysis is able to determine political, economic, socio-cultural, technological, environmental and legal key-factors that may influence the system, assess their impact and take corrective actions, when necessary. It is an important tool when new fields are explored or in cases where there is a lack of adequate experience, such as the systems under examination, because it can track, in a structured way, challenges that have not yet been addressed. The reason this method was chosen is that it can capture information and data from different fields that could possibly affect the system. Thus, way the challenges could be mitigated while the opportunities could be maximized. It is a multidisciplinary tool for assessing impacts and determining the strategy of the sector. In addition, it can provide information to multiple different stakeholders, from constructors and operators to environmental organizations or the state, giving a broad picture of the system's environment. However, these data can be interpreted differently from each stakeholder, based on their perspective. The information provided is easily understood, but it usually lacks specific metrics and it runs the risk to accumulate excessive data or oversimplify some parameters. Furthermore, an advantage of the method is that it is easy to be implemented, but it needs to be re-evaluated periodically and their findings need to be updated constantly, enabling the agility of the sector, its adaptation to changes, which are continuous in the ORES field, and the prompt shift of strategic planning, if deemed necessary. Also, although it analyses the macro environment, it lacks to capture the parameters of the micro environment of the system, while the perspective of the researcher may play some role in the parameters that they will include.

Generally, in this analysis, the parameters included were filtered from literature, so that could coincide and reach consensus, although such analyses are limited, mainly due to the fact that there is no commercial operation of multi-use offshore platforms till now and deployment of ORESs is also limited. For this reason, below mentioned factors should not be considered as exhaustive, as sector is still under development (Collu & Bachynski, 2019), while for some sectors, such as legal, political or cultural, are expected to be affected by the specific country in which offshore RE systems will be employed.

## 5.1 Political & Legal

The political and legal fields include parameters that are often overlapping. The political factors include policies and regulations regarding fiscal, labour, environmental and trade aspects, such as taxation, tariffs, trade agreements, environmental policies, waste reduction policies, health regulations, as well as infrastructure and education. They, further, include corruption aspects, political ideologies of the stakeholders, geopolitical stability and conflicts -which can extend to national sovereignty issues-, foreign trade policies and trade restrictions, governmental support and funding, as well as bureaucracy and they can affect the decisions of manufacturers, operators, investors and other relative parties for entering the market.

Tools used by governments to assist investors and support them during the development of their projects encompass a stable political environment, in order for companies to be able to support their long-term strategies and feel confident in investing. Other tools include protecting and promoting ORESs' policies, renewable energy initiatives and funding (Agyekum et al., 2024). Trade policies can further assist investors' decisions, while trade restrictions and environmental laws usually act as a barrier. Among the countries' national strategies, energy security is ranked high and for this reason there is a need for ORESs to evolve at a fast pace, since they compete with fossil fuels' energy sector, thus, if energy from RESs is not adequate to support demand, greater percentage of fossil fuels will enter the energy mix.

The promotion of sustainable energy through RESs is reinforced by the United Nations, and other bodies and organizations, such as the International Energy Association (IEA) and the International Renewable Energy Agency (IRENA) in international level, as well as the Agency for the Cooperation of Energy Regulators and the European Ocean Energy Association in EU level (Kolios & Read, 2013, Segura et al. 2018). All these bodies share knowledge, provide funding and set policy requirements towards the achievement of sustainability (Kolios & Read, 2013).

Regarding legal factors, these include the legal framework for the initial requirements, permits and operation of the stakeholders, employment laws, health and safety guidelines,

intellectual property for new technologies’ protection -such as patents-, market regulations, tariffs, trade restrictions, environmental legislation, as well as liability issues. Legal factors can even extend to renewable energy targets. A renewable energy target, as described by the REN21 on their 2014 report is “an official commitment, plan, or goal set by a government (at the local, state, national, or regional level) to achieve a certain amount of renewable energy by a future date. Some targets are legislated while others are set by regulatory agencies or ministries.” (REN 21, 2014).

Apart from the local and national laws, international laws should, also, be taken into account, when designing new legislation on ORESs’ sector, due to the fact that use of oceans is falling under international law convention.

More specifically, the UN Convention on the Law of the Sea (UNCLOS), is determining the territorial sea of a coastal or archipelagic state “up to a limit not exceeding 12 nautical miles, measured from baselines determined in accordance with this Convention”. Furthermore, according to UNCLOS, the sovereignty of subject coastal or archipelagic state “extends to the air space over the territorial sea as well as to its bed and subsoil.” (United Nations, 1982). “Beyond and adjacent to the territorial sea” extends the Exclusive Economic Zone, up to “200 nautical miles from the baselines from which the breadth of the territorial sea is measured.” (United Nations, 1982). At the Exclusive Economic Zone, the coastal state can explore and exploit, conserve and manage the natural resources, for the production of energy from the water, currents and winds – among others, as well as for “the establishment and use of artificial islands, installations and structures” (United Nations, 1982).

Thus, a legal framework of the marine spatial planning, not only in the territorial sea and the exclusive economic zone, but, also, in the open seas for future uses must be implemented. This way the overlapping authorities and jurisdictions can be better regulated. A rigid legal framework regulating co-existence and co-ownership of ORESs platforms should further be evolved for future conflicts to be minimized.

Most ORESs are, currently, expected to be deployed at the Exclusive Economic Zone. However, there is still a lack of legislation from some EU countries for such structures (Segura et al. 2018) and it is not uncommon for legal framework of offshore O&G sector to be used in some cases of ORESs platforms’ employment. And although RE targets for combating GHG emissions have been set into place by all EU member states, some of these

targets may be part of a country's greater policy, aiming in additional parameters, such as energy security and social justice (Agyekum et al., 2024) or even national security concerns.

Furthermore, one of the greatest issues that many countries face during the incorporation procedure of ORESs into their energy mix is that the environment in which the decisions are made is highly fragmented into national and international institutions, as well as within local authorities, making it hard for decisions to be made and investors to proceed (Agyekum et al., 2024). For example, in Denmark, just for the licencing in the ocean energy sector, the authorities involved include Danish Coastal Authority, Danish Maritime Authority, Danish Energy Agency, Danish Environmental Agency and Ministry of Defence (Segura et al. 2018). Equivalently defragmented are the procedures in other countries.

Sweden is another example of how different authorities can have an impact on development of ORESs projects. In November 4<sup>th</sup>, 2024, the country cancelled 13 projects of OWTs, of a total capacity of about 32GW, which were at their development stage, due to military concerns in the Baltic Sea and fears from the department of Defence that such installations would delay detection and shut-down of missiles in case of an attack (Reuters Staff, 2024, Santaella, 2024).

The problem of defragmentation of authorities' decisions is further expanding as the different sources use different technologies, many of which are at different level of maturity (Segura et al. 2018). Thus, a movement towards a strategy of one-stop shop, the digitalization of the permitting procedure and the setting of an auction calendar could save time and designate a single body, which the stakeholders could address to (*Offshore Renewables Paving the Way for a Competitive and Climate-Neutral Europe by 2050*, 2024).

## 5.2 Economic

The main aspects connected to the economic sector are the economic growth, the inflation and interest rates, the employment and the household disposable income. The more stable the economic environment which a project is developed in and the higher the support it receives, the higher the possibilities to be successful. In the field of ORESs, issues such as finance, fund-raising and profitability of a project play pivotal role in the decision of an

investor to enter the market. Other issues include economic sustainability of the project and insurance risks (*UNITED - Waterborne.eu*, 2023).

One of the main factors the investors usually refrain from such projects is the high LCOE, mainly stemming from the high capital cost, in contrast to maintenance cost, which is usually relatively low. And, although LCOE is lower in the case of ORESs, mainly due to infrastructure sharing, high capital cost can, yet, put at risk the entire project, since most of these technologies are still evolving, data are not largely available and the return on investment is not secured. At the same time, high LCOE of ORESs reduces their competitiveness compared to other, more mature land-based RESs' technologies (Agyekum et al., 2024). And although LCOE is expected to fall in the future, for a sustainable growth to be achieved these sources currently need financial support and state subsidisation, in order to attract investments and be viable.

Investments and deployment of ORESs are considered to be more important factors in reduction of LCOE than time, because technology is evolving based on data collection, innovation, learning and experience (Segura et al., 2018) and these can be gained from real-life trials. In the initial stage of technological development, public funding can support the investors. During the stage of array deployment loan guarantees and pull or push strategies, such as feed-in tariffs, investment tax credits, production tax credits, government grants, power purchase agreements and Contracts for Difference (CfD) can be used to attract investments (*Offshore Renewables Paving the Way for a Competitive and Climate-Neutral Europe by 2050*, 2024, Agyekum et al., 2024, Segura et al., 2018). Project-funding based on the level of technological readiness of each source is expected to carry greater benefits in isometric evolvement of the different sources.

### **5.3 Socio-cultural**

The socio-cultural sector includes aspects of the social environment and how the employment of ORESs can impact the local communities, their cultural perceptions, their everyday life, their standards of living, their quality of life and social mobility. Among the sea-users and activities which are expected to be impacted are fishermen, aquaculture



farmers, people living close to coastal or island regions where the ORESs will be employed, military and defence sector through the restriction of sea-space, environmentally protected areas, vessels' routes, local touristic and recreational businesses, local authorities carrying the responsibility of taking decisions, etc. (Segura et al. 2018).

Impacts on wellbeing and quality of life may include fears on the preservation of cultural and national heritage and the natural landscape, fears of degradation of the area and devaluation of the properties and can even extend to fears of unemployment in sectors such as fishery. Visual, vibration and noise impacts to the local communities should not be undermined, either (Agyekum et al., 2024, Soukissian et al., 2023). All these issues can lead to tensions between local communities and project developers.

For minimization of conflicts between the local communities and sea-users on one hand and the ORESs' developers on the other, an inclusion scheme of information-sharing and decision-making is important to be implemented. Such schemes can be put into effect both during project planning, as well as the implementation phase (Baulaz et al., 2023) and vary in context, from simple information providing schemes to those schemes inviting relative parties for active involvement.

In the simplest form of such schemes, developers are just informing relative parties on the project. In more advanced schemes, developers, apart from information sharing are, also, requesting parties to express their opinions, without being mandatory that these opinions will be considered. This is the level of schemes that constitute the minimum requirement by the EU for ORESs projects' development and are significant in providing developers a general idea of the public perception. The EU requirements during implementation phase further include submission of Environmental Impact Assessment by the member state to the local authorities and the public (Baulaz et al., 2023). On the next level of conciliation schemes, parties have some degree of decision-making power and it is common for negotiations between developers and the other parties to take place. In partnership schemes, engagement of local communities and stakeholders is higher. Negotiations, in this case, may include issues such as location, spatial extend, as well as technical characteristics of the project. Higher inclusion of local communities is achieved through delegation schemes. In these schemes, the community is the main decision-maker and it is, also, responsible for additional tasks, such as communication and management of the project. In the higher level

of public engagement and the most advanced schemes, community can participate in the ownership, as well as in the possible gains and risks of the project (Agyekum et al., 2024, Baulaz et al., 2023, Segura et al. 2018).

The greater the engagement of local communities and the earlier the stage of engagement in the project procedure, the higher is the possibility of the project to receive public acceptance and the possibility to succeed, but the time-frame of the project is significantly prolonged in this case. Trust, confidence, and understanding among all parties and their concerns or initiatives are key-factors for public acceptance of a project (Segura et al. 2018).

ORESs can further promote social growth and living standards through the creation of new jobs or the movement of employees from offshore O&G sector, during the transitional phase from fossil fuels to renewable energy era. These benefits, although initially localised, they have the potential to expand nationally, as a result of investments' attraction, which, in turn, can lead to grid expansion and port developments (Soukissian et al., 2023).

Job creation can expand to various fields, from metallurgy and shipbuilding to engineering, oceanography, computer science, cable manufacturing, transport, logistics and maintenance sectors (Agyekum et al., 2024, Segura et al. 2018). Legal advisory, accounting and management can contribute to job creation expansion, too. In their 2022 study based on two different scenarios, (Ruiz-Minguella et al., 2022) estimated that tidal and wave energy alone have the potential to provide between 127,765 and 263,308 direct and indirect jobs in Europe by 2050.

Many offshore energy harvesting devices are large and heavy, while their transportation is expensive and needs special vehicles. For this reason, most devices are expected to be manufactured and assembled at plants close to the installation areas (Segura et al. 2018). The shipbuilding of specialized ships which will be needed for the installation of some offshore structures, however, can only be done in highly specialized shipyards, which carry the technology and the resources for such constructions.

Training and acquirement of new skills is essential for the implementation of offshore RE devices, while workforce from relevant sectors, such as land-based wind and solar or offshore O&G, can assist towards this direction (Soukissian et al., 2023). University courses oriented to offshore RE sector could enhance the skills of researchers (Segura et al. 2018).

Universities and research centres can, also, collaborate with manufactures in new studies and promote the implementation of new, more efficient technologies. The industry, which can better detect the particular needs of the sector, as well as certification-providing organizations, such as DNV, can also act as employees' trainers. Studies on social effects from offshore RE need further assessment, though, since the sector is relatively new and long-term data need to be acquired, as the projects are evolving (Soukissian et al., 2023).

## 5.4 Technological

Technology is highly linked to safety, efficiency, performance, longevity, and, hence, the individual and total costs of a system. In the field of MUOP, technological is a very broad sector which includes different areas of expertise, from materials and components to devices, cables, software, control systems and management of produced energy, as well as the synchronization of these areas (*UNITED - Waterborne.eu*, 2023). It incorporates innovation and automation, applied learning and research and development (R&D) for optimization of underwater interconnections and materials working in harsh environments. Means for installation of devices and cables, logistics and supply chain, as well as management of the power load, energy storage and optimal use of the produced electricity fall under this category, too. Technological advancements can significantly accelerate the implementation of offshore RE production, but they need to be supported by high investments.

Initially, the materials used should, not only be technologically advanced and able to perform under harsh environments, but they should also take into consideration factors such as environmental friendliness (Segura et al. 2018), end-of-life disposal, recyclability, contribution to the project's GHG life-cycle emissions etc. (Agyekum et al., 2024). Main issues to be addressed in the case of materials is corrosion, biofouling and devices' fatigue, induced due to heavy loads and high wind and waves. In the case of energy-transferring cables, topology and technology, such as wet-mates for quick underwater connections and disconnections, may affect significantly the reduction of grid-connection and maintenance costs, while in the case of PTO systems, innovative technology with lean and compact design, which reduces failure risks and promotes reliability, can further compress

maintenance costs, expand the intermediate time between scheduled services and reduce the downtimes of the entire system (Segura et al. 2018).

Further reduction of above-mentioned costs can be achieved through standardization, modularity and reduction in variability of devices and components of the system. Variability is heavily influenced by the level of immaturity of most ORESs' technologies. While offshore wind and – to some extent – solar panels' technology seems to have reached an adequate level of maturity, other ORESs are still falling behind, with, tidal energy, however, making steps towards a more consensus design. This is placing less matured ORESs to be less competitive than others (Agyekum et al., 2024). Technological Readiness Level (TRL)<sup>2</sup> comprises a significant tool of readiness assessment and incorporation of relative technologies into the system (Segura et al. 2018), but the small number of ORESs' prototypes and the small size of companies engaged to the sector until recently, mainly due to investment risks, dictated a slow pace to the sector.

Small-scale prototypes and small-sized companies in collaboration with institutes, organizations and universities constitute an essential initial step and their contribution in the evolution of these technologies cannot be underestimated. Such prototypes and the simulation procedures have given initial data and have reduced the time and cost of testing, since this stage is performed in laboratories, under controlled conditions, without the high costs of anchoring the platform, connecting it to the grid and using large, specialized vehicles to transfer the devices and their components (Segura et al. 2018).

Full-scale projects and large companies, on the other hand, can accelerate the pace of technological advancements, as already proven by offshore wind and solar panels' technological evolution, and contribute in the collection and validation of real-life data. The involvement of large companies, with higher investment power, have assisted and are further expected to assist in the more complex study of arrays, co-location and synergies of combined ORESs. The engagement of companies from the O&G sector further enhances this procedure and reduces technical barriers and know-how costs, through technology-

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<sup>2</sup> TRL is a structured, tiered method for the estimation of technological maturity. It comprises from 9 levels, with level 1 being the least mature and level 9 being the fully matured, ready for commercialisation, technology. The method was initially developed by NASA in the 1970s and is able to compare technological maturity between different devices and types of technology.

sharing and the accumulated experience of such companies in harsh offshore environments and the energy sector (Agyekum et al., 2024).

Knowledge exchange and collaboration in research among companies, institutions, organizations and governments are of paramount importance, as data and technology are shared, the R&D and innovation sectors are moving faster, the technology is evolving quicker and duplication of tests and studies is avoided (Segura et al. 2018). This creates a systems dynamics' reinforcing effect, as new, more advanced technologies reduce risk and provide higher security for companies to invest in the sector. This effect should be further reinforced through public funding, in order for trial studies to move to commercialisation (Segura et al. 2018). The movement of trials from prototypes and stand-alone devices to commercialised, integrated and co-located structures is expected to produce higher volume and more accurate data regarding synergetic operations, enabling better assessment of environmental impact of MUOP platforms (Agyekum et al., 2024) and optimizing topologies across the devices.

The importance of open-sea test centres in such procedures is undeniable. These centres are already connected to the grid and can provide their facilities for full-scale testing of devices with low risks for developers. Other advantages of these centres include independent assessment of devices, easiness of access to a real-life testing environment, decreased security costs, reduction of barriers in deployment and consenting procedures. International collaboration among these centres could, also, reinforce data-sharing and test validation results and accelerate the whole procedure of offshore RE production (Segura et al. 2018).

Additional tools and equipment for enhancing performance and efficiency and reducing costs are the various control systems and sensors, as well as condition-monitoring systems and computer software. Control systems can optimize the volume of produced energy, while at the same time they can reduce damages, caused by the continuous wave movement or extreme weather, and the effects of fatigue in the devices, their components and the entire system. Thus, control systems, in synergy with spatial design for fatigue mitigation can reduce the system's cost by increasing its survivability and, thus, its lifespan (Segura et al. 2018).

Sensors can remotely monitor the condition of the structures and software can prevent malfunctions, manage energy load and intervene remotely to restore problems. The early



detection of maintenance issues, the designing provision of a device, so that its components can be easily accessible for maintenance (e.g. devices emerging at sea-level or above), its robust structure and the minimization of unscheduled maintenance services are main elements of operation and maintenance (O&M) reduction costs. Additionally, unmanned service procedures, usage of smaller, general-purpose vessels and a better scheduling of routine maintenance to optimize the use of weather window, as well as good weather forecasting, logistics and inventory provision for spares' adequate stock can further assist towards O&M cost reduction (Segura et al. 2018).

Computerised systems can, also, be used for power management. The management of power in such complicated systems is very important for grid instability prevention and overload, for optimal use of storage devices (e.g. charging and discharging battery management systems for prolongation of battery life) and for power-sharing and energy distribution to other sources when demand is low (e.g. green hydrogen production during the night) (Abhinav et al., 2020).

Co-located and integrated systems can better exploit common structures, such as cable connections, platforms and sea-space. Logistics and the economies of scale created by the transportation of components and spares through a common supply chain are reducing time and errors and increasing the overall value of the supply network. Limited number of suppliers are currently producing the specialized materials and devices needed for ORESs systems. This fact is limiting the choices of suppliers, it keeps prices high, because spare parts and devices are produced in small batches, and it creates long supply chains, since producers and final deployment of devices may be far away from each other. As technology progresses from pre-commercial to commercial stage these weaknesses are expected to be alleviated, supported, also, by the accumulation of practical experience. The technological maturity, the consensus in design and the mass production of components and devices can promote more robust supply chains, using less and simpler means of transport. The production sites are expected to move closer to the final destinations, creating shorter, more reliable and more competitive supply chains, which will increase the confidence of investors (Segura et al. 2018).

Co-location and integration can additionally affect positively the variability in ORESs' energy production and enhance the total volume of produced energy. Wave effects and

relative fatigue caused to OWTs are mitigated in case of co-location of such turbines with WECs, wave turbulence, which is negatively affecting finfish farming, is limited in case of synergies of aquaculture and WECs (Collu & Bachynski, 2019), highly nutrient cold deep-sea water is used and temperature control is achieved in aquaculture facilities when OTECs produce energy in close proximity to aquaculture facilities (Daniel, 1985), and more stability to the grid is reached when offshore solar panels are sharing space with wind farms, through the complementary production of energy from wind and sun.

## 5.5 Environmental

The potential environmental impacts from ORESs platforms include risk of collision and noise effects on animals, change of habitats / habitat loss, Barrier effect, changes in oceanographic processes / oceanic dynamics, electromagnetic fields effects, changes in the quality of water, structural impediments, chemical risks etc. (Abhinav et al., 2020, Farr et al., 2021, Thennakoon et al., 2023).

Animals' collision risk is probably one of the most common environmental risks and it can affect animals both below and above water, from sea mammals and fish to local or migrating birds. Subject risk is weighted higher in vulnerable ecosystems, environmentally protected areas and when endangered animals are concerned. Collisions may occur between animals and static or dynamic parts of a structure. Static are the non-movable parts of the structure, such as cables and anchoring systems, while dynamic are the movable parts, such as blades or OWSCs. And, although oceanic static structures are known for their characteristic to attract animals (Pirttimaa & Cruz, 2020), collisions to static parts do not carry significant level of concern, as shown by relative experience in wave and tidal energy. Greater challenges are connected to collision between animals and dynamic parts (Thennakoon et al., 2023).

The studies regarding animals' collisions to offshore RE structures, however, are limited to laboratory simulations (Pirttimaa & Cruz, 2020) or -in real life conditions- mainly connected to OWTs. And, although a legal order was issued in 2023 for dismantling of land-based turbines due to endangered golden eagles' collisions in France (Deconinck, 2023), recent report findings regarding OWTs and the behaviour of seabirds suggest that seabirds avoid

turbines (Tjørnløv et al., 2023). Similar are the findings for seal behaviour in regards to tidal turbines, as per (Copping et al., 2017). Subject study concluded that the possibility of a seal to suffer a serious or fatal injury by a tidal turbine was extremely low and that there seemed to be a deliberate avoidance of the turbines' locations by the seals. Collisions between sea mammals and WECs have not been detected either, although collision risk for diving seabirds might be real in the case of WECs (Grecian et al., 2010). In addition, laboratory simulations show that collisions between fish and tidal turbines, while fish are swimming close to them, are unlikely (Pirttimaa & Cruz, 2020). Painting the blades (Rahman et al., 2022), using technologies to scare animals away or using sensors to detect animals and shut down blades / machines are among the solutions for mitigation of the problem, while studies for better understanding of the risk and its effects are still continuing (Thennakoon et al., 2023).

In regards to underwater noise and vibrations, extra attention should be drawn. The reason is that many marine animals use their hearing and sound-based traits, such as sound navigation systems, for orientation, interaction, communication, predation and evasion reasons, although frequency range may differ among different species (Pirttimaa & Cruz, 2020, Copping et al., 2016). Thus, high levels of noise may interact with their abilities to feed, evade or navigate and they can even affect their hearing ability temporarily or permanently.

Noise connected to ORESs may occur mainly during construction of bases, anchoring points and underwater cables, as well as installation, operation and decommissioning of ORESs' structures and devices. Vessels' traffic for installation and maintenance reasons of the ORESs systems and their network should, also, be considered (Copping et al., 2016).

Studies' findings regarding produced noise during the operation of offshore RE systems generally coincide. The level of noise generated is considered low and not expected to have significant impacts on marine animals (Pirttimaa & Cruz, 2020, Abhinav et al., 2020). However, it has been noted that noise may attract or alienate some species, without causing them harm, however (Agyekum et al., 2024, Pirttimaa & Cruz, 2020).

There is a lack of studies, though, between long-term operational noise and its effects on marine life. In addition, simultaneous operation of multiple devices and arrays of ORESs need further study (Copping et al., 2016, Pirttimaa & Cruz, 2020), since combined noise of

devices could cause communication problems and orientation issues among marine animals' populations (Agyekum et al., 2024, Abhinav et al., 2020).

The construction phase of fixed-bottom structures bearing piles and jackets, however, yields very high level of noise and vibrations, due to the need of hammering the base into the seabed, using a procedure known as pile-driving. Anchored structures or structures placed on the seabed generate lower level of noise during their installation and decommissioning phase. Pile-driving, noise level of which can reach 140dB and have significant effects to marine animals, is common for installation of shallow-water OWTs, with fixed-bottom bases (Agyekum et al., 2024, Abhinav et al., 2020). Wave, and tidal devices, on the other hand, are usually either anchored or placed on the seabed (Abhinav et al., 2020, Pirttimaa & Cruz, 2020), while solar and floating OWT, also use anchoring systems to stay in place.

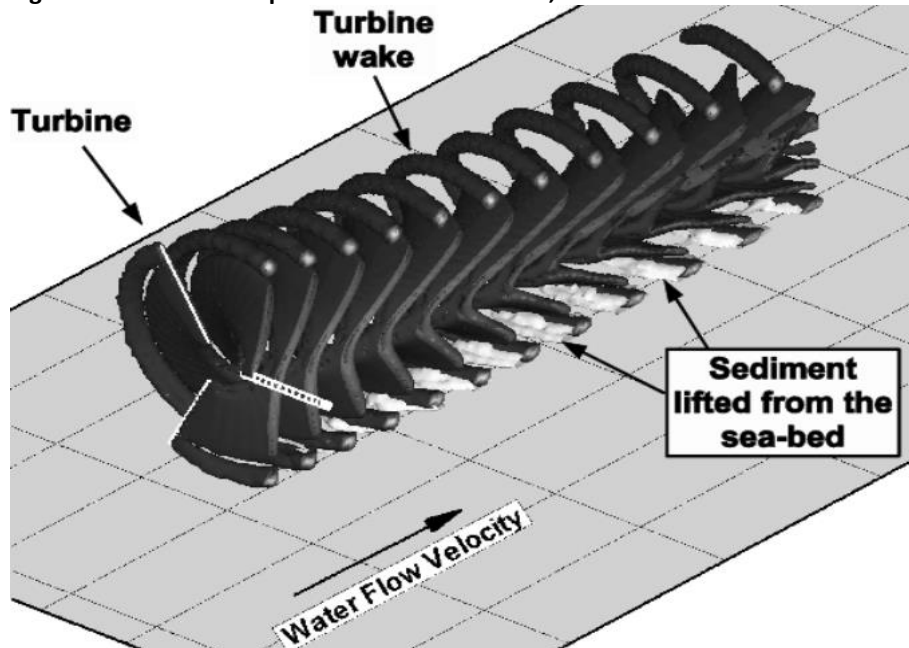
Another parameter that should be taken into account when installation of ORESs systems is designed is how such systems may affect the seabed, water column and surficial conditions, leading to change or loss of habitat for marine animals and birds. In this case, too, the hydrodynamics, the oceanographic processes and the seabed conditions can be affected for short periods, e.g. during installations of anchors and cables, or for the entire period of the project, e.g. during operation of tidal turbines (Pirttimaa & Cruz, 2020).

The installation and operation of these devices have local effects, most common of which are: changes in the waterbody which is close to the seabed (benthic), change in currents' patterns, changes in sedimentation patterns, changes in distribution of nutrients etc. These changes are leading to disturbance, loss of -benthic mainly- species, alteration in animals' behaviour, intrusion of new, non-native, species, degradation of habitat and water quality. The degree in which such changes stem from the installation and operation of RESs is hard to be determined, because sea dynamics lead to constant changes of conditions during natural procedures, too (Thennakoon et al., 2023, Pirttimaa & Cruz, 2020).

One of the most important factors in changing of dynamics, either above sea surface or below water is wake effect. This effect is changing the air-flow / waterbody flow patterns as the air or water masses are passing through a turbine and, apart from reducing the production of the turbines in vicinity, it can, also, increase water turbidity and lead to sediment displacement, the same way a helicopter displaces sand, when landing on desert (Farr et al., 2021, Kelly et al., 2009). Fig. 71 presents sediment displacement, as result of

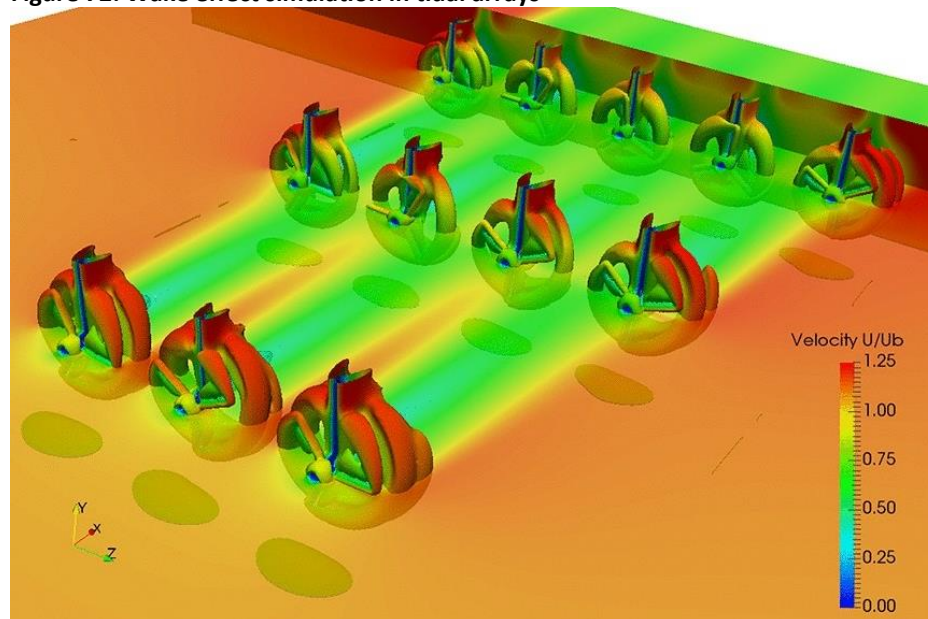
wake effect in a tidal turbine and Fig. 72 presents wake effect simulation in tidal arrays. Loss of habitat can be detected in close proximity of such devices (Pirttimaa & Cruz, 2020), as high volume of kinetic energy extraction alters the flows and natural movement of water (Copping et al., 2016).

Figure 71: Sediment displacement on the seabed, as a result of tidal turbine wake effect



Source: (Kelly et al., 2009)

Figure 72: Wake effect simulation in tidal arrays



Source: (Apsley et al., 2018)



Generally, floating structures which do not cause water turbulence and sediment displacement, such as floating wind turbines, as well as their mooring lines and cables are considered less intrusive for marine ecosystems than fixed-based OWTs, which are operating at shallower waters and which have an effect on wave propagation, although the interaction of floating OWTs with local wind conditions should be taken into account, too (Farr et al., 2021).

The works during installation of submarine pipelines or cables -in case the project is connected to the grid- affect the local environments, since they involve trenching and sediment displacement. Their effects have been found to be temporary, though, and the flora is able to recover after a short period. Some loss of fauna is, however, inevitable (Segura et al., 2017). But, because some underwater structures can attract marine life and act as artificial reefs, habitats for new species are expected to emerge (Thennakoon et al., 2023).

Underwater structures for energy producing purposes do not seem to bear heavy impacts on the marine environment, although changes in hydrodynamics, biodiversity and disturbance have been detected (Thennakoon et al., 2023, Pirttimaa & Cruz, 2020, Copping et al., 2016). A significant aspect, though, is that, since arrays of such underwater devices are not used commercially, the data come either from stand-alone test-devices or from simulations and small-scale laboratory experiments. Fallon et al., (Fallon et al., 2014) in their simulation study of tidal arrays concluded that the morphology of the seafloor could be modified significantly, due to arrays of tidal turbines and that this fact would have an impact to the flora, and -in turn- to the fauna, possibly leading to migration of species.

Installation of small-scale projects do not seem to have significant effects to marine ecosystem. There is a point of energy extraction, however, usually referred as tipping point, after which the system is expected to collapse and many studies are oriented in detecting when this point is reached (Copping et al., 2016).

Above sea-level, on the other hand, one of the main concerns regarding OWTs is that they might force migrating birds to change their routes (Thennakoon et al., 2023). Displacement of this type can lead to longer, more exhausting routes for birds and to feeding and roosting problems for them. The change of bird's migration flyways due to wind-farms is known as Barrier effect and, depending on miscellaneous factors, it can vary from a small change of routes to significant deviations (Drewitt & Langston, 2006). In 2017, 80 land-based wind

turbines were decommissioned in Changdao county, China, after a reduction in birds' populations and a pest increase, following the installation of wind turbines (Meng et al., 2024).

Although electromagnetic fields naturally exist to seawater, due to earth's rotation, its magnetic field and the motion of currents, they can be amplified by anthropogenic sources, such as underwater cables connecting the ORESs devices to shore. Some marine animals, like marine turtles, eels, dolphins, sharks, whales or even prawns and lobsters can be attracted or diverted by such fields. The main effect of electromagnetic fields to marine life is that they may lead marine animals to alter their migratory routes, but till now there are no evidence of electromagnetic fields of anthropogenic sources causing significant biological impacts to marine life or large alteration of their migratory routes. However, since this is a relatively new field, further studies need to be conducted, taking into account accumulative effects of ORESs, too (Agyekum et al., 2024, Pirttimaa & Cruz, 2020).

In case aquaculture is included into an ORESs system, additional parameters should be taken into account. Finfish in aquaculture, such as salmon, may cause further degradation to seafloor, due to medicines for treat of diseases and anti-fouling chemicals used in such plants (Tett et al., 2018, BurrIDGE et al., 2010). In addition, organic and nutrient wastes from aquaculture can further degrade benthic water-quality and reduce oxygen, leading to reduction of population of benthic life and imbalance of organisms.

Other risks of aquaculture to the marine environment include escape of fish and interbreeding with local wild fish, parasites and diseases of aquaculture fish be passed to wild fish, higher accumulation of predators, displacement of wild fish due to aquaculture etc. (Abhinav et al., 2020, Tett et al., 2018). The interaction, however, between ORESs and offshore aquaculture is not well understood yet. Within Europe the assessment of impacts of such interaction are mainly provided by some EU-funded projects, such as TROPOS and MERMAID, but further studies need to be conducted (Abhinav et al., 2020).

## 6. Conclusions

In the effort of this study to combine different means and sources in order to reduce cost and increase efficiency of an offshore energy harnessing system, the different means and their relative technologies have been described. Additional tools, which could further assist towards the direction of cost-efficiency, versatility and reduction of the system's GHG emissions have been analysed and a theoretical framework for a multi-use platform synergic system has been presented. Renewables potentials globally and in the Mediterranean Sea basin have, also, been highlighted and alternatives during transitional phase from offshore fossil fuels to offshore renewables have been introduced. The impacts and challenges of offshore renewables have been exhibited to the extent possible, since additional data from stand-alone and synergic systems in the field need to be collected for a better assessment of the sector. The economical support and subsidies of the states at this stage of ORESs' evolution, as well as a reduction of bureaucratic procedures and a rigid legal framework have been identified as highly important.

The main contribution of this study was that it moved from the examination of offshore standalone or dyadic systems, such as wind-wave, wind-solar etc., which are usually studied in the academic literature, to more complex structures. It tried to spot the advantages that could arise from such synergic structures and how more sources could be incorporated into such systems, optimizing, also, sea-space. It, also, presented a theoretical framework, based on which further studies could elaborate. It proposed ways that additional sources, such as multicultural aquaculture, can enter such systems, be benefited from them, make common use of infrastructure and reduce their costs.

According to our findings, such structures are feasible, although there is a lack of incentives for companies to invest, mainly due to risks stemming from high CAPEX and TRL of devices. Additional search needs to focus on more detailed impacts that co-located and hybrid systems may have.

The goal of reduction of greenhouse gases to net-zero by 2050 is achievable through the use of offshore RE systems, but all nations need to commit and share knowledge in order for this goal to be reached. Population growth and the increased demand for energy, stemming

from this growth, and from additional factors, such as global warming, need to be taken into account in the pursue of this goal. Innovation and research are expected to play significant role towards this direction. Geopolitical stability is, also, important factor.

Green hydrocarbon, produced from seawater, also, presents high potential, as a mean of reduction of fossil fuels and GHGs, since it is able to decarbonize those sectors that are harder to move away from fossil fuels. The global policies, however, need to set rigid guidelines. As the exploration and licencing for new offshore O&G fields continues, the establishment of offshore RE sector is further delayed.

A further study of ORESs in the Mediterranean basin area could consider the idea of use of uninhabited isles, as a base, around which an offshore energy system could be developed. This way, the high cost of creation of an artificial island would be eliminated, while stable ground for the operations followed by higher risks, as well as for storage of more sensitive equipment and for accommodation of personnel during maintenance could be utilised. Such a solution could, furthermore, reduce hazards to the marine environment in case of an accident (e.g. hydrogen production facility or batteries placed on an offshore platform VS an uninhabited isle and the impacts or risks of each option in case of an accident).

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Note: All links provided above have been latest accessed on 31/1/2025

**Author's Statement:**

I declare that, in accordance with the provisions of article 8 of Law 1599/1986, the present thesis is exclusively a product of my own, personal work, and does not violate any form of intellectual property rights, personality and personal data of third parties, does not contain works/contributions of third parties for which permission of the authors/owners is required and has not been copied either in part or in full, and the sources used are limited to bibliographical references only, and meet the standards of scientific citation