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AN INVESTIGATION INTO OFFSHORE WIND TECHNOLOGIES, COMBINED WITH ALTERNATIVE ENERGY SOLUTIONS

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ABSTRACT

The continued transition from fossil fuels towards a green energy supply is essential for Scotland to achieve its goal of a net-zero carbon economy by 2045. Implementing established technologies rather than developing new technologies has proven to be more effective when new products are being introduced into a market. The renewable energy industry is therefore reliant on the continual and rapid maturation of the Technology Readiness Level (TRL) of these innovations, in order to reach the cost effectiveness and efficiency levels that will make the industry viable. Combining energy generation methods, as a hybrid offshore renewable system, may provide benefits in meeting these viability targets.

This study reviews the most commonly used offshore renewable energy systems and a less obvious solution. It investigates the configurations and the different supporting structures that can be used. The main objective of this study is to determine whether attaching a second energy generation system to an offshore wind turbine could reduce the through life costs and produce an increase in energy yield. It does this by using a series of Decision Analysis Matrices to provide an objective insight into the most suitable solution.

ACKNOWLEDGEMENT

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K_{wells} – Wells turbine ratio of pressure drop to air flow

$V_{Chamber}$ – volume of the air chamber

P_{atm} – atmospheric pressure, 101.3kPa

γ – air specific heat ratio, 1.4

$I(\omega)$ – the added masses of the WEC inertia and hydrodynamics of the platform,

$D(\omega)$ – the floating wind turbine's platform and the WEC hydrodynamic damping and the Wells turbine power takeoff.

K – hydrostatic stiffnesses and linkage coupling between the floating wind turbines and the WEC

$P_{Cap,kW}$ – the power capacity in kW

$M_{Steel,kg}$ and $M_{Concrete,kg}$ – mass of steel and concrete in kg

C.F. – manufacturing complexity factor = 2

C_1 – adsorbent capacity after 1 elution cycle

C_0 – initial adsorbent capacity

d – relative loss of adsorbent capacity after an elution cycle

n – number of cycles

t – length of time the adsorbent is exposed to seawater

τ – adsorption time constant ~ 14 days

R – recovery rate

T_h – harvesting period

ΔP_H – Change in Real Power generated from the hybrid system

ΔP_W – Change in Real Power generated from the wind turbine

ΔP_T – Change in Real Power generated from the tidal turbine

ΔQ_{DFIG} – Change in Reactive Power generated from the DFIG turbine

ΔQ_{DDPMSG} – Change in Reactive Power generated from the DDPMSG turbine

ΔQ_{SG} – Change in Reactive Power generated from the diesel generator

ΔQ_{COM} – Change in Reactive Power generated from the compensator

ΔQ_L – Change in Reactive Power generated when connected to the load

ΔV – terminal voltage of the system

I_{qr} – current along the qr axis

I_{dr} – current along the dr axis

CAPEX – Capital Cost

OPEX – Operational Costs

E_t – net energy produced

t – period of years

r – reduction in energy rate

ACRONYMS

AEP – Annual Energy Production
AOE – Annual Operating Expense
CAES – Compressed Air Energy Storage
DDPMSG – Direct Drive Permanent Magnetic Synchronous Generator
DFIG – Doubly-Fed Induction Generator
FACTS – Flexible Alternating Current Transmission System
FCR – Fixed Charge Rate
FWT – Floating Wind Turbine
ICC – Installed Capital Costs
JAEA – Japanese Atomic Energy Agency
LCOE – Levelised Costs of Energy
NDA – Non-uniformly Distributed Array
NREL – National Renewable Energy Laboratory
O&M – Operations and Maintenance
OWC – Oscillating Water Column
PDA – Peripherally Distributed Array
PTO – Power Take Off
SMORE – Symbiotic Machine for Ocean uRanium Extraction
SSP – Semi-submersible Platform
STOR – Short Term Operating Reserve
TLP – Tensioned-leg Platform
TRL – Technology Readiness Level
UDA – Uniformly Distributed Array
WEC – Wave Energy Converter
WUSABI – Wind and Uranium from the Seawater Acquisition synBiotic Infrastructure

1 INTRODUCTION

1.1 Problem definition

Offshore wind is an essential source of renewable energy and has been proven to be stronger and more reliable than onshore wind. As a result, offshore wind has emerged as one of the fastest growing renewable energy sectors over the past decade, with the EU total installed capacity of wind turbines to exceed 40 GW by 2020 and 150 GW by 2030 (Campanile, Piscopo and Scamardella, 2018). Until recently, offshore wind turbines were restricted to relatively shallow depths and used fixed supporting structures such as a mono-pile or a jacket foundation. However, as the industry looks to go further into the ocean, these structures no longer become a viable option. At sites exceeding 50 metre depths, wind turbines supported on a floating platform provide a better solution than the original design structures which would require significantly larger substructures to anchor to the seabed.

However, floating wind turbines are currently significantly more expensive than onshore wind turbines with a levelised cost of energy (LCOE) ranging from $0.12-0.27 /kWh for offshore wind, compared to $0.07 /kWh for onshore wind (Myhr et al., 2014). The high cost faced by the floating wind turbine is due to the challenges of stabilisation which have previously only been resolved by increasing the mass of the large concrete/steel platform, the addition of an active water ballast, and by increasing the tension of the mooring cables.

A hybrid marine energy system combines multiple disparate energy extraction systems in a single solution. In many hybrid systems the two energy generation systems are decoupled. This allows, for example, the Wave Energy Converter (WEC) to continue to produce energy when the required wind force is not achieved to generate wind energy, thereby extending the productive energy generation period (Hanssen et al., 2015). Attaching a second energy generation system onto a floating wind turbine in this way could significantly reduce non-activity hours and the number of grid disconnections (Pérez-Collazo, Greaves and Iglesias, 2014).

However, developing a suitable hybrid energy system is very challenging. The second energy generation system must produce energy on the same MW scale as the wind turbines, in order for it to be considered suitable. The majority of offshore floating wind turbine platforms are only designed to carry and support a singular wind turbine, resulting in a limitation of space to accommodate the second system. The mass of the additional system must also be considered, ensuring the floating platform is stable and remains seaworthy. It is important that the correct arrangement and substructure is chosen and typically produces > 6 MW. Until recently, this was not a realistic option (Hanssen et al., 2015).

Offshore wind technology can benefit considerably from cross-sector modifications, improvements, and the transfer of knowledge. Implementing proven technology from other renewable energy generation systems is often considered to be more efficient than developing new systems. This allows a wider range of experiences and ideas to be brought together and, in turn, improves the probability of reducing the costs incurred from floating wind turbines (Smyth, 2020). Combining offshore renewable energy systems could result in many positive synergies which are discussed later.

The addition of a second energy generation system in the unoccupied space of the wind farm i.e. the space between the wind turbines, raises the possibility of using the same power cables and grid connections. This addition could result in the wind turbines assisting the second generation system and subsequently, reducing the cost of energy, making it more economical. The more components that the two energy generation systems are able to utilise, the lower the cost of the energy produced (Muliawan, Karimirad, Gao and Moan, 2013). Therefore, the combining of an offshore floating wind turbine with a second additional energy generation system is an extremely attractive concept.

1.2 Aim

The aim of this thesis is to determine whether attaching a second energy generation system to an offshore wind turbine could reduce the through life costs and produce an increase in energy yield.

The objectives of the study are to:

- determine a suitable arrangement of the offshore wind turbines and the additional energy generation system.
- determine the most suitable substructure of wind turbine onto which the additional energy system can be attached.
- identify the most appropriate energy generation system from:
    - Wave Energy Converters (WECs)
    - Uranium Harvesting Devices
    - Tidal Turbines
- Having determined the most appropriate energy generation system, determine its most suitable form.

1.3 Structure of the Thesis

In order to meet the objectives of the study, the following structure was used:

- Literature Review

The literature review is divided into two subsections, Background and Potential Energy Systems. The Background subsection reviews literature on additional energy systems - Wave Energy Converters (WECs), Uranium Harvesting Devices and Tidal Turbines, providing an overview of the three energy solutions and describing the capture of the desired energy or uranium. The Potential Energy Systems subsection discusses the various arrangements each system can support in combination with the offshore wind turbine, the substructures of the wind turbine and the economic viability of each system.

- Methodology

This section describes in detail the Decision Analysis Matrices used to objectively determine the optimum solution by assessing the:

  - System Arrangement
  - Structure of the Combined System
  - Additional Energy System
  - Wave Energy Converters

- Results

An analysis of the outcome of each Decision Matrix.

- Discussion

A detailed discussion of the rationale of the results, the positive and negative aspects of each system and a full description of the proposed solution based on the results obtained in this thesis.

2 LITERATURE REVIEW

2.1 Background

Recent advancements in wind energy technology are enabling more efficient and greater power output due to the shift from onshore to the offshore environment. With this shift, there has been a drive to move wind turbines from coastlines to areas of deep water, which necessitates floating wind turbines (FWT). The available space that wind turbines can occupy offshore compared to onshore, allows the developers to benefit from the stronger winds typically experienced; can maximise the size of the turbines; and optimise the spatial separation to extract the greatest energy from these winds. The primary expense for offshore wind turbines is driven by the challenge to stabilise the platform in what can be a very extreme environment (Karimirad, 2016). This can be resolved easily for fixed bed turbines as they use larger concrete and steel static structures to hold them in place.

This, however, is not the case for FWTs whose platforms are significantly less stable. The motion experienced on the FWT platforms can result in numerous problems for the turbines; it is extremely detrimental to the aerodynamics of the rotor and to the control of the turbine, and it can also cause an increase in stress to the blades, therefore resulting in a decrease of the overall efficiency of each FWT (Haji, Kluger, Sapsis and Slocum, 2018). This study will determine that the addition of other offshore energy systems to the FWT platform can increase efficiency and reduce the through life cost of the system. If the addition of these alternative energy systems is able to stabilise the floating platforms, then this can also allow the mooring lines and the steel platforms to be reduced, to further reduce installation and maintenance costs. This study considers the addition of three energy systems: wave energy converters (WECs), uranium harvesting devices and tidal turbines.

2.1.1 Wave Energy Converters (WECs)

WECs have been included in this study as the power obtained from waves is very predictable and consistent compared to wind power. This predictability and consistency is key for electric grid operations. However, despite these benefits, the cost of producing energy from a WEC ranges from \$0.28-\$1.00/ kWh. The high costs are a result of the challenging and harsh sea conditions WECs face and the cost of each component. Over 50% of the overall cost of WECs is due to the steel frame of the WEC, the mooring lines and transmission lines. However, the costs of several of these components could be prevented or reduced by attaching them onto the FWT structure. The addition of a WEC could also significantly reduce the rocking motion of the FWT platform, resulting in an increase in the efficiency of the FWT and generating more energy through the WEC.

Offshore floating wind turbines and WECs occupy the same harsh marine environment and subsequently, they face similar technological and organisational barriers. Exploiting the natural resources, along with the incentive for each industry to reduce costs, offers an enticing opportunity to explore the combination of offshore wind with wave energy. Merging these two energy systems has many advantages. It will reduce operation and maintenance costs and increase benefits from the synergies between the two technologies. These can be split into two groups: technological and legislative (Pérez-Collazo, Greaves and Iglesias, 2014).

Further technological advancements in the marine sector will play a significant role in increasing the economy over the next couple of decades. There are many important legislative areas in which having a combined system will result in significant synergies, such as:

- A common regulatory framework. Marine renewable energy systems have a lengthy return on investment periods, along with significant costs in their initial development. It is for this reason that the development of these systems is dependent on political commitments, such as investment objectives, EU/national energy targets, as well as strategic decisions. To achieve a suitable environment to improve marine energy systems, it is therefore imperative to establish clear objectives for fixing the framework, reliable legislative background, and have suitable political support. A suitable example of regulatory framework has been developed in the UK. This framework has allowed the UK to become leaders in the offshore renewable energy sector.
- Maritime spatial planning. In comparison with onshore energy systems, the marine sector has been recognised as lacking in organised planning. However, the EU is beginning to develop plans over the next few years which include Maritime Spatial Planning as well as Integrated Coastal Protection Management.

These initiatives are the beginning in the recognition of planning requirements for the space and location occupied by the marine systems, combining their operation and uses. Due to the similarities of each marine energy system, combining systems would significantly improve the efficiency and effectiveness of their development and maintenance.

- A simplified licensing procedure. Engineers and other developers involved in producing marine energy systems have a significant disadvantage as they have little experience in licensing procedures for this new domain. As a result, the development of systems can be extensively delayed, for example, due to the environmental impact assessment, which in some cases can delay the project for years until final approval has been reached. Because of the similarities in the marine energy systems, merging the procedures under the same licensing application will result in a reduction of the planning approval process.
- Infrastructure and planning. Electric grid and supporting networks play a vital role when developing offshore energy systems. By electrically combining the systems on the platform, the grid infrastructure required is minimised, i.e. one grid infrastructure for the combined system, rather than two for individual systems.

There are a number of synergies, at a project and technological level, that significantly benefit marine energies. The synergies can substantially improve the energy yield produced, reduce the costs required for operation and maintenance, as well as through life costs (Pérez-Collazo, Greaves and Iglesias, 2014). The synergies can be characterized as:

- Enhanced energy yield. Merging multiple marine energies will increase the overall energy yield per unit area. As a result, the natural resources are more effectively utilised.
- Better predictability. Wave energy is a much more reliable and predictable energy source than wind energy. Combining these systems will increase development costs but reduce the overall payback period.
- Smoothed power output. Despite each system being reliant on the same weather system, the wave energy peaks trail the wind energy peaks. Therefore, the merger of the two energy systems would result in fewer unexpected disconnections from the electric grid and, as a result the output forecast is more reliable and precise.

- Common grid infrastructure. One of the largest expenses for offshore projects is the electric grid infrastructure. Incorporating a system that produces electricity using a shared grid infrastructure would play an essential role in reducing energy costs.
- Common substructure or foundation systems. Merging the wave and wind technology onto one platform or hybrid structure would negate the need and resultant cost of a second substructure.
- Shared operation and maintenance (O&M). Due to the harsh conditions faced by offshore wind projects, it is essential to use specialised technicians to make sure the O&M is efficient. As the wave and wind energy systems share the same platform, there would be a decrease in costs as the use of technicians and installations would be shared.
- Environmental benefits. As wind and wave energy technology continues to be developed and enhanced, it is vital that the environmental impacts are considered. Merging the systems together can reduce the environmental impacts and could lead to improved utilisation of natural resources.

2.1.2 Uranium Harvesting Devices

Another area of research addressed by this study is attaching a system onto the offshore wind turbine to extract uranium from seawater. This does not directly generate energy at the wind farm. However, sales revenue would offset the operational costs and energy would be generated offsite. It is estimated that approximately 4 billion tonnes of uranium exists in the ocean, found in the form of uranyl ions, which has a concentration of 3-3.3 µg/l (Picard et al., 2014). Many different separation techniques have been tested; membrane filtration, precipitation and coagulation were all determined to be undesirable due to their high operating costs, their impact on the environment, as well as their poor durability. The most effective method to adsorb minerals is through the use of chelating polymers, as they can be used to accurately target specific minerals from the seawater, even when the concentrations are low. Chelating polymers have a high adsorption capability and have been found to be less harmful to the environment than the other separation techniques.

Much research has been undertaken to determine the feasibility, performance, and cost effectiveness of the polymer adsorbent. The Japanese Atomic Energy Agency (JAEA) has developed a system of adsorbent material arranged in stacks and suspended on floating buoys. The significant weight of the mooring required for this system was responsible for over 70% of the overall cost for this method. To overcome this issue, researchers had identified that a reduction of 40% in the costs of recovering the uranium could be made, by using a buoyant braided adsorbent that comprised of 10 cm high density polyethylene fibres. To attract the uranium, the fibres must go through a process of radiation induced co-polymerization containing amidoxime and a polar co-monomer, in order to increase the polymers hydrophilicity. The fibres of the polymer are woven into strands of 60 m lengths, before being submerged in the ocean and moored to the seabed. The adsorbent is then washed with an acidic solution to remove the unwanted components leaving only the uranium attached to the polymer. This process also allows the polymer to be used repeatedly (Picard et al., 2014).

This process relies on the adsorbent being transported to the surface so that the elution process can be carried out before the polymers are then re-submerged into the sea. The objective of the elution process is to extract the desired material by washing with a solvent. The adsorbent is washed in two individual stages, firstly it is washed thoroughly by hydrochloric acid, before being washed again with nitric acid. The resultant product of this process is a solution of acid, the uranium ions in the form of uranyl ions, and the adsorbent that can then be used again.

This system has substantial challenges to face when considering its deployment, specifically the practical and economic challenges arising from the systems mooring and deployment costs, as well as the overall operating costs (Haji, 2017; Haji and Slocum, 2016). However, merging a uranium harvesting device with a floating offshore wind turbine structure could significantly offset these running costs of the harvesting device. In addition, this diversification of the platform usage will mitigate the operational costs of the energy generator system.

2.1.3 Tidal Turbines

It is recognised that individual renewable energy sources cannot produce energy continuously. Combining a tidal turbine with an offshore floating wind turbine could reduce the occasional lag in energy and decrease the hours of non-activity. Tidal power is the most predictable of the renewable energy sources (Li et al., 2018). In combining these systems, a more reliable energy source is created. Wind and tidal turbines have a number of similarities in their electrical components, therefore allowing them to integrate with the power grid with relative ease.

There are two different systems currently in place to produce tidal energy; these systems can either be horizontal turbines or vertical turbines. Despite the differences in the two systems, both work in the same way, as both have rotors that are driven by the oceans' tides (Fan, Mu and Ma, 2016). Tidal Turbine systems can essentially be considered as underwater wind turbines, functioning in the same way, though differing in their driving source. Acquired knowledge and experience of wind turbines can therefore be transferred, relatively easily, to the tidal industry. Merging a tidal turbine onto an existing offshore floating wind turbine would appear to be a realistic and feasible option. As a result, a hybrid energy system combining wind and tidal power, is considered in this study. There are two key challenges that must be overcome to ensure this hybrid system can produce sufficient energy and most importantly to determine whether it is feasible (Fan, Mu and Ma, 2016).

The first challenge in combining the two systems is to create an increase in synergies, while at the same time, being efficient and cost effective. Previous studies, (Muliawan, Karimirad and Moan, 2013), have shown that, in the most common form of hybrid system, the wind turbine and tidal turbine have their own main components isolated in individual casing, known as nacelles. These nacelles can include the gearboxes, the electricity generation components, etc. The two systems are only combined by their power generation systems and their mechanical transmissions. However, these systems share the supporting structure onto which they are mounted; the connection to the grid, port structures, and maintenance staff. A result of this increase in plant on the platform, is an increase in strain on the supporting structure and can result in structural damage due to vibration and structural fatigue. Therefore, as the likelihood of damage increases, additional maintenance must be undertaken on the system to ensure it continues to function properly and efficiently, resulting in an increase in costs. This combination of systems is clearly suboptimal.

Another system has been proposed (Buhagiar, Sant, Micallef and Farrugia, 2015), to replace the mechanical gear boxes with an open loop hydraulic drive to transfer the energy that has been produced, as well as attaching the power generation systems directly on to the tower. This system has been shown to reduce the weight that is exerted on the supporting structure, increasing the consistency of the transmission and therefore reducing maintenance costs. The open loop hydraulic transmission has proven to be up to 80% more efficient than the previous systems, as well as being more reliable. An additional benefit to using this new transmission system, is that it converted the energy obtained from the wind and tidal turbines (kinetic energy) into hydraulic energy before being used to generate electricity. This conversion resulted in a significant reduction in costs for power generation as less equipment was required (Fan, Mu and Ma, 2016).

The second challenge is matching the supply of energy from the hybrid system with the overall consumer demand. As the power output from wind and tidal energy sources is never constant, due to the uncontrollable nature of their sources, the power generated is often unstable. In order to provide a steady and reliable power output, the addition of an energy storage system onto the hybrid system, for example, hydrogen storage, could be considered. This would allow the generation and storage of a renewable energy source, such as green hydrogen, when potential supply outweighs demand. This could then be converted into energy when demand exceeds the primary wind farm supply. The use of this peak load supply could be utilised at the wind farm or onshore.

2.2 Potential Combined Energy Systems

2.2.1 WECs

As presented before, combining offshore wind energy and wave energy into a single system can be beneficial. However, there are two main challenges of combining these systems:

- ensuring that the offshore wind turbine does not impede the WEC power harvesting motion
- ensuring that the WEC system reduces the overall motion of the wind turbine.

If the system is designed correctly, the inertia of the WEC can be used to improve the overall stabilisation of the platform both:

- the lateral (surge and sway) of the platform
- the heaving motion – this will also reduce the overall strain on the platform from the vertical loads it supports.

These combined systems can be typically categorised dependent on:

- the depth of water (shallow or deep)
- geographical location (shoreline or offshore)

There are numerous connectivity configurations that can be supported between the WECs and the wind turbines (Pérez-Collazo, Greaves and Iglesias, 2014). These can be broadly classified as:

- Co-located
- Hybrid
- Island

2.2.1.1 Co-located systems

Individual Co-located systems have the simplest configuration of wind turbines and wave technologies that are currently in development. However, despite occupying the same space, grid connections and O&M equipment, each system has its own individual foundation. The concept for Co-located systems was built upon pre-existing offshore wind farms, which can be either floating or fixed bottom wind turbines. A significant benefit to using co-location, is that the system does not require any additional significant developments to evolve into a combined wind and wave system. There are two different classifications under which Co-located systems can fall:

- wind turbines and WECs are kept separate from one another - this is known as Co-located Independent Array
- wind turbines and WECs are interspersed – this is known as Co-located Combined Array.

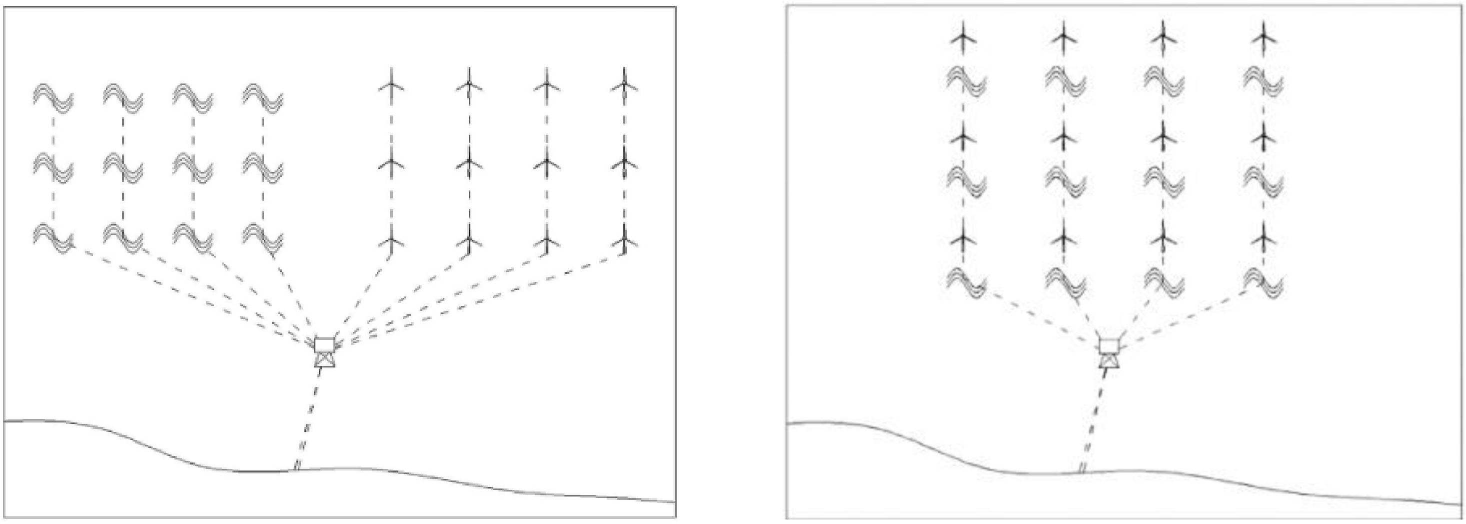


Figure I: Schematic of Co-located Independent Array and Co-located Combined Array. (Pérez-Collazo, Greaves and Iglesias, 2014)

2.2.1.1.1 Co-located Independent Arrays

Co-located Independent Arrays are systems that consist of two separate offshore energy farms inhabiting different areas in the ocean. These farms are still in close enough proximity to enable them to share the same electrical grid connections, as well as share the same installation and maintenance technicians.

2.2.1.1.2 Co-located Combined Arrays

Co-located Combined Arrays are the opposite of Independent Arrays. The two energy source systems inhabit the same areas of the ocean as well as sharing the same infrastructure. It can then be said that the overall energy system is one singular array. Combined Arrays can be assigned into three sub-categories:

- Uniformly Distributed Array (UDA)
- Peripherally Distributed Array (PDA)
- Non-uniformly Distributed Array (NDA)

Firstly, in a UDA, wind turbines and WECs are arranged equally and uniformly across the entire array. UDAs are achieved when the offshore wind turbines and WECs are evenly dispersed among one another. In a PDA arrangement, all WECs are dispersed along the perimeter of the wind farm, facing the most common wind direction. This is to enable the WECs to act as a shield to protect the wind turbines from oncoming waves. However, this results in a significant decrease in wave energy in the centre of the array.

An NDA arrangement comprises of WECs spread randomly throughout the array. In this array the WECs are situated to ensure maximum efficiency is achieved without being inhibited by the other systems.

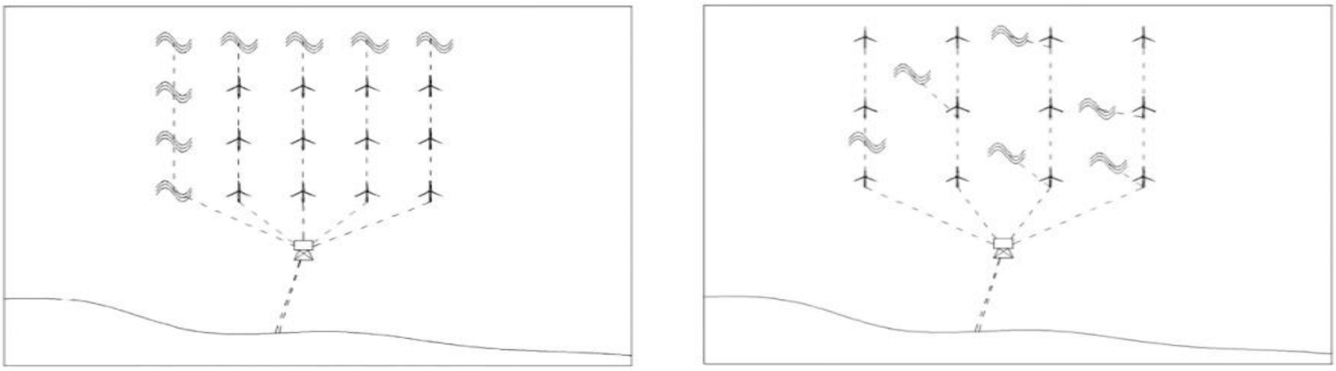


Figure II: Schematic depicting Co-located Peripherally Distributed Array and Non-uniformly Distributed Array, (Pérez-Collazo, Greaves and Iglesias, 2014)

2.2.1.2 Hybrid Systems

Hybrid systems are a combination of an offshore wind turbine and a WEC merged on to the same structure (Breton and Moe, 2009). Recently there have been two projects, funded by the EU, looking into offshore hybrid systems:

- MARINA – a project to define specific criteria that can be used to successfully evaluate hybrid platforms for offshore renewable energy (MARINA Platform, 2020).
- TROPOS – a research and development study into a multi-purpose platform system that can be used in deep water. It was determined that these hybrid systems can be placed into two classifications: fixed bottom and floating systems (The TROPOS Project – Troposplatform, 2020).

2.2.1.2.1 Fixed Bottom Hybrids

Current offshore wind turbines have been further developed and enhanced to accommodate a WEC to produce a fixed bottom wave and wind hybrid system. This integration has positive effects on the hybrid structure, protecting it from the repeated impact from the waves. However, with these developments come difficulties. Having been originally designed for a single wind turbine, there is limited space on the platform for a second energy system. In addition, testing must be carried out to ensure the additional weight can be accommodated by the substructure. Further research must be undertaken to ensure the relationship between offshore wind structures and WECs is clearly understood.

2.2.1.2.2 Floating Hybrids

Floating Hybrids is an area of research that is attracting interest and prototypes are being developed to accommodate wind turbines and WECs. Floating Hybrids have attracted this interest due to the large volume of energy resources that exist in deep water. These resource rich areas of the ocean are unsuitable for Fixed Bottom Hybrid Systems and therefore floating systems are vital.

2.2.1.3 Island Systems

The final system used to obtain both wind and wave energy is Island Systems. Like the Hybrid System, Island Systems are also considered to be multipurpose platforms. Island Systems are similar to Hybrid Systems, although they are likely to be significantly larger and combine the development of two resources (wind and wave) onto the same platform. Island Systems can be classified as either:

- Artificial Islands
- Floating Islands (Pérez-Collazo, Greaves and Iglesias, 2014).

Artificial Islands are most commonly developed on large pre-existing reefs to accommodate wind turbines and WECs. The reefs can then be further utilised as structures to be used for large scale storage platforms. Floating Islands are essentially floating multipurpose platforms. The platforms are typically large in scale. However, they are smaller than most Artificial Islands.

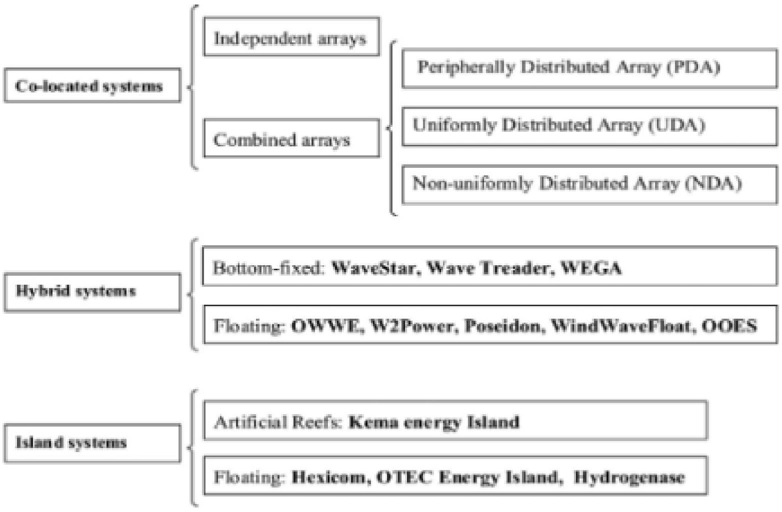


Figure III: Classification of Combined Wind and Wave Systems (Pérez-Collazo, Greaves and Iglesias, 2014)

2.2.1.4 Structures of Hybrid Wind and Wave Systems

To further enhance the hybrid wind and wave systems as described previously, it is essential that the technology used is continually developed. It is vital that consideration is made of the systems' substructure. Each substructure plays an important role as it is the link between the environment and the technology. Hence, in order to effectively harness the energy produced from a hybrid wind and wave system, an extensive understanding is required of substructures that are currently in place, as well as their limitations (Byrne and Houlsby, 2003).

Offshore wind turbines have been in development for the past couple of decades. Their developments have been both simple and extensive as researchers were able to use their existing knowledge of onshore wind turbines and apply them onto offshore structures. However, over the years there have been significant developments in offshore wind turbine substructures, which are vastly different to that of onshore wind turbines (Pérez-Collazo, Greaves and Iglesias, 2014). The substructures used for offshore wind turbines can be separated into three categories depending on the depth of water in which they are situated:

- shallow water
- transitional water
- deep water

Each classification of substructure can be further divided into subcategories, based on the substructure type. However, due to each of the substructure types having different technical characteristics, this results in the wind turbines and the WECs being combined differently. This study focuses primarily on deep water systems.

Due to the vast potential of energy resources located at deep water sites, the development of deep water or floating substructures is an ever increasing area of research. The offshore renewable industry has been determined to venture further into the oceans and it is essential therefore, that each substructure is equipped to appropriately handle the harsh conditions that will be experienced there. However, floating substructures are still in their preliminary stages of development.

Deep water substructures can be divided into three main groups:

- spar floaters
- tensioned-leg platforms (TLP)
- semi-submersible platforms (SSP) (Campanile, Piscopo and Scamardella, 2018).

2.2.1.4.1 Spar Floaters

Developers have used the design of the spar buoy configuration found on offshore oil and gas rigs as the basis for their design of the spar floater substructure, Figure IV. This substructure uses a large, slim tower that is extended below the surface of the water and is attached to the ocean bed by three mooring cables. These components provide the substructure with buoyancy and stability and, due to the mass of the tower, the motion felt on the substructure due to the impact of the waves, is significantly reduced. Due to these advantages, the spar floater configuration has been chosen for the Hywind and SWAY project models (Pérez-Collazo, Greaves and Iglesias, 2014).

2.2.1.4.2 Tensioned-leg Platform

Tensioned-leg platforms are designed similarly to the Spar Floaters. However, at the base of the tower, there are three additional legs that are secured to the floor of the ocean by pre-tensioned mooring cables, Figure IV. Each pre-tensioned mooring line significantly reduces the motion of the platform and increases the horizontal stabilization. As a result, due to the reduction in motion, the overall efficiency of the wind turbine is increased. Another benefit of using the tensioned leg platform is its cost effectiveness. Despite these benefits, further research must be undertaken on the mooring lines, as they are potentially the greatest weakness of this system. The TLP systems have been used in the Netherlands on the Blue Hydrogen project (Pérez-Collazo, Greaves and Iglesias, 2014).

2.2.1.4.3 Semi-submersible Platform

Semi-submersible Platforms have also been derived from a concept used in the oil and gas industry. This system uses multiple semi-submerged towers to increase the buoyancy of the system, while supporting the overall structure. The main benefit of this system is its flexibility. The system can be moved from one location to another with relative ease and can also be easily altered to compensate for the depth of water in which it is relocated. However, this is also one of the key issues of the system. As the Semi-submersible Platforms are not moored to the seabed, the platform is prone to undesirable movements. Despite this issue, this system has been deployed in the USA, Norway, and the Netherlands for their respective projects, WindFloat, W2Power and Poseidon (Pérez-Collazo, Greaves and Iglesias, 2014).

Figure IV: Floating Substructures - Spar Floater, TLP and SSP (Pérez-Collazo, Greaves and Iglesias, 2014)

2.2.1.5 WEC Technology for Combined Systems

Wave energy is a relatively new technology in comparison to wind. It is crucial that further research and development be undertaken to develop the WECs to raise the Technology Readiness Level (TRL) to the same as wind. However, despite this relatively young technology, there are already three different categories of WECs (Pérez-Collazo, Jakobsen, Buckland and Fernández-Chozas, 2013):

- Oscillating Water Columns
- Oscillating Bodies
- Overtopping Devices

The WECs described below all have a similar capacity factor of 0.3. In order to maintain a consistent capacity factor, the overall power produced must be restricted when the WECs are situated in more extreme maritime conditions. The required reduction in power can be achieved by the addition of an air bypass valve. By implementing the valve, the capacity factor is maintained at ~ 0.3 and the power produced is maintained, despite the extreme maritime conditions. Decreasing the power allows the levelised cost of energy (LCOE) to be improved and, in the occurrence of storms, there is a reduction in the potential for damage to the system (Pérez-Collazo, Greaves and Iglesias, 2014). Further research in this area would be beneficial, as optimising the capacity factor of the WECs, depending on location, can significantly improve the desired energy output.

2.2.1.5.1 Oscillating Water Columns (OWCs)

Oscillating Water Columns are systems in which a chamber is partially submerged, allowing an air pocket to be trapped above the water column. The column, acts like a piston, driving up and down, due to gravity and the force of the waves, and results in the air being pushed in and out of the chamber. As the air is continually pushed out of the chamber, at high speeds, it is fed into a turbine generator producing the desired energy output. By installing an OWC onto the hybrid system, the overall reliability of the system is improved (Perez and Iglesias, 2012). The system is reliable and easy to maintain as there are no moving parts other than the column and turbine. Due to the simplicity of the system, it can be easily adapted to suit multiple conditions for wave energy production and prototypes for shoreline and offshore have already been manufactured. In addition, due to their simplicity, OWCs are currently in use for many projects including Pico Plant (Portugal), Oceanix (Australia), GreenWave (UK). An example of an Oscillating Water Column can be seen in Figure V (Pérez-Collazo, Greaves and Iglesias, 2014).

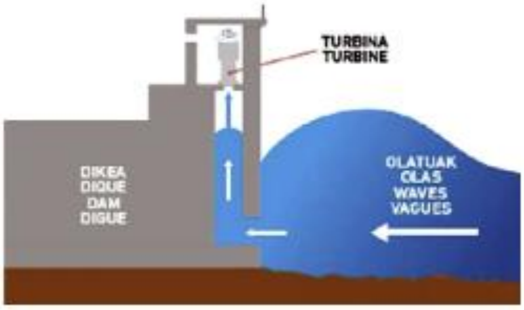


Figure V: Schematic of a standard Oscillating Water Column. (Pérez-Collazo, Greaves and Iglesias, 2014).

2.2.1.5.2 Oscillating Bodies

A varying range of Oscillating Bodies fall under the category of WEC. As a whole, all systems that extract wave energy through a structure, and produce energy via an oscillatory movement, can be classified as either a floater or a buoy. Oscillating Bodies are designed to be durable and they are therefore able to take advantage of the harsher and more effective deep water waves. They can be developed as either floating or fixed bottom devices. Consequently, this results in Oscillating Bodies being more complicated than OWCs, especially in regard to the Power Take Off systems (PTO). Several design concepts and techniques to convert the oscillating movement into energy have been produced in order to reduce the complexity of the PTO; for example, linear electric generators, piston pumps and hydraulic generators. Despite the complexity of Oscillating Bodies, one of its key advantages is its size. Being a relatively small device allows a larger number of systems to occupy an energy farm, producing a larger energy output. However, despite the positive aspects of Oscillating Bodies, research has not yet determined the most suitable and efficient form of PTO system, nor a solution to resolve the problems with mooring cables. It is therefore evident that further research must be conducted in order to achieve a viable and effective technology. The most common forms of Oscillating Bodies are: PowerBuoy (US) Pelamis II (UK) and WaveStar (Denmark) – Figure VI (Pérez-Collazo, Greaves and Iglesias, 2014).

Figure VI: Illustrations of Pelamis II and PowerBuoy Oscillating Bodies, (Pérez-Collazo, Greaves and Iglesias, 2014).

2.2.1.5.3 Overtopping Devices

Overtopping Devices are WEC systems that works specifically as either floating offshore systems or fixed bottom shoreline systems. The Overtopping Devices have two long arms that are used to guide the water into the centre and up a curved ramp into the reservoir where the water is stored. The water then proceeds to pass through several hydro turbines. The water pressure spins the turbines and produces electricity. Due to the height of the waterhead, the potential energy as it passes through to the turbines results in a large energy output. Due to their large size and mass, Overtopping Devices are able to combat rolling and pitching and therefore, endure harsh maritime conditions. The height also plays an important role as it allows large winds and waves to pass over the converter easily.

However, just like Oscillating Water Columns, the main advantage of Overtopping Devices is its simplicity. The water is stored in a reservoir and when it reaches the desired volume it passes through the hydro turbines. A disadvantage of this system is its size. Due to the length of the arms, very few hybrid systems would be able to occupy the farm in any given area. Commonly found Overtopping Devices currently in production are: WaveDragon (Denmark), WaveCat (Spain), the Seawave Slot-Cone Generator (Norway) – Figure VII.

Figure VII: WaveDragon Overtopping Converter (left) and the WaveCat Overtopping Converter (right). (Pérez-Collazo, Greaves and Iglesias, 2014).

2.2.1.6 Dynamic Model of Hybrid Wind and Wave System

Using the linear coupled equations of motion, with a trial and error method to determine the frequency of the long-wavelengths, the dynamics of a hybrid wind and wave system can be modelled (Haji, Kluger, Sapsis and Slocum, 2018).

Equation 1

$$I(\omega)x'' + D(\omega)x' + K(\omega)x = f(x)$$

where (‘) signifies the time derivative and the vector x comprises of 23 coupled degrees of freedom. These can include the three rotational and three translational motions of the structure’s platform, the two lowest fore-aft bending modes of the tower, the heaving motion of each water column and the air pressure of each of the tubes.

Using the proportionality coefficient, the air pressure within each of the tubes can be correlated linearly to the motion between the water columns and the tubes (Haji, Kluger, Sapsis and Slocum, 2018),

Equation 2

$$C = \frac{Kwells\ Vchamber}{\gamma Patm}$$

where:

- K_{wells} denotes the Wells turbine ratio of pressure drop to air flow
- $V_{Chamber}$ denotes the volume of the air chamber

- P_{atm} is the atmospheric pressure 101.3kPa
- γ is the air specific heat ratio 1.4

Due to the symmetry of the design of this system, it results in the overall motion of the hybrid system (roll, yaw and sway) to equal 0. The remaining symbols in the linear equation $I(\omega)$ denote the added masses of the WEC inertia and hydrodynamics of the platform, $D(\omega)$ denotes the floating wind turbine platform and the WEC hydrodynamic damping and the Wells turbine power takeoff. The symbol K denotes the hydrostatic stiffness and linkage coupling between the floating wind turbines and the WEC.

To model the effects of the added masses on the hydrodynamics, the force the wave exerts on the platform and the damping, the WAMIT panel method must be used for each floating wind turbine (Haji, Kluger, Sapsis and Slocum, 2018). The long wavelength approximations from G.I Taylor and Haskind are used to model:

- effects of the added masses
- force of the waves
- damping on each of the WECs.

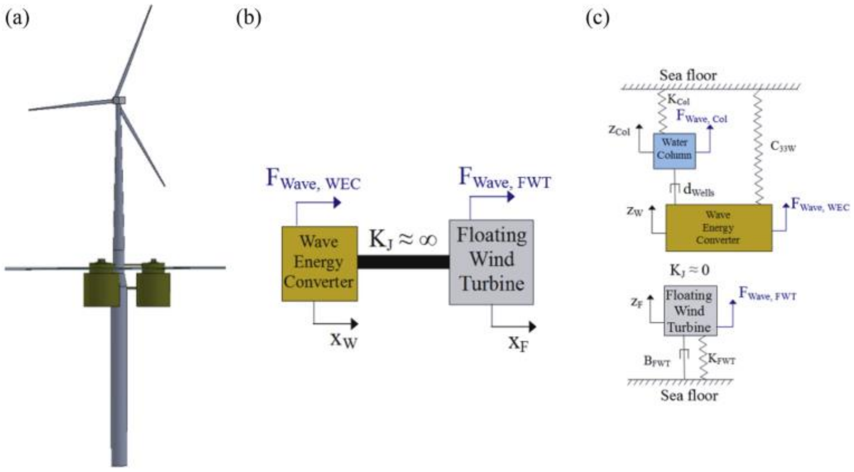


Figure VIII: Schematic of model (Haji, Kluger, Sapsis and Slocum, 2018)

In Figure VIII, the wind turbine and the WEC move together in a lateral direction. Due to the vigorous movement of the system, the hydrodynamic and hydrostatic properties of each of the WECs as well as their inertia, are added to the turbine and increases the pitch angle of the turbine blades. This method of modelling the system assumes that the wind is at a steady state and therefore, results in a damping effect for the lateral motion of the platform and improves the damping coefficient. The Bretschneider spectrum is used to model each wave as it approaches the hybrid system and then proceeds to use the Weiner-Khinchine theorem to determine the system's statistic reaction caused by the waves. The constant pitch motion and surges of the platform can result in a bowing and weakening of the tower structure. Using the model from Jonkman, 2007 and Klunger, Sapsis and Slocum, 2016, the eigenmodes stress on the tower can be determined and this data can be converted to stress statistics to determine the effects this can cause over the 20 year lifecycle of the hybrid system.

2.2.1.7 WEC Cost Model

In aiming to establish whether combining two maritime energy systems together can result in an increase in the total energy produced, whilst reducing the overall LCOE for each individual system, (Castro-Santos, Martins and Guedes Soares, 2017), the LCOE for WECs can be determined using the equation,

Equation 3

$$LCOE = \frac{(ICC)(FCR) + AOE}{AEP}$$

where:

- the levelized cost of energy is determined by the Installed Capital Cost (ICC)
- the fixed charge rate (FCR) accounts for the costs of taxes, financing, and the depreciation of the combined system
- AEP denotes the annual energy production
- AOE is the annual operating expenses of the system with a power capacity of $P_{Cap,kW}$, which equates to $\$215P_{Cap,kW}$ (Weinzettel, Reenaas, Solli and Hertwich, 2009).

The ICC can be determined by combining the masses of the steel and concrete used in the structure and the power capacity. This equation for WECs has been taken from the models derived from the Sandia National Laboratories (Neary et al.,2014),

Equation 4

$$ICC_{WEC,\$} = 5020P_{Cap,kW} + 1.3C.F.\ M_{Steel,kg} + 0.1M_{Concrete,kg}$$

where:

- $M_{Steel,kg}$ and $M_{Concrete,kg}$ accounts for the mass of steel and concrete
- C.F.= 2 and indicates the manufacturing complexity factor (Weinzettel, Reenaas, Solli and Hertwich, 2009)

A summary of the expenditure of a floating hybrid wind and wave system can be seen in Figure IX. In combining wind and wave systems, the costs of the infrastructure and the mooring cables can be removed as they are already pre-existing on the wind turbine structure.

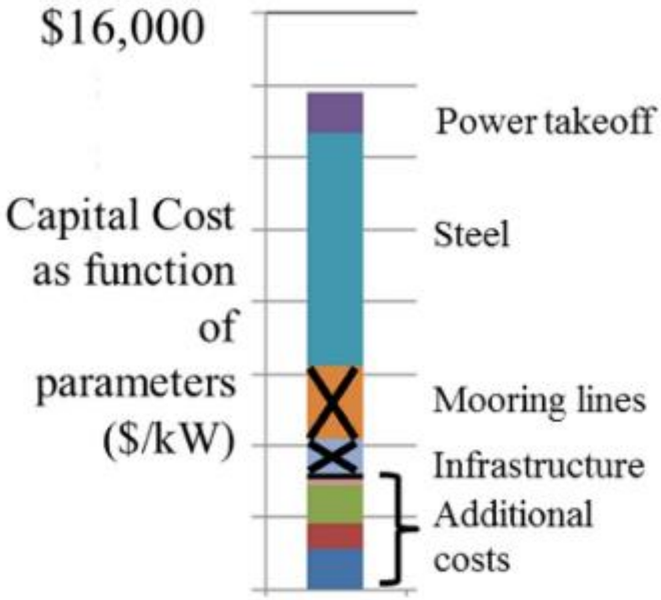


Figure IX: Summary of ICC of wave system, (Haji, Kluger, Sapsis and Slocum, 2018)

Wave energy is at a critical point in its development lifecycle as it begins to reach the required TRL to lower its energy costs. Combining the two systems may be the appropriate solution for the current economic and generation needs of each system and would be mutually beneficial. Energy costs can be decreased by using the same infrastructure and also by sharing the grid connection and logistics (Haji, Kluger, Sapsis and Slocum, 2018). The addition of a WEC would result in the reduction in operational costs for floating wind farms as they would share O&M costs and each WEC could be used as a shield to reduce the impact of the waves against the tower structure and consequently, increase the weather window so technicians could access the turbines more frequently and easily.

2.2.2 Uranium Harvesting Devices

Like the WEC, the combining of a uranium harvesting device with an offshore wind turbine, has the advantage of offsetting the costs of deployment, recovery and mooring. One proposed design by Picard et al. (2014) is the Wind and Uranium from the Seawater Acquisition symBiotic Infrastructure (WUSABI). This system comprises of belts that circulate in and out of the water, with each belt covered in adsorbent, and a platform at the bottom of the floating turbine to hold the elution and chemical storage tank. The belts circulate through the seawater at the foot of the turbine and then proceed into the elution tank where the elution process can occur. The proposed system is expected to capture 1.2 tonnes of uranium each year, which is the equivalent required to support the powering of a typical nuclear power plant for a year.

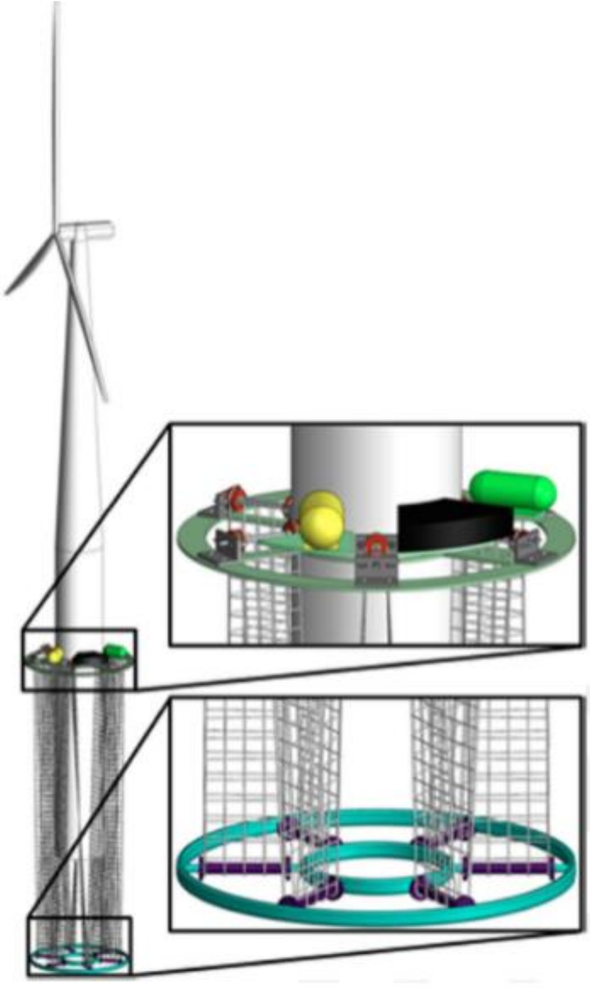


Figure X: Illustration of the WUSABI system as described by Picard et al. (2014)

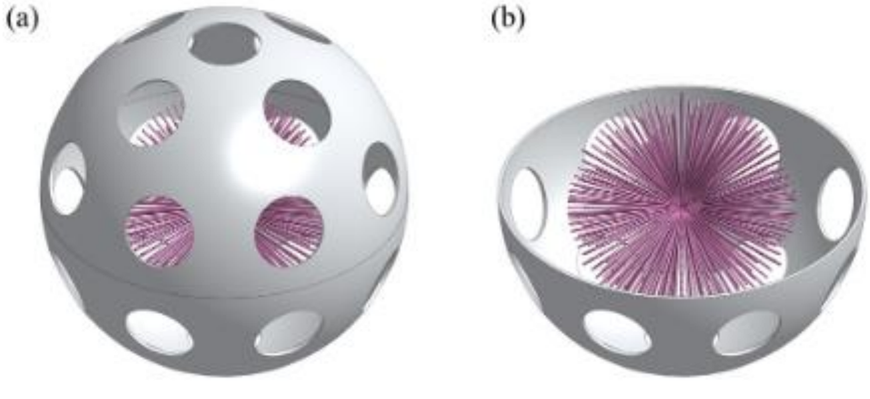


Figure XI: Illustration of enclosed shell adsorbent, Picard et al. (2014)

The originally proposed adsorbents by Xing et al., (2013) were found to have low uranium adsorption properties, despite the polymers having a high durability and tensile strength. As a result, the adsorbent belts proposed by Picard et al. (2014) may possibly face issues when deployed in the maritime conditions. A new confined shell system was therefore developed where the system would decouple the chemical and mechanical needs of the adsorbent, Figure XI.

The enclosed shell system has high adsorbent properties and is surrounded by a thick porous shell that increases the mechanical strength of the adsorbent and its durability, which is essential for the harsh offshore maritime conditions, as well as increasing the chemical resistance of the adsorbent when they pass through the elution process. The advancements in the chemical and mechanical characteristics has facilitated further improvements in this process. These improvements have allowed researchers to investigate the efficiency of higher performing but less robust adsorbents.

A further advantage of using the enclosed shell adsorbent, is that it can be integrated with the Symbiotic Machine for Ocean uRanium Extraction (SMORE), Figure XII, which allows the shells to be spaced out equally along a high strength mooring line, similar to the adsorbent chain belts suggested by Picard et al. (2014). The adsorbent balls are threaded together in a chain to produce a netting that can be used to increase the adsorptivity and with the addition of cross-members, significantly decrease the chances of the netting intertwining (Haji, 2017, Haji and Slocum, 2016 Haji, Drysdale, Buesseler and Slocum, 2017). There are two variations of this system that can be deployed:

- the netted chain can continually rotate through the water to increase water flow
- the netting is static and the water flow is achieved solely due to the currents.

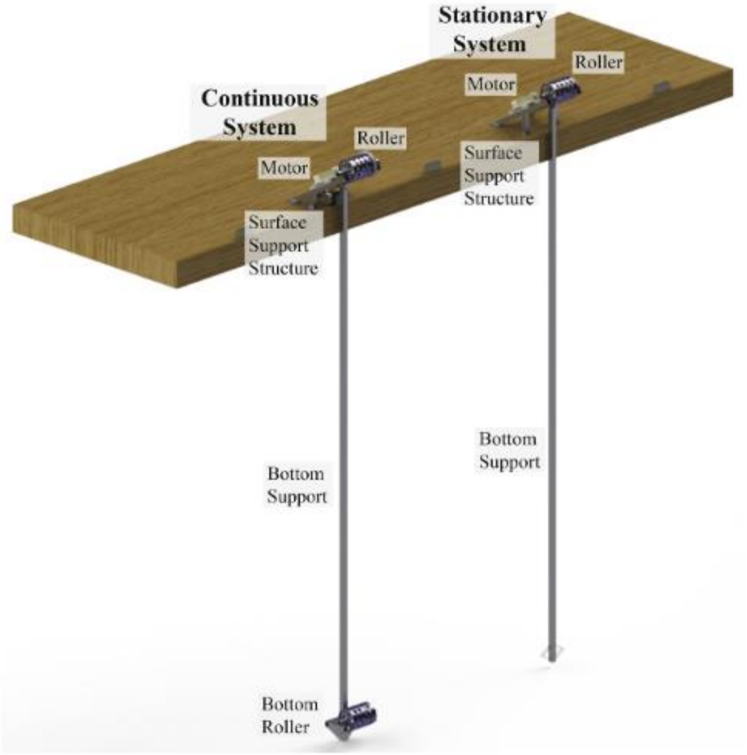


Figure XII: Model of the SMORE design (Haji, 2017)

2.2.2.1 Adsorbent Behaviour

When developing an appropriate uranium harvesting device, there are two important considerations of the properties of the adsorbent material (Picard et al., 2014):

- the degradation of the adsorbent, having been exposed to the acid during the elution process
- the recovery rate of the uranium

2.2.2.1.1 Degradation

Due to the harsh and intense maritime conditions, the adsorbent is capable of losing up to 20% of its original capacity after five cycles. It is therefore essential that degradation must be taken into account. Due to the adsorbent's continual exposure to the acidic solution, it is recognised that this results in severe damage to the polymers' functional groups and further reduces the capacity of the adsorbents. It is important to note when modelling the degradation, that the pH of the solution during the elution process and the adsorbents exposure period to the acid, will remain constant despite the recovery period (Picard et al., 2014). It can then be presumed that the adsorbent capacity losses remain constant during all of the elution cycles, as the damage to the adsorbent is similar at each cycle. The adsorbents capacity after one elution cycle, C_1 can be determined from

Equation 5

$$C_1 = C_0(1-d)$$

where:

- C_0 is the initial capacity of the adsorbent
- d signifies the relative loss of adsorbent capacity after an elution cycle (Picard et al., 2014)

This equation can be expanded to account for all the elution cycles. Where n is the number of adsorption/elution cycles.

Equation 6

$$C_n = C_0(1-d)^n$$

Using these equations and geometric progression, the average capacity of the adsorbents over n cycles can be calculated,

Equation 7

$$\bar{C} = \frac{1}{n}\sum_{k=0}^{n-1} C_0(1-d_e)^k = \frac{C_0}{n}\left(\frac{1-(1-d_e)^n}{d_e}\right)$$

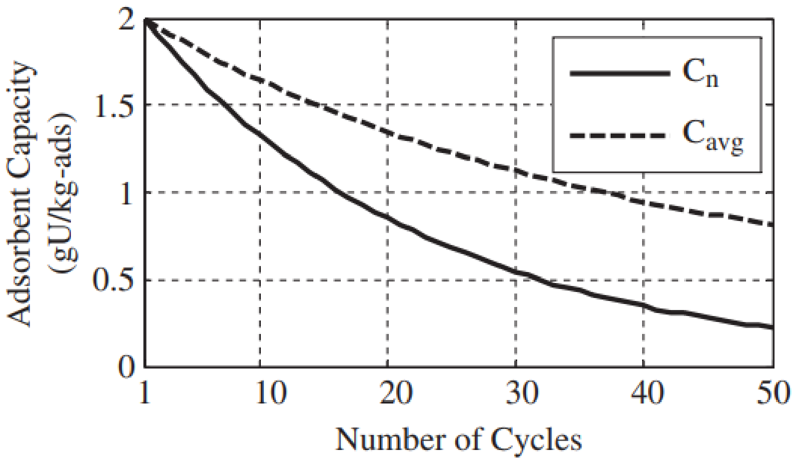


Figure XIII: Graph depicting the adsorbent capabilities for each cycle, (Picard et al., 2014)

Figure XIII indicates the progression of the adsorbent capacity and the average adsorbent capacity over numerous adsorption/elution cycles. For this system, the initial capacity of the adsorbent was at 2 g U/kg - ads and each elution cycle had a degradation of 4.4% (Tamada, Seko, Kasai and Shimizu, 2006). In the graph the adsorption capacity is indicated by the solid line and the broken line indicates the average adsorption capacity. The graph highlights the severity of degradation of the adsorbent, as after only 15 elution cycles, the absorption capacity falls to half of its initial value, 1 g U/kg – ads.

2.2.2.1.2 Recovery Rate

The recovery rate is the rate at which the adsorbent adsorbs the uranium and depends on the adsorption kinetics and capacity – Figure XIV. The adsorbent capacity chosen for this study was 2 mg U/g, based on reports conducted by Rudzinski and Plazinski. It was determined that the first-order kinetic model was capable of delivering a quality match with the data obtained for uranium adsorption (Tamada, Seko, Kasai and Shimizu, 2006). The concentration of adsorbed uranium can then be calculated from:

Equation 8

$$C = C_0\left(1 - e^{-t/\tau}\right)$$

where:

- the symbol C_o is the capacity of the adsorbent, 2 mg U/g
- t signifies the length of time the adsorbent is exposed to the seawater
- τ is the adsorption time constant, ~ 14 days

However, it is possible to improve the recovery rate of uranium by varying the kinetics of the adsorbent and by increasing the frequency of uranium collection. The Recovery rate, R, can be determined from the equation below (Tamada, Seko, Kasai and Shimizu, 2006), where T_h is the harvesting period:

Equation 9

$$R = \frac{C(T_h)}{T_h} = \frac{C_0\left(1 - e^{-\frac{T_h}{\tau}}\right)}{T_h}$$

The recovery rate can then achieve its peak when $T_h \rightarrow 0$.

Equation 10

$$\lim_{T_h \rightarrow 0} R = \frac{C_0}{\tau} = \frac{c_0\left(1-e^{-\frac{T_h}{\tau}}\right)}{Th}$$

The decision must be taken on the optimisation between the recovery rate and the damage to the adsorbent due to its frequency of use and to its frequency of exposure to the elution.

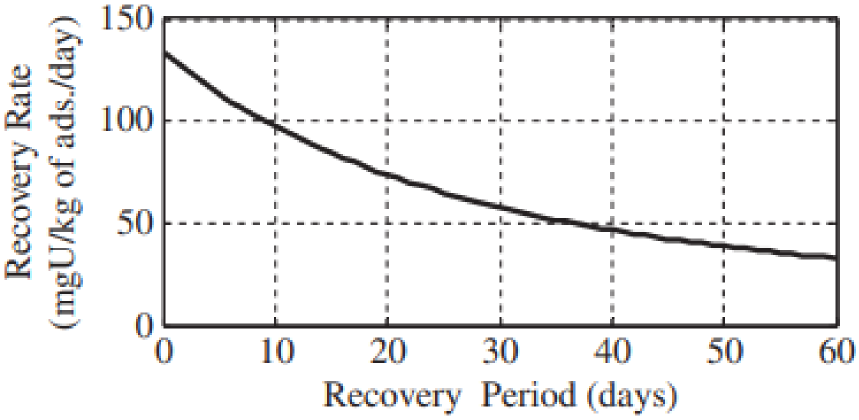


Figure XIV: Uranium's rate of Recovery, (Tamada, Seko, Kasai and Shimizu, 2006)

2.2.2.2 Harvesting Systems

By adding a Uranium Harvesting Device to an existing structure, the need for additional mooring systems and location to harvest the uranium is eliminated. Extracting uranium from seawater can be an expensive process. This cost however, can be reduced by increasing the adsorbents' exposure time to the seawater and the system's cycle period, as this will result in an increased yield (Picard et al., 2014). Each Harvesting Device is designed to continually produce the maximum amount of uranium by fully utilising the adsorbent, in order to reduce the capital costs.

Two designs have been proposed to increase the adsorbance of the polymers in the system – a netting configuration and a cable configuration, Figure XV. In the netting design (a), the adsorbent is in a grid structure and is attached together by two cables on either side. In the cable configuration (b), the adsorbent surrounds a singular cable.

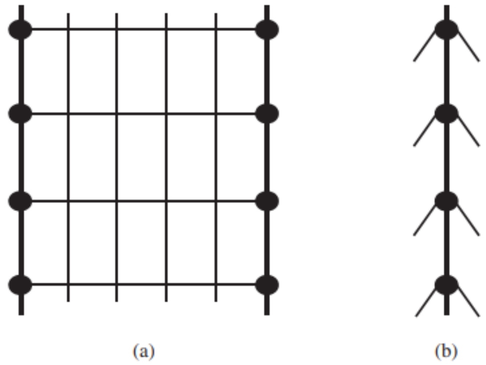


Figure XV: Designs of the adsorbent material. (Picard et al., 2014)

When comparing the adsorbent densities of the two designs, the netting design is capable of carrying 41 metres of adsorbent polymers with each grid spaced at 1 metre apart and with the overall width of the netting being 20 metres. In order to achieve 41 metres of adsorbent in the singular cable configuration, 5 singular cables are required. Each cable must be 5 metres in length with 3 metres between each of the cables (Picard et al., 2014).

Each adsorbent design can be run on a single offshore floating wind turbine structure or alternatively can be run across two turbine structures, Figure XVI. Connecting the adsorbent designs over two turbines results in a more efficient use of the unutilised space between the turbines in the energy farm. However, a potential issue with this concept is, that the tension on netting or cables could result in the two turbines being dragged closer together, potentially damaging the turbine structure.

The harvesting extraction is situated on a circular platform attached to the tower of the turbine. The adsorbents rise from the water up to the platform and loop around the structures. As a result, this improves the extraction capacity of the system. With the use of strong cables, the adsorbent material rotates around the system with the support of pulleys and shafts. Rollers on a lower platform support the adsorbent belt, ensure that the belt is kept at the prerequisite tension and prevent it from becoming tangled.

To ensure the maximum 5 MW output is achieved, a system with a belt length of 4000 metres must have 20 loops at a depth of 100 metres and must be continually running at 38 days/cycle. The system must also include two storage tanks capable of holding at least one month's supply of chemicals required for the elution process, before a maintenance crew is able to retrieve the produced uranium and replenish the tanks (Picard et al., 2014).

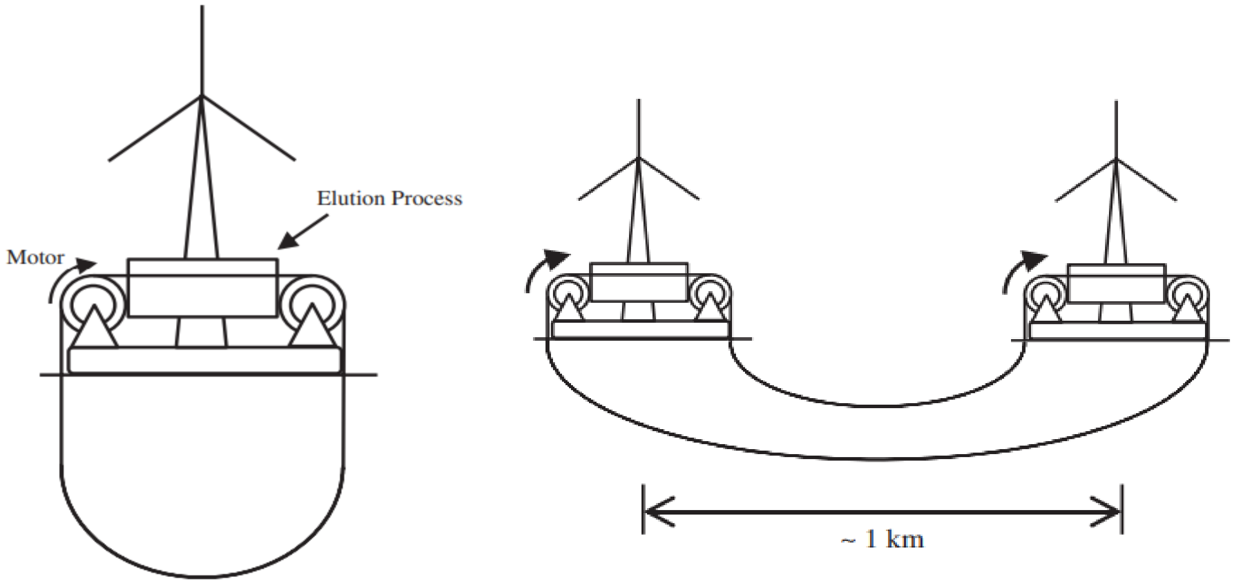


Figure XVI: Schematic of the single and multiple turbine layouts (Picard et al., 2014)

2.2.2.3 Economics

The capital cost of each individual system is relatively high. Developing a combined Uranium Harvesting Device and an offshore floating wind turbine can significantly reduce capital costs, by combining the mooring needs of each system. A cost analysis of the combined system was undertaken by Tamada, Seko, Kasai and Shimizu, 2006. This analysis was then compared with an individual Uranium Harvesting Device as a reference, where the adsorbent polymer was in the netted configuration. The analysis concluded that combining the systems could result in a decrease in the production cost of uranium from $450 – 890/ kg U to $400 – 850/ kg U, a reduction of at least 11%. Further identified enhancements to the development of the design of the system, could decrease the cost by a further 20% (Byers, Haji, Slocum and Schneider, 2016; Byers, Haji, Slocum and Schneider, 2018). Figure XVII highlights the results obtained from the cost analysis report. Each element in this analysis can be divided into 3 subcategories:

- Elution and Regeneration,
- Mooring and Deployment,
- Adsorbent Production

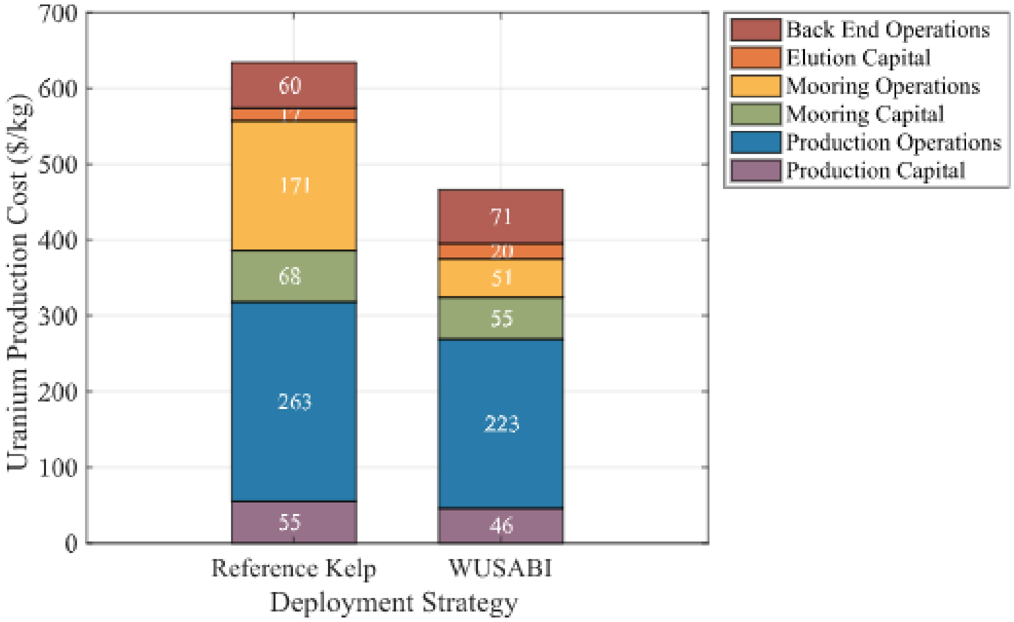


Figure XVII: Cost analysis of Uranium Harvesting Devices (Byers, Haji, Slocum and Schneider, 2018)

The graph reveals that significant savings can be made in the mooring operations category by attaching a Uranium Harvesting Device onto a wind turbine. However, the graph does not consider the effects of biofouling on the adsorbents' capabilities nor on the adsorbents' degradation and therefore, does not reflect the costs of replacing the adsorbents. This analysis also concludes that the mooring and deployment costs for the combined system (WUSABI) are reduced by 55% when compared to an individual harvesting device. Savings have been realised in Production Operations and Production Capital. There are however slight increases in the Elution Capital costs. This increase in cost could be due to an increase in the volume of hydrochloric acid and nitric acid required for a continuous system and subsequently, a large storage tank required for the increase in uranium harvested.

There are of course health and safety issues to be considered in the extraction of uranium from the seawater. As a highly toxic chemical, exposure to large quantities of uranium can cause cancer and kidney damage. Preventative measures would be required to minimize the risk of exposure to uranium and would consequently result in additional costs.

2.2.3 Tidal Turbines

The hybrid wind and tidal system described in this project consists of two tidal turbines mounted to the sides of the SPAR design of a floating wind turbine, Figure XVIII.

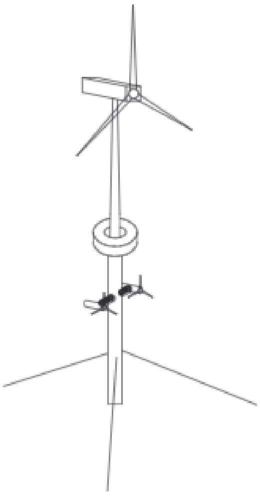


Figure XVIII: Hybrid Wind and Wave system with a SPAR structure (Li et al., 2018).

Tidal Turbines operate in exactly the same way as wind turbines and, as a result, this hybrid system is the easiest to maintain as it requires similarly low levels of maintenance. However, in order to attain as much energy output as possible, it is essential that turbine sizes are correct and do not interfere with one another. There are many similarities between wind and tidal turbines; for example, they have the same electrical design which allows them both to connect to the electrical grid in the same way. Tidal power produces less energy than wind power, as the wind turbines rotate at a higher velocity, thereby driving the generators proportionally (Li et al., 2019).

Different forms of Tidal Turbines exist, and they differ depending on the type of generator used in the turbine, either a Doubly-Fed Induction Generator (DFIG) or a Direct Drive Permanent Magnetic Synchronous Generator (DDPMSG) (Mohanty et al., 2019). Each of these turbines is comprised of power electronic devices, also known as Flexible Alternating Current Transmission Systems or FACTS devices, installed into the AC transmission in order to transmit the electrical energy produced more easily into the grid, Figure XIX. As a result, these devices further improve the reliability of the system allowing a more simplified integration of each individual power system. However, despite the reliability of this system, it is not uncommon to store a backup diesel generator, connected to the hybrid system, in order to compensate for any losses in production or spikes in load demand.

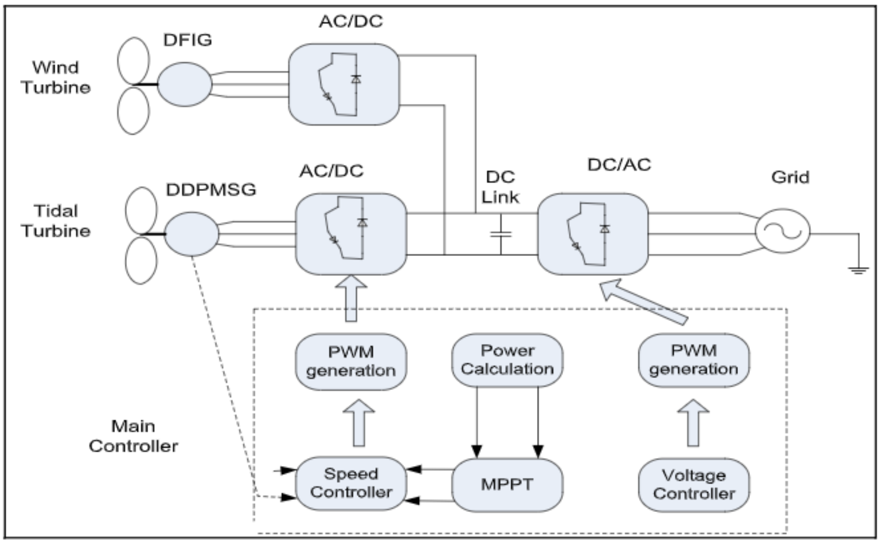


Figure XIX: Hybrid Wind and Tidal System Schematic, (Mohanty et al., 2019)

The reliability of the hybrid system is a result of the simplicity of the design.

Equation 11

$$\Delta P_H = \Delta P_w + \Delta P_T$$

Equation (11) shows the overall change in Real Power for the hybrid system, ΔP_H, is a result of the change in Real Power generated from the wind turbine, ΔP_w plus the change in Real Power of the tidal turbine, ΔP_T (Mohanty, Viswavandya, Ray and Mohanty, 2016).

Equation 12

$$\Delta Q_{DDPMSG} + \Delta Q_{DFIG} = \Delta Q_{SG} + \Delta Q_{COM}$$

The Reactive Powers of each of the turbines, ΔQ_{DDPMSG}, ΔQ_{DFIG}, can be calculated using equation (12), (Mohanty, Viswavandya, Ray and Mohanty, 2016), as they equate to change in Reactive Power of the diesel generator, ΔQ_{SG} plus the change in Reactive power of the compensator, ΔQ_{COM}. When the system is connected to the load, as shown in Figure XX, equations (13) and (14) apply and allow calculations of the terminal voltage of the system (Mohanty et al., 2019).

Equation 13

$$\Delta Q_{DDPMSG} + \Delta Q_{DFIG} + \Delta Q_{L} = \Delta Q_{SG} + \Delta Q_{COM}$$

Equation 14

$$\Delta V = \Delta Q_{SG} + \Delta Q_{COM} - \Delta Q_{L} - \Delta Q_{DFIG} - \Delta Q_{DDPMSG}$$

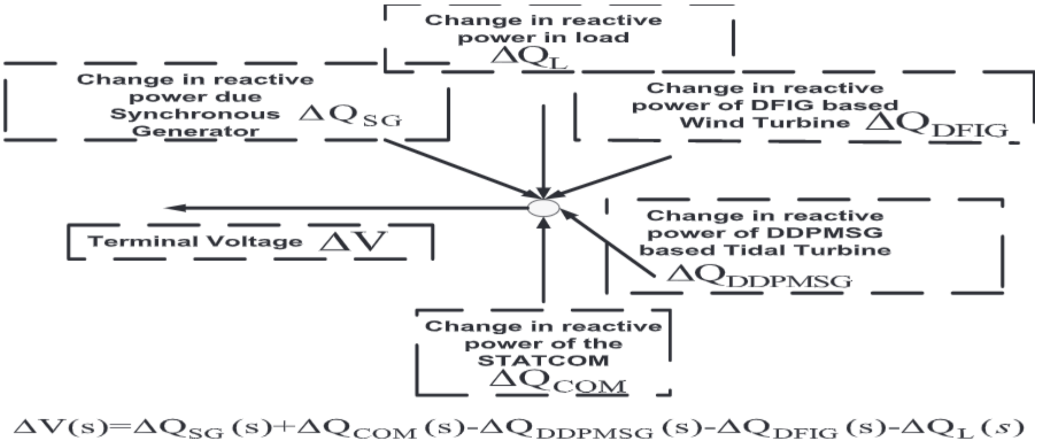


Figure XX: Reactive Power Schematic for a Hybrid Wind and Wave System, (Mohanty, Viswavandya, Ray and Mohanty, 2016).

2.2.3.1 Doubly-Fed Induction Generators (DFIG)

This tidal turbine is equipped with a wound rotor induction generator which allows the generated power to flow easily from the rotor to the electrical grid with the assistance of AC/DC/AC converters. Figure XXI illustrates a single line block flow diagram of a DFIG. The main advantage of a DFIG is that the DC link voltage remains constant due to the effects of the supply side converter without determining the rotor power flow direction. It also indicates that by influencing the currents Iqr and Idr using the rotor side converter, we are able to alter the active and reactive power that can be produced, and the linear reactive power can then be calculated from the equation, (Mohanty et al., 2019),

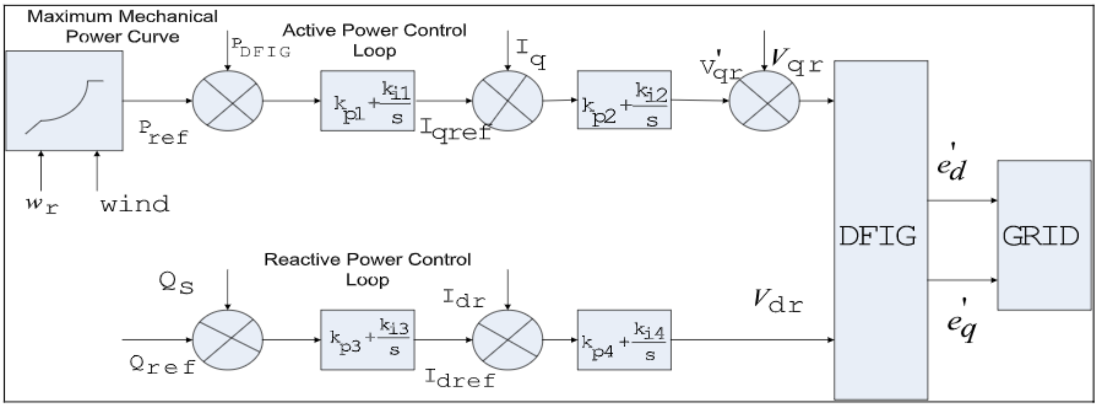


Figure XXI: Single line block flow diagram of a DFIG, (Mohanty, Viswavandya, Ray and Mohanty, 2016).

2.2.3.2 Direct Drive Permanent Magnetic Synchronous Generator (DDPMSG)

The design of the DDPMSG is crucial in order to determine the suitable type of permanent magnets required, the size of the magnet, the cost, and the external magnetic field. It is also important to consider the operating temperature of the magnets, to ensure that they are working optimally.

A benefit of using a DDPMSG rather than a DFIG is that even at low speeds the direct drive technology prevents the generator from losing energy. Therefore, the DDPMSG system is considered to be more reliable and efficient, hence its popularity as a generator with the majority of wind and tidal turbines (Mohanty, Viswavandya, Ray and Mohanty, 2016).

There are three categories of permanent magnets used in these generators which can be separated due to their chemical configuration and the properties of the materials:

- AlNiCo magnets comprised of aluminium, nickel and cobalt,
- samarium cobalt magnets, SmCo
- neodymium magnets, NdFeB.

Due to its anisotropic and crystal orientated structure, AlNiCo is the most effective magnet and yields the most energy, having been recorded to produce a maximum energy of 70 kJ/m^3. This magnet is also the cheapest and has a high corrosion resistance. AlNiCo is most frequently used in generators as the other magnets are composed of rare earth elements and therefore, more expensive (Mohanty, Viswavandya, Ray and Mohanty, 2016).

2.2.3.3 Tidal Cost Model

Much like the WECs, the levelised cost of energy can be used to determine and compare the lifetime costs of tidal power and can be calculated using the formula:

Equation 15

$$LCOE = \frac{\sum_t \left[(CAPEX_t + OPEX_t)(1+r)^{-t}\right]}{\sum_t \left[E_t \, (1+r)^{-t}\right]}$$

The LCOE is calculated using the capital costs, $CAPEX_t$, that occur over a period of t years, which consists of the initial planning costs of the turbines as well as the overall development cost. The costs of running the turbines and their required maintenance falls under the category of operational costs, $OPEX_t$ which must also be considered. The remaining components in this equation are the net energy produced, E_t, over a period of t years, with the potential reduction in energy rate, r due to the risks encountered during the process (Lande-Sudall, Stallard and Stansby, 2018).

However, operational costs can fluctuate considerably depending on the location in which the Tidal Turbines are deployed, the distance of the seaport from the final site, the accessibility of the site, and the variable nature of the prevailing weather conditions. The number of turbines installed in the farm as well as the supporting structures also have a significant effect on the operational cost of the site.

Uncertainty exists concerning the accuracy of the LCOE and the life cycle costs for a hybrid wind and tidal system, as it is a still a relatively new technology. This is evident by the range of CAPEX and LCOE estimates produced by a number of projects (Heptonstall, Gross, Greenacre and Cockerill, 2012). The large variation is a result of the earliest offshore floating wind farms coming to the end of their life cycle and, since their initial deployment, the significant advancements in offshore wind technology. The proposed estimates, in Table I, offer a baseline of the upper and lower limits of the CAPEX and LCOE that can be utilised.

Table I: CAPEX and LCOE estimates range for offshore Wind and Tidal Turbines

	CAPEX, £ m/MW	LCOE, £/MWh
Offshore wind	1.5-3.5	100-140
Tidal Turbines	2.25-4.0	150-320

Due to the relatively few Tidal Turbines currently deployed, the confidence levels of the cost estimates surrounding tidal power are low when compared to offshore wind farms. Moreover, as the Tidal Turbines have had limited operational exposure, the technology used is often taken from other industries without optimising modifications. Therefore, when developing a combined wind and tidal system, a more appropriate estimate of the capital costs must be determined by understanding the expense of key components and how they differ, relative to individual wind and Tidal Turbine solutions. When more accurate data is available, the cost estimate range can be reduced, and a more accurate cost analysis of the hybrid system can be produced (Lande-Sudall, Stallard and Stansby, 2019).

An analysis of the capital cost of both structures, Figure XXII, highlights an analytical cost breakdown per MW capacity. This indicates that the cost of the structures supporting the energy system, i.e. the tower and foundations, accounts for 22-27% of the capital cost. It also confirms that the majority of the costs of offshore wind turbines ~ 50 % is the result of steel and other materials required for the turbines to withstand the overall weight of the structure.

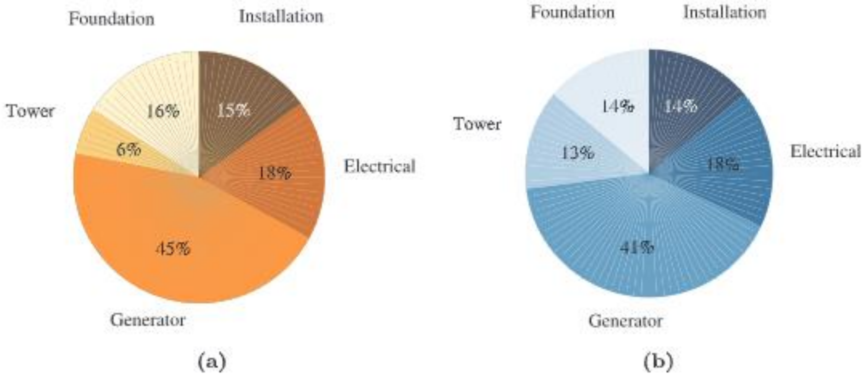


Figure XXII: Cost Breakdown per MW capacity (Lande-Sudall, Stallard and Stansby, 2019)

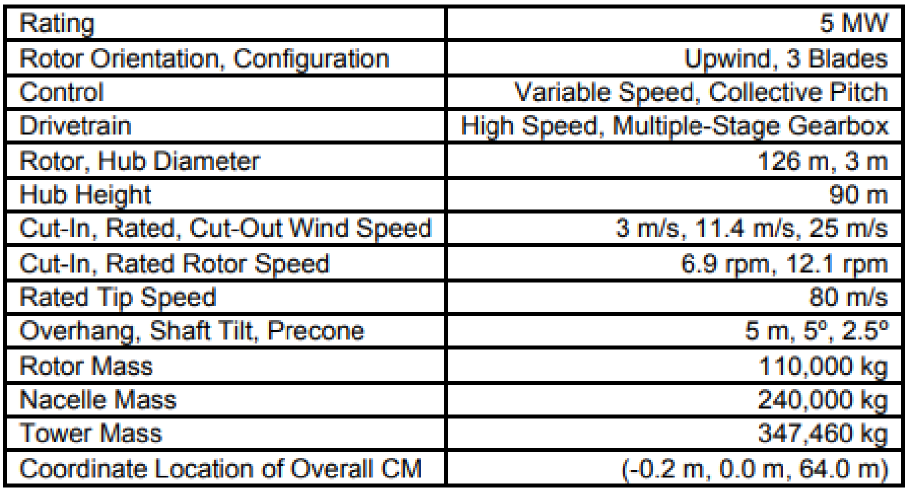
3 METHODOLOGY

The aim of this study is to determine the most effective configuration of energy sources from WEC, Uranium Harvesting Devices or Tidal Turbines that can be combined with an offshore wind turbine. The combined energy system must produce an effective energy yield and have a suitable energy payback period. In addition, the system must be cost effective, and not have a negative impact on the environment.

3.1 Turbine Specification

Before determining which additional energy source would be most beneficial to combine with an offshore wind turbine, analysis must be undertaken to determine the specific characteristics of the wind turbine and the suitable foundations that can be used. The wind turbine chosen for this was study was developed by the National Renewable Energy Laboratory (NREL). The turbine consists of three blades, with an overall rotor diameter of 126 metres and results in a max power output of 5MW. Further properties of the NREL turbine are listed in Table II.

Table II: NREL 5MW Wind Turbine properties, (Jonkman, Butterfield, Musial and Scott, 2009)



Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

3.2 System Arrangement

Combined systems can be categorised into three different types of arrangements: Co-located, Hybrid and Island. The combined arrangements were analysed and assessed against six criteria to determine the most suitable arrangement:

- Costs – the overall expenditure of the arrangement after taking into account any shared component, length of cables required, number of separate energy system installations etc
- Wind Turbine Protection – whether the arrangement would provide the wind turbine with added protection from the harsh maritime environment
- Accessibility – whether the arrangement restricts technicians and maintenance crews from accessing the wind turbines
- Utilisation of Space – restrictions on the number of systems in the energy farm due to available space
- Shared O&M – shared operations and maintenance
- Enhanced Energy Yield – does the combined arrangement allow for an increase in energy yield and does it have a suitable energy payback period?

3.3 Structure of the Combined System

Once the arrangement was selected, the foundation of the overall structure was considered. It was a requirement that the foundation would be able to accommodate each of the three energy sources without interfering with another structure. A similar decision matrix was utilised to consider the most appropriate structure:

- Costs – determining the overall expenditure of the structure including the mooring cables, should they be required, to hold the structure in place and whether additional maintenance cost would be required
- Accessibility – the ease with which access could be gained for maintenance and the simplicity of manoeuvring around the energy farm
- Utilisation of Space – analysis of the volume of each structure, to determine if the energy farm was being fully utilised
- Environmental Impact – an estimation of the impact (positive or negative) on the environment

3.4 Additional Energy System

Having determined the most suitable foundation for the combined energy farm, the next objective was to establish, which energy system was the most effective and feasible to attach to the offshore wind turbine. This was determined using a similar decision matrix method as the System Arrangement and Structure. Each energy system was assessed on eight key elements in order to identify the appropriate combination for the system:

- Costs – are additional costs required to develop this energy system and does this system require additional maintenance costs over the course of a year?
- Environmental Impact - does the addition of this system result in a negative impact on the environment and have the potential to cause harm to marine life?
- Utilisation of Space – is the additional energy system able to fully utilise the space in the energy farm? Are there any restrictions limiting the number of additional systems?
- Predictability – does the addition of the combined energy source make the energy output more predictable?
- Smoothed Power Output – with the addition of this energy system, will it result in the reduction in the number of unexpected grid disconnections and therefore result in the reduction of non-activity hours?
- Shared Logistics – there are specific and expensive plant and facilities required for offshore renewable energy projects. Would the combination of these energy systems be able to share the plant and facilities and therefore result in a reduction in cost?
- Common Grid Infrastructure – are the systems able to share the grid infrastructure?
- Enhanced Energy Yield – does the combination of energy systems increase the total energy yield of the energy farm and, as a result, better utilise the natural resources?

3.5 Wave Energy Converter

Having identified the energy system wind turbine combination, this study proceeded to analyse each of the WECs to determine which was most appropriate to attach to the hybrid floating wind turbine. Each WEC was compared on its:

- Efficiency
- Practicality
- Utilisation of Space
- Environmental Impact

4 RESULTS

In the analysis each WEC was assigned a value from 1-3; with 1 indicating the best performing. The results were then calculated and the system with the lowest score was determined to be the most suitable for that section.

4.1 System Arrangement

Table III: Decision matrix to determine the arrangement of the Combined System

Systems arrangement	Costs	Wind Turbine Protection	Accessibility	Utilisation of Space	Shared O&M	Enhanced Energy Yield	Total
Co-located	3	1	3	3	3	3	16
Hybrid	1	3	1	1	1	1	8
Island	2	2	2	2	2	2	12

The overall ratings of each System Arrangement were calculated and are displayed in Table III. The table shows that the Co-located arrangement performed poorest of the three alternatives, scoring the highest marks in the majority of the examined categories. The Hybrid arrangement however performed best, scoring the lowest marks in every category except one. Based on this model the Hybrid arrangement is the most suitable for combined offshore wind turbines.

4.2 Structure of the Combined System

Table IV: Decision Matrix to determine the Structure of the Combined System

Structure	Costs	Accessibility	Utilisation of Space	Environmental Impact	Total
Spar Floater	1	1	1	1	4
TLP	2	2	2	3	9
SSP	3	3	3	2	11

From this model, the SSP was the poorest performing in every category other than Environmental Impact. The Spar Floater structure performed best in each of the categories and is therefore the most suitable choice of hybrid structure.

4.3 Additional Energy System

Table V: Decision Matrix to determine the Additional Energy System

Energy System	Costs	Environment Impact	Utilisation of Space	Predictability	Smoothed Power Output	Shared Logistics	Common Grid Infrastructure	Enhanced Energy Yield	Total
WEC	3	1	1	2	1	2	2	1	13
Uranium	2	3	2	3	3	3	3	3	22
Tidal	1	2	3	1	2	1	1	2	13

The model shows a large variation in performance. The Uranium Harvesting Device performed worst overall and is therefore not a viable option for this hybrid system. WEC and the Tidal Turbines scored the same overall total once analysis was concluded. However due to the greater Enhanced Energy Yield, WECs were selected to be combined with the wind turbine, as the most suitable Additional Energy System.

4.4 Wave Energy Converter

Table VI: Decision Matrix to determine the WEC

Wave Energy Converter	Efficiency	Practicality	Utilisation of Space	Environmental Impact	Total
Oscillating Water Columns	3	3	2	2	10
Oscillating Bodies	2	1	1	1	5
Overtopping Devices	1	2	3	3	9

After analysis of the three WECs, it was determined that the Oscillating Water Columns were the poorest performing. The decision matrix highlighted that the Oscillating Bodies were the most effective WEC and are best suited for attaching to the floating offshore wind turbine.

The conclusion of the Decision Matrix Analysis identified that the most suitable configuration of a combined offshore wind turbine energy farm is a 5 MW NREL floating wind turbine with a Spar Floater structure, in a Hybrid System Arrangement with attached Oscillating Bodies, as shown in Figure XXIII.

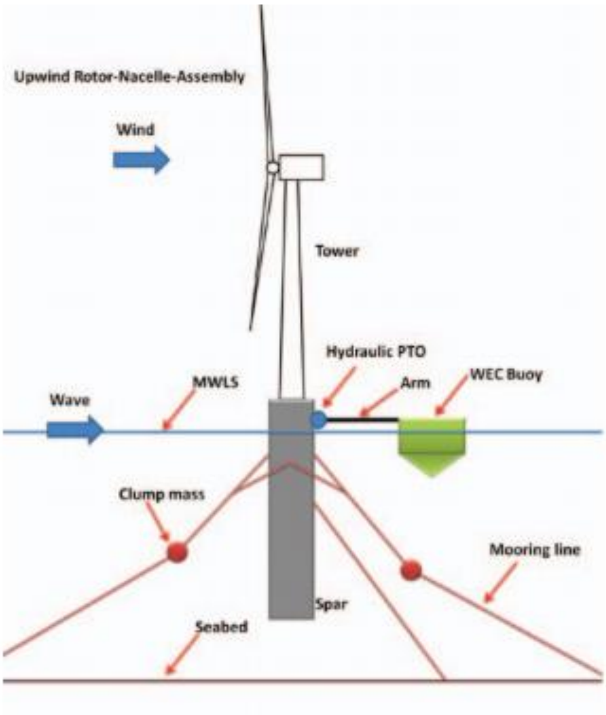


Figure XXIII: Hybrid Floating Offshore Wind and Wave System (Karimirad, 2016)

5 DISCUSSION

5.1 System Arrangement

When developing the combined system, it is essential to consider the geographical location where the system is to be situated. Offshore wind turbines are currently rarely located where tidal and wave energy systems are being deployed, due mainly to the fact that the waves and tidal streams can cause the platform of the turbine to sway, resulting in a loss of efficiency. Therefore, in order to combat this, additional costs must be incurred to stabilise the platform by either:

- strengthening the mooring cables of the system
- increasing the weight of the wind turbine platform
- reinforcing the foundations of the wind turbine
- using the additional energy systems to assist the stabilisation as proposed in this study

A compromise has to be reached when selecting the location of the hybrid energy farm. The maritime area must consist of either:

- less powerful waves and tidal streams, which will reduce the motion felt on the platform but will result in an overall reduction in energy yield or
- more powerful waves and tidal streams, which will increase the motion felt on the platform but could result in an overall increased energy yield, but only if the platform motion in mitigated by increasing weight, strengthening mooring cables, etc, all of which will incur additional costs.

5.1.1 Co-located Arrangement

The Co-located Arrangement performed the poorest of the three system arrangements scoring the worst mark for Costs. This is due to the high number of cables required to transfer the electricity onshore. Cost savings were not achievable as the energy systems were not able to share foundations or infrastructures apart from the same electric grid connection. Each energy system has to be installed separately and therefore the energy systems do not share the same operation and maintenance and thus require separate technicians.

The Co-located Arrangement performed best in the Wind Turbine Protection category. As the two energy systems share only a grid connection, it allows the energy system to be situated along the perimeter of the wind turbine farm. This layout allows the additional energy system to adsorb the impact of high waves and protects the wind turbines from damage.

For WECs this arrangement enables them to produce the largest energy output, as the waves are not inhibited by the offshore wind turbine structures. However, as a result, the Co-located Arrangement performs poorly in the Accessibility category. This is due to the additional energy systems being located around the perimeter of the wind turbines, preventing easy access to the wind turbines themselves for the maintenance crew. This arrangement can also restrict the number of additional energy systems in the combined farm as shown in Figure II.

For the Co-located Independent Arrangement, further planning permission must be undertaken to acquire the marine area adjacent to the existing wind turbines or limit the number of each energy system, in order to contain both wind turbines and the other energy system in the one original maritime area. The Co-located Arrangement also prevents the two energy systems from sharing operation and maintenance. As they occupy separate marine areas, the additional energy source is unable to utilise the wind turbines existing foundations or functions. Finally, despite being able to combine the energy produced by both systems, the Co-located Arrangement still obtained the poorest rating in the Enhanced Energy Yield category. Being unable to utilize the maritime space effectively, the amount of additional energy produced per m^2 is significantly less than can be obtained from other arrangements and therefore the energy payback back period of the Co-located Arrangement is longer than the other configurations.

5.1.2 Hybrid Arrangement

From the model the Hybrid Arrangement is the most successful and suitable of the three energy system configurations. This arrangement performed best in the Costs category. This is a result of the additional energy system being attached on to the existing wind turbine and therefore its ability to share foundations and other components. The two energy systems occupy the same maritime area which allows fewer cables to be installed to transfer the electricity onshore and enables the systems to share operations and maintenance.

The Hybrid Arrangement performed poorest in the Wind Turbine Protection category. Unlike the Co-located system, the Hybrid Arrangement provides little protection for the wind turbine. The Hybrid Arrangement is unable to use the additional energy system as a perimeter barrier and, as a result, the waves continually hit the tower of the wind turbine and result in increased maintenance and inspection. However, this arrangement is the most easily accessible arrangement for technicians and maintenance crews.

The Hybrid Arrangement utilises the maritime area better than the other arrangements. Combining the two systems in this arrangement allows for the maximum number of wind turbines and additional energy systems to occupy the energy farm without impeding or inhibiting any of the other systems. It also allows the maximum amount of energy to be produced from the combined energy farm. The Hybrid Arrangement can effectively share operations and maintenance as the systems are attached to each other. This allows the wind turbine to support the additional energy system and, if it experiences any unexpected issues, the second system continues to produce energy rather than shutting down. Finally, the Hybrid Arrangement achieved the best rating for Enhanced Energy Yield, due to the energy system density within the farm and as a result has the shortest energy payback period of all the arrangements.

5.1.3 Island Arrangement

Although scoring well in every category, the Island Arrangement did not perform as well as the Hybrid Arrangement. As the energy systems are occupied on the same platform, the Island Arrangement does not require a large number of cables to transfer the energy to the mainland. There are significant cost savings as the energy systems are able to share foundations, electrical grid connections and infrastructures. As a result, this system is able to use the same technicians and maintenance crews for both energy systems and therefore will continue to save money. The Island Arrangement performs well in the Wind Turbine Protection category. Due to the large shape of the platform, it can act as a barrier to absorb and prevent high waves from hitting the turbine structure and potentially causing damage. However, this arrangement is not as effective, relative to the Co-located Arrangement in this category, as the additional energy systems cannot be moved in the Island Arrangement and therefore cannot be used as a perimeter wall. The Accessibility of this arrangement is also poor. The addition of the second energy source adds significantly to the already large island-shaped platform. This makes it even more difficult for maintenance crews and technicians to access the energy farm when issues occur.

Another significant drawback to this arrangement, is its utilisation of the maritime area. Due to the large size of the island platforms and the number of combined energy systems in the farm, the energy density has to be restricted otherwise the energy systems have a potential to cause interference and damage to each other. Due to the two energy systems occupying the same maritime area, they are able to share operations and maintenance. As the energy systems share the same foundations and infrastructure, they are able to rely and support each other if any problems or issues arise. Finally, despite being able to combine the energy produced by both energy systems, the Island Arrangement did not achieve the best rating for its Enhanced Energy Yield. As a result of the arrangement being unable to fully utilize the maritime area effectively, there are less energy systems located in the energy farm, when compared with the Hybrid Arrangement. The Island Arrangement therefore produces significantly less energy and the energy payback period is longer than the Hybrid Arrangement.

5.2 Structure of the Combined System

5.2.1 Spar Floater

The Spar Floater structure was the most successful in this study, scoring the best mark in each category. This structure was determined to be the most cost effective. This is due to the structure consisting only of a singular tower and as a result, the amount of steel required to develop the tower is significantly less than the other structures. The individual tower also allows the system to be more accessible for maintenance crews, who do not have to navigate around multiple other external components. The small size allows the Spar Floater to fully utilise the energy farm, allowing for the maximum number of energy systems and the greatest possible output. Due to the size and shape of this structure it has the lowest Environmental Impact of the three considered structures.

5.2.2 Tensioned-leg Platform

The Tensioned-leg Platform did not perform as well as the Spar Floater in the analysis. Like the Spar Floater structure, the TLP consists of one singular tower. However, at the base of the tower, it splits into three horizontal support beams used by the mooring cables to hold the structure in place. These support beams are comprised of steel and therefore, add significantly to the material costs. The support beams can reduce the accessibility to the energy farm. During the initial development of the energy farm, the support beams can restrict the access of the vessels required to tow the other systems into their correct location. The large size and shape of the TLP prevent the farm from being fully utilised. Using only TLP structures would reduce the number of energy systems within the marine area, resulting in a lower energy output production than the Spar Floater structure. The TLP produced the poorest rating for Environmental Impact, as the mooring cables and support beams could have a negative effect on marine life.

5.2.3 Semi-submersible Platform

The Semi-submersible Platform performed the worst of the three structures in this analysis. The SSP consists of three steel towers held together by a series of support beams. The quantity of metal required for the development of this structure results in the highest material and production costs. Like the TLP, during the initial development of the SSP, the support beams and additional towers can restrict the manoeuvrability and the access of vessels towing other hybrid systems into the farm. An energy farm comprised of these structures would prove difficult for maintenance crews to navigate in poor weather due to the fact that this structure is not moored to the seabed and can be prone to undesirable movement. An energy farm consisting of SSP structures would not be fully utilised due to their large size and shape and result in a low energy density. This low energy system density results unfavourably in a low energy output.

5.3 Additional Energy Systems

5.3.1 WECs

Determining the additional energy system required a more complex decision matrix due to the number of variables that can affect each system, and this results in each energy system being compared in eight different categories.

WECs and Tidal Turbines had similar scores but despite Tidal Turbines being a very suitable additional energy system, WECs resulted in a higher Enhanced Energy Yield and therefore were selected. However, the initial cost analysis of the WECs is poor. This is a result of the steel structures required to encapsulate the energy generation components of the system, attracting a high material cost. Due to the WECs being deployed on the surface of the ocean, they have very little impact on the environment and marine life and as a result the WECs were awarded the best mark in this category.

The size and shape of these energy systems allow them to better utilise the space in the energy farm. Three WECs can be placed around each of the offshore wind turbines, ensuring that the WECs are spread 120° apart for maximum efficiency. Wave energy is considered to be one of the most reliable and predictable energy sources. Despite its predictability, it was only awarded a rating of 2, as Tidal Turbines are generally considered to be the most predictable energy source. Due to their reliability, WECs are capable of a producing a significant amount of energy and therefore the overall energy output of the combined system is better suited to match times of high consumer demand. However, as wind turbines and WECs rely on wind, the combined system can experience sudden grid disconnections and non-activity hours are possible, if no wind is present.

Attaching a WEC on to an offshore wind turbine would allow these systems to share infrastructure and would result in a decrease in operation and maintenance costs. Combining three WECs around the offshore wind turbine would result in a significant increase in energy production. The addition of WECs would significantly enhance the energy yield of the overall system and reduce the energy payback period.

5.3.2 Uranium Harvesting Devices

The Uranium Harvesting Device performed the worst of the three energy systems. This energy system requires steel for the supporting frame, a separate tank for the elution process, the required chemicals for this process and an additional tank for the captured uranium, resulting in an extremely high overall cost. However, although the uranium is not converted into energy at site, it is able to be sold to a nuclear plant at an extremely high price and thereby mitigating the high overall cost.

The Uranium Harvesting Device achieved the poorest rating in the Environmental Impact category. With this method the main hazard for the environment is the containment of the captured uranium. It is vital that the storage tanks are lined with the correct materials to ensure that no radioactive materials are exposed to the environment. The adsorbent netting and winch gear can also cause problems for the environment risking injury to marine life. Uranium Harvesting Device performed well in the category of Utilisation of Space. Allowing the process to occur over two wind turbines, as shown in Figure XVI, with an elution and storage tank on each wind turbine and allowing the adsorbents netting to pass through each process, can significantly increase the yield of uranium captured, by effectively utilising the volume of water between the structures. This increase in yield could result in creating an overall higher energy supply once the uranium has undergone the fission process onshore. However, despite there being an estimated four billion tonnes of uranium in the ocean, the predictability of the system is low. The amount of uranium captured daily can fluctuate significantly and as each elution process occurs, the adsorbents capacity decreases, resulting in the capture of less uranium.

Due to the very different nature of wind energy and uranium extraction, the combined system is not capable of sharing any equipment or facilities. The main difference in this combination is that the uranium is not converted into energy at the turbines and no infrastructure is shared. The only component shared by the energy systems is the wind turbine foundation and, as a result, the cost reduction is minimal. Consequently, the Uranium Harvesting Device has the poorest rating in Shared Logistics and Common Grid Infrastructure. As the uranium is not converted into energy on site and has to be transported to a nuclear power plant, the Enhanced Energy Yield of the overall combined system is low.

5.3.3 Tidal Turbines

Tidal Turbines are a very suitable option for a hybrid offshore floating wind turbine. This system performed well in the Decision Matrix Analysis. The overall Costs of the Tidal Turbines were considered to be better than WECs. As Tidal Turbines have the same components as a wind turbine, they are able to share equipment, development facilities and technological advancements. This use of common components significantly reduces the number of spares that have to be retained, resulting in a cost saving. Due to their similar infrastructures, a combined system would eliminate the need for each system to have its own individual infrastructure resulting in a significant reduction in costs and also resulting in the best performance in the categories of Shared Logistics and Common Grid Infrastructure.

This energy system was considered to be less environmentally friendly than WECs, due to the likelihood of injury to marine life by the Tidal Turbine. The Tidal Turbine achieved the poorest rating of Utilisation of Space. The proposed concept has only two turbines attached to the tower of the wind turbine and therefore, does not fully maximise the space provided on the structure. However, despite this drawback, Tidal Turbines achieved the best rating in the Predictability category. Tidal power is considered one of the most reliable and predictable energy sources, so a combined wind-tidal system would result in a steady supply of output energy. Although a combined wind-tidal system has a steady output, this system would produce a low energy yield, with only two turbines in place. This system could result in more non-activity hours than a wave-wind system.

5.4 Wave Energy Converters

Having identified the best combined system, the WECs were evaluated using the decision matrix to determine; the efficiency of each system; the practicality of each system being located in deep water; how well the systems utilised the surrounding space; and their Environmental Impact.

5.4.1 Oscillating Water Columns

The Oscillating Water Columns were deemed to be the least efficient of the three systems. The Oscillating Water Columns consist of only one turbine generator and require the waves to enter the water column with a degree of force in order for the trapped air to be pushed through the generator. Without sufficient force, no energy will be produced. Due to the deep water conditions in which this system is situated, it was deemed to be the least practical. As there is low probability of continually achieving the correct wave force to produce energy, it is likely that the system would be sitting idle for an extended period of time with increased non-activity hours. The OWCs were considered ineffective at utilising the space around the wind turbine. As the OWCs are only capable of obtaining wave energy from one direction, as shown in Figure V, only one system can be attached onto the foundations of the turbine and therefore, the OWCs are unable to fully utilise the space of the energy farm.

5.4.2 Oscillating Bodies

Oscillating Bodies was concluded to be the best of the three examined systems. The only category in which this system did not outperform was Efficiency. The Oscillating Bodies system was found to be the most practical as it was continually able to produce energy in all wave conditions. This system is also able to utilise the space in the energy farm better than the other systems, as three Oscillating Bodies can surround the foundation of the wind turbine, allowing for maximum energy output. Having very little impact on the environment, this system is also the most environmentally friendly.

5.4.3 Overtopping Devices

Overtopping Devices was found to be the most efficient WEC. Due to the large storage capabilities, large volumes of water can be pushed through multiple turbines to create a significant energy output. However, the water has to reach a certain level before being passed through the turbines and, as a result the, Overtopping Device may be sitting idle for long periods of time and therefore, is not as practical as the Oscillating Bodies. Due to the size and shape of these systems there is a limit to one system per turbine and as a result they are unable to fully utilise the energy farm. Like Oscillating Bodies, Overtopping Devices have little effect on the environment when situated on the water. However, due to the significant amount of steel required for the structure, they can produce harmful emissions whilst in production and therefore attracted the poorest Environmental Impact score.

6 CONCLUSION

Due to the high costs associated with offshore renewable energy systems, this thesis seeks to propose a mitigating solution by attaching an additional energy source on to a floating wind turbine in order to produce an increase in energy output, whilst simultaneously, significantly reducing the overall development and through life costs, by sharing foundations and infrastructure. This study was able to conclude that the most cost effective and viable option was to attach three Oscillating Bodies onto the Spar Floater structure of a Hybrid floating wind turbine.

The abundance of resources and numerous synergies, technological and legislative, existing between offshore wind turbines and WECs, makes a compelling argument for the production of a hybrid solution. The hybrid energy system proposed in this study has the potential to play a vital role in ensuring that Scotland achieves its goal of net-zero economy by 2045.

6.1 Limitations of this Thesis

The Covid-19 environment prevented any opportunity to visit relevant sites, interview or talk directly to companies and restricted access to individuals. Consequently, it was difficult to obtain any ‘commercial in confidence’ information such as costs savings, percentage improvement yields, etc. As such, this thesis was constrained to be internet focused.

In addition, this study was undertaken without the capability of modelling each of the variations presented, as there was no access to university modelling resources. Because no modelling could be undertaken, the assumption was made that the criteria in each decision matrix were of equal weighting. This study also assumed that the offshore wind turbine is operating continually due to a constant flow of wind.

6.2 Direction for future investigations

Future work on this project may include using more efficient offshore wind turbines in order to increase the energy output and further reduce the energy payback period. The addition of more tidal turbines on the tower of the wind turbine structure is also worth consideration, to enhance the energy yield and further utilise the space in the energy farm. This thesis only considered the combining of two diverse energy generation sources. Future research may consider the combination of more than two diverse systems to optimise the space on the wind turbine structure.

Another interesting area for future research is a focus on cable optimisation. Selecting the appropriate cable size is essential for transporting electricity onshore with as little energy loss as possible. For example, the use of a 9 MW cable to transport the electricity produced from a 7 MW energy farm would not be cost effective use of a large expensive cable. Limiting the cable size, for example, to 5 MW, could result in an efficient continual maximum flow of electricity and could allow the remaining 2 MW to be used to produce hydrogen, storing it in the energy farm for future use. A full cost benefit analysis of these scenarios would have to be performed.

Future research could also be undertaken to determine the appropriate weighting of criteria in each decision matrix, resulting in a more accurate conclusion. It must also be noted that these weighting will vary for each installation, depending on the government legislation, geography, and the financial environment at that time.

Additional grid services, where power storage becomes part of the solution could also be considered for future projects. With any grid connection, power can be delivered or stored through the same cabling. A benefit of being offshore is that you have potentially deep water beneath the turbine installation. This allows for the relatively simple addition of Compressed Air Energy Storage (CAES), which in its simplest form requires large “bladders” ballasted to the seabed, into which air is pumped, thus inflating them. This compresses air can be returned, via turbines, as electricity on-demand to the grid, allowing power to be sold at peak times and stored at other times. This approach has the added bonus of being able to use surplus grid power from other onshore generators and store it for use at peak times.

By offering Grid Balancing or STOR (Short Term Operating Reserve) services to the national grid from your combined power generation system can result in lucrative income. This involves being paid to provide power at specific times, or indeed to remove loading at other times of the day or night. The income from these services can be quite substantial, offsetting operating and maintenance costs and significantly reduce the energy payback period.

A further area of interest could be to produce desalinated water on the offshore wind turbine platform, pump it onshore and sell the electricity produced. This approach would not use electric generation at the heart of the turbines, but hydraulic energy extraction instead, as this method is not limited in the same way as electric generators. Hydraulically extracting energy, then using heat pump (multi-stage) to produce steam, to then produce electricity on-demand, while creating a by-product of desalinated water, may indeed be the optimum solution for a particular country’s needs. This running cost mitigation is similar to the business case for Uranium Harvesting Device discussed in this thesis.

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