Multiple use of a floating offshore wind energy platform – A case study on the Hexicon concept

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Mångsidig användning av en flytande havsbaserad plattform med integrerad vind energi

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Sammanfattning

Ökad medvetenhet om klimatförändringar ökar efterfrågan på förnybara energikällor. Vindkraft väntas utgöra en stor del av denna ökade andel förnybar energi och en stor del av dagens utveckling är inriktad på en utbyggnad av havsbaserad vindkraft. Flytande havsbaserade vindkrafts parker utvecklas för att kunna utnyttja större havsområden, oberoende av vattendjup. På grund av höga initiala investeringskostnader för flytande plattformar finns ett intresse att öka användningen av plattformarna och utnyttja de till fler nyttor. Denna studie syftar till att utvärdera möjligheterna att öka användandegraden av en plattform, under utveckling av Hexicon AB.

Studien delades upp i två faser; en initial utforskande del och en senare utvärderande del. I den första fasen utfördes en workshop som syftade till att generera idéer för tänkbara funktionaliteter lämpliga som tillägg till plattformen. Workshopen låg även till grund för ett val av tre funktionaliteter för vidare utvärdering. Litteraturstudier kombinerat med semistrukturerade intervjuer användes för att skapa en kunskapsbas kring de tre koncepten varpå tre individuella koncept utvecklades och utvärderades. Både kvalitativa och kvantitativa faktorer användes i utvärderingsprocessen. De tre koncepten som utvärderades baserades på tillägg av solceller, vågkraft och en anläggning för fiskodling.

Resultaten visade på en varierande påverkan från de olika tilläggen på plattformen, ur ett tekniskt perspektiv. Den största effekten sågs i vågenergikonceptet där det skulle krävas en betydande omkonstruktion av plattformen. Påverkan av kostnaden för energin producerad (LCOE) undersöktes också, där liten påverkan sågs förutom för tillägget av solceller som gav en 11% sänkning av LCOE-värdet. Kostnaden för energi ökade med tillägget av vågkraft, trots att många gemensamma kostnader kunde räknas bort. Tillägget av fiskodlingsanläggning indikerade potential till ökade intäkter. Utfallen av de ekonomiska beräkningarna påverkades kraftigt av vindförhållanden vid respektive lokalitet vilket försvårade en rättvis jämförelse av de olika koncepten. Alla tre tillägg sågs som ett sätt att nå nya marknader samt att vinna konkurrensfördelar på olika marknader. Rekommendationer på vidare studier presenteras.

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Abstract

Increasing awareness of climate changes increases the demand for renewable energy sources. Wind energy is expected to constitute a major part of this increased capacity of renewable energy and much of the development is focused on an expansion of offshore wind energy. Floating offshore wind energy farms are being developed to access deeper waters. Some developers are looking into possibilities to increase the utilisation of the platform foundations for the wind turbines. This study aims to evaluate the potential to utilise a multiple turbine platform concept, under development by Hexicon AB, for multiple uses.

The study was divided into two stages; an initial explorative and a latter evaluative. In the first stage an idea generation and screening workshop was held to produce a limited number of potential functionalities suitable to add to the platform. Literature studies combined with semi-structured interviews were used to create an information base from which three concepts and scenarios were created and evaluated. Both qualitative and quantitative factors were used in the evaluation process. The three concepts for multiple use of the platform were based on the addition of solar energy in the form of photovoltaics, wave energy converters and aquaculture equipment respectively.

The results showed varying impact on the Hexicon platform from the added functionalities, from a technical perspective. The largest impact was found in the wave energy concept where significant redesign of the platform would be required. Impact on cost of energy was also investigated, where little impact was seen except for the addition of photovoltaics which gave an 11 % decrease of the LCOE-value. The addition of wave energy converters did not lower the cost of energy in this scenario despite benefits of shared costs for some components. The integration of aquaculture equipment indicated potential of increased revenues. The results, from an economic perspective, were very dependent on the location due to varying wind resources. Additions of the three functionalities were seen as a way to access other market shares and increase competitiveness. Recommendations for future work was presented as well.

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NOMENCLATURE

Wordlist:

Feed-in tariffs = A policy mechanism designed to accelerate development and investment in renewable energy technologies. Energy producers are paid a cost-based price for the electricity supplied.

Return period = The number of years between which a certain condition can be expected to occur, for example an extreme wind or wave condition.

Notations

Symbol	Description
g	*Gram*
J	*Joule*
kW/m	*Kilowatt per meter*
m	*Meter*
m/s	*Meter per second*
m^2	*Square meter*
m^3	*Cubic meter*
N	*Newton*
t	*Tons*
V	*Volt*
W	*Watts*
Wp	*Watt peak capacity*

Abbreviations

AC	*Alternating Current*
AM	*Air Mass*
BOS	*Balance Of System cost*
CAPEX	*Capital Expenditures, the cost of initial investments*
DC	*Direct Current*
LCOE	*Levelised cost of energy*
MENA	*Middle East and North Africa region*
O&M	*Operations and Maintenance*
OPEX	*Operating expenditures, the cost of O&M*

PV	*Photovoltaics*
R&D	*Research and development*
STC	*Standard Test Conditions*
TRL	*Technology readiness level*
WACC	*Weighted average cost of capital*

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1 INTRODUCTION

The increasing awareness of the issues with climate changes in recent years has contributed to an increased demand for other energy sources than those based on fossil fuels. The European Union (EU) has put up ambitious climate targets in the so-called Europe 2020 Strategy.[1] Three main goals are set out to be reached before 2020:

- The 1990 levels of EU greenhouse gas emissions shall be reduced by a minimum of 20%
- 20 % of the energy consumption shall has its origin from renewable sources
- Lowering the overall energy consumption with 20%

When looking at wind energy there are two main types of installations, onshore and offshore. Onshore installations are by far more common and constituted 94% of the cumulative installed capacity in Europe 2013[4]. However, the offshore sector is growing, with a global growth of 32% installed capacity in 2012[2]. There are several benefits with offshore wind installations, the two main ones being stronger and more reliable winds and less visual impact. There is also a lack of inexpensive land close to populated areas suitable for onshore wind farm development.[3] Another argument is that coastal regions often are the most populated with high energy demand and therefore is an advantage to have the energy source relatively close to the demand.

Naturally there are also disadvantages with offshore installations. These disadvantages are mainly related to accessibility, which is necessary for maintenance. The installations are only accessible by boat or helicopter, which are both expensive means of transport. Due to the harsh offshore environment the time where access is possible is also limited. Boat access on most offshore wind sites in the United Kingdom is limited to 80% of the time.[4] The time the offshore wind turbines can produce power is also lower than their onshore counterparts, with a ratio of 90% of the total time for offshore compared to 98% for onshore installations. This is mostly due to limited accessibility.[5]

Despite the disadvantages and difficulties with offshore wind, the benefits involved are by many considered to outweigh the drawbacks. A proof of this is an already relatively extensive development of seabed foundation offshore wind parks. Also several concepts built on floating foundations have been developed in different regions. As for onshore wind energy, Europe has been the region leading the development. Being a relatively new field within offshore wind, yet to become commercially viable, the new technical challenges as a result of the difficult environment create huge costs, which are a barrier for commercialisation. Most developers focus solely on the use of wind turbines on their floating platforms. However, some try to gain competitive advantage by multiple uses of the platforms through the combination with other energy generators, commonly those harvesting energy from waves and ocean currents. The main reason behind this development is the advantage of being able to generate energy from resources that are available to a larger extent of time compared to wind solely, which could be an important factor in the reduction of intermittency, which is a problem for all renewable energy sources. There are also not only energy generating additions that are of interest to place in an offshore environment. Activities that already take place offshore could possible utilise to platform structure and some activities could possibly benefit from a move offshore. This kind of development can be considered to be a highly innovative project.

When exploring the possibility of developing highly innovative products or systems, such as a floating wind energy platform or even multiple use platforms, there is need to evaluate options thoroughly in order to make the right investment decision. These kinds of innovation projects are linked to high risk, uncertainty and a high failure rate.[6] Generally investment projects are evaluated with quantitative or qualitative evaluation methods, or a combination of the two are used.[7]

Some of the most common quantitative methods used for project evaluation are internal rate of return (IRR) and net present value (NPV). However, these can be misleading when it comes to high-risk innovation projects due to the difficulty of doing accurate quantifiable estimates.[8] Moreover, the financial prospects does not say it all. A project's long term strategic implications may have great effect on the company's future and direction. Hence many argue there is a need for using both quantitative and qualitative factors when evaluating innovation projects.[9] [10] [11] When going towards a less known context with a higher level of uncertainty, the general conclusion in this field of research points to the necessity of using qualitative measures.[12]

An investigation of the possibilities of extended utilisation of a multiple turbine platform developed by the Swedish company Hexicon has been put forward. The extended utilisation should not necessarily be limited to energy generating additions.

1.1 Problem Definition

A barrier for the realisation of floating wind energy concepts is the increased costs compared to onshore installations as well as fixed foundations in shallow water resulting in a higher cost of energy. Large capital investments and an environment with high risks further contribute to the challenge to attract sufficient investments.

The industry is looking for ways to overcome this barrier. Multiple use, by adding additional functionality to floating wind energy platforms, either another energy source or other functionalities that would contribute with extra revenues, has been identified as one way to achieve this. Some companies are developing concepts that combine different energy sources but they remain few in numbers. Most studies have been on a conceptual level or early idea stage. So is the case with Hexicon as well, most ideas for combination projects have previously remained at the idea stage. But it has been put forward as a way of increasing competitiveness.

Naturally an additional functionality would incur increased cost for development and integration. However the offshore installation procedure constitute a significant cost of each commissioned platform and this cost is likely to only change moderately with an added functionality. Therefore this cost can be spread over more revenues. A well-integrated added functionality could also increase the concept’s competitiveness by adding other values, such as positive image or opening up new markets, resulting in more appeal to potential investors and customers.

The integration of an additional functionality is considered to be a highly innovative venture. Research within the field of innovation project selection suggests increased consideration of other aspects than merely economic. Due to the high-risk characteristics of an innovation project, there is a need for a more holistic evaluation process based on both qualitative and quantitative factors. This would help to create a more comprehensive evaluation of a multiple use platform concept.

1.2 Aim and Objectives

1.2.1 Aim

The aim of this study was to create an initial appreciation of how multiple use of the Hexicon platform would affect the original concept from a comprehensive perspective, including both qualitative and quantitative factors. It is thought as a foundation for further research of the concepts proposed in this study.

1.2.2 Objectives

The specific objectives of this study was to:

- Investigate how an added functionality would affect the basic platform from a technical perspective.
- Investigate if multiple use of the platform could contribute to lowering the cost of energy for floating wind energy concepts.
- Evaluate a number of concepts based on multiple use of the Hexicon platform using quantitative and qualitative factors.

1.3 Method of attack

To reach the objectives stated a general explorative approach was held. The study was divided into two stages, an initial explorative stage and a latter evaluative stage.

Exploration stage

- The initial phase aimed to explore many possible added functionalities.
- A selection process resulted in three concepts for further evaluation.
- Background studies of the area of each of the selected concept were carried out.

Evaluation stage

- Three cases were created.
- A case study was performed on each case. The evaluation was based on both quantitative and qualitative factors.
- Recommendations were put forward on what would be of interest to further investigate.

1.4 Delimitations

To narrow the scope of the study, a limited number of technical aspects of how the platform would be affected by an additional functionality were evaluated. These were: added loads on the platform, additional weight, interference with existing structure and mooring system and technology readiness level (TRL).

Further, when looking at geographical placements of the evaluated concepts this was limited to European locations. This was partly chosen to have a comparable level of cost for production and maintenance of the installations.

Specific energy market conditions with regards to favourable financial support systems were only mentioned, but were not included in the financial estimations. Neither was any electricity price considered, instead only the cost of energy production was investigated. Hence, feed-in tariffs were not considered in the economic evaluations.

For each of the three concepts, specific adjustments were made to some extent to how detailed data that the evaluations were based on. This was due to the varying level of available information on each individual concept.

Some renewable energy systems would use some kind of energy storage to limit the intermittency. The use of an energy storage system to even out energy delivery to the grid has not been considered in this study.

2 FRAME OF REFERENCE

This frame of reference firstly aims give a broad background to the area of floating wind energy and then to provide understanding of the factors that will be used to analyse the potential of the combination concepts that will be produced in this study. It touches upon quantitative measurements but the focus in this chapter is on qualitative factors relevant for assessments of R&D projects.

2.1 Background

The offshore wind industry has so far mainly seen installation of turbines on seabed foundations. But the development of floating offshore wind energy moves fast. The main reason for the floating structures is the ability to utilise deeper waters. Industry consensus is that floating structures are more cost efficient in water depths of 45 metres and more, and since this part of the industry is in the early stages of development, one can expect significant cost and risk reductions presumably moving the cost efficiency limit to even shallower depths.[13]

Another factor that is likely to increase the demand for floating structures is the lack of shallow water areas. Looking at key markets almost two thirds of the US offshore wind resources are in waters deeper than 100 metres, almost all of Japan's resources are in deep water and also a majority of the resources in Europe require floating structures.[14] The already planned offshore wind investment round, UK Round 3, contain some areas for exploitation in deep water that will require floating structures.[15] Except for the necessity to have floating structures due to water depth, the fact that these can be built and commissioned onshore or in a sheltered harbour and then towed out to the offshore site when weather conditions allow, installation costs and risks can be reduced.

2.1.1 Floating wind energy platforms

Floating wind energy requires a floating foundation that can carry the wind turbine or turbines and be kept in a somewhat steady positioning to be able to connect to the electrical grid. The positioning can be solved through the use of thrusters keeping the structure in place or by mooring it to the seabed, the latter one being the most used method.[16]

There are three general ways to design the floating substructure.[16]

Spar floater
Based on conventional offshore spar buoy technology collected from the oil and gas industry, the spar floater is a long and slender cylinder that goes deep below water surface. The stability is created by the deep draft and heavy ballast. Due to the large mass of the substructure, wave induced motions are reduced.

Tensioned-leg platform (TLP)
A TLP is a submerged platform tethered to the seabed with tensioned mooring lines. Due to the pre-tension caused by the natural buoyancy of the platform and the counter working mooring lines, wave induced heave motion is reduced and therefore increasing the horizontal stability. However, a weakness lies in the constant force working on the tension lines.

Semi-submersible platform
This technology, like the spar buoy, comes from the oil and gas industry. A semi-submersible platform normally consists of vertical cylinders and interconnecting beams holding the structure together. It has most of the structure below the water surface and gains its stability from the buoyancy that is created by the bottom of the structure, keeping the upper structure above water.

It is very flexible in placement, since it is not very dependent on water depth and can easily be moved from one site to another. Due to the buoyancy and relatively shallow draft its main disadvantage is that it is difficult to avoid wave-induced motions.

2.1.2 Floating offshore wind energy concepts

As the demand for solutions for deep water increases concepts for floating platforms are being developed in many places around the world. The stages of development vary from design phase to full scale testing in offshore environments.[17]

In Japan a number of development projects on floating platforms are taking place. An important driver for the development is the fact that 80% of the offshore wind resources are in deep water. Also the Fukushima nuclear accident in March 2011 accelerated the development towards renewable alternatives to the nuclear energy. The furthest developed project is the Fukushima floating offshore demonstration project FORWARD with a full-scale prototype being assembled at the moment with the plan to be deployed during 2015.[18]

Also in the US, an important factor driving the development towards floating wind energy is the majority of wind resources being in deep water. The U.S. Department of Energy has deployed a financing plan for R&D efforts in the offshore wind sector funding a number of projects that will receive up to $4 million each to complete engineering, site evaluation and planning phase. Up to three projects will receive further funding to achieve commercial operation by 2017. There are four projects in total using floating foundations: WindFloat[19], DeepCWind VolturnUS[20], Pelastar[21] and Nautica Windpower AFT[22]. WindFloat being most developed project with full-scale pilot testing since 2011.

As for offshore wind in general, a significant part of the development of floating wind energy worldwide is taking place in Europe. Most European countries have a majority of their wind resources in water depths above 50 m.[14] The key drivers for the relatively intensive development stems mainly from the climate goals set up by the European Union, stating a 20% energy contribution from renewable energy sources by 2020, where offshore wind is seen as a major renewable energy growth market[23]. These goals rises to 27 % in 2030.The increasing water depths in projected installation areas increase the costs for bottom foundations which results in the need of floating foundations. In total there are 17 ongoing projects developing floating concepts, the more developed ones with full scale prototypes being: Statoil Hywind, with a full scale demonstration turbine operating since 2009[24] and Winflo in France[25] with full scale prototype commissioned in 2014.

2.1.3 Multiple use concepts

A few concepts where wind and wave energy is combined already exist. The W2Power by Norwegian Pelagic Power[26] is a hybrid platform designed to harvest both wind and wave energy. The platform combines two 3.6 MW wind turbines with arrays of buoys working on a water pump system elevating water thus creating potential energy. The water is then released through a singular Pelton turbine generating energy. The platform is rated to 10 MW in total. Another concept is Danish project Floating Power Plant[27]. This concept has been under development since 1995, the current design being an 80 metres wide semi-submersible platform with a single 5 MW wind turbine mounted and a wave power take off (PTO) system consisting of floaters creating a rotational force on a hydraulic system with a rated capacity of 2.6 MW. A 1:50-scale model has been tested in combinations of wind and waves conditions in 2013 and 2014 and the company behind the project claims it is proven stable in appropriate conditions for a commercial-scale device.

2.1.4 The Hexicon concept

Hexicon AB is a company developing a concept for floating offshore wind energy. The concept is based on a floating platform foundation on top of which multiple wind turbines are installed. The unique features of the Hexicon concept are the formation of turbine placement and the ability to rotate the platform to accommodate for all possible wind directions without the disturbance of turbulence, the wake that occurs behind a wind turbine. Since the platform rotates the entire line of turbines, it is possible to place turbines close together without any wake affecting other turbines. This reduces the area needed for a wind farm with a set rated capacity with approximately 40% compared to singular-turbine platforms.[28] Figure 2.1 shows multiple views of the platform.

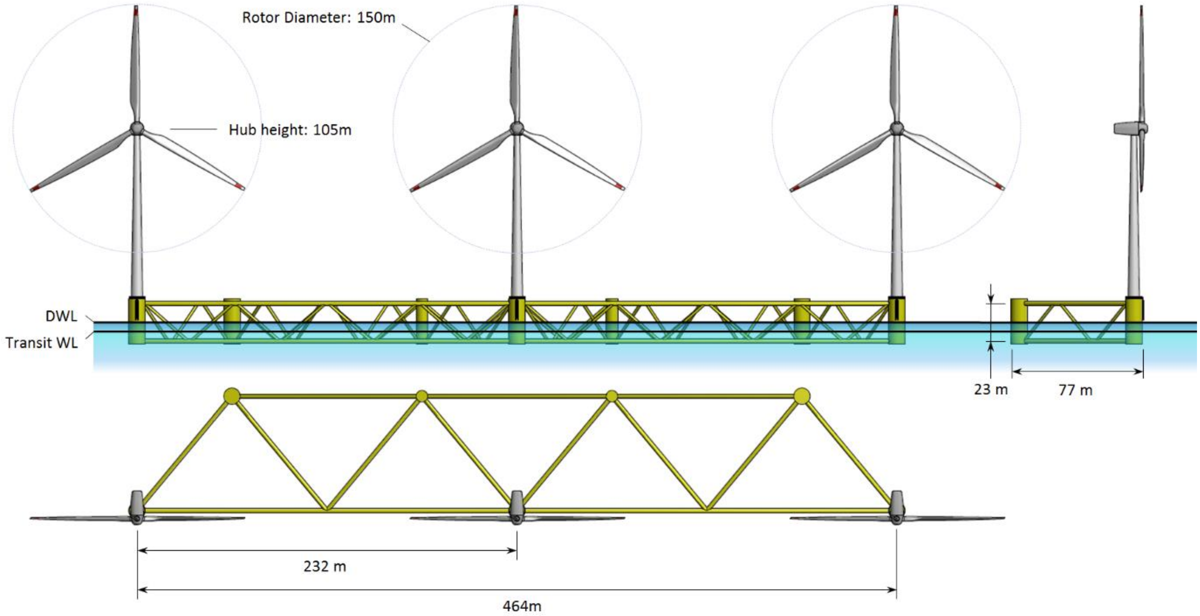

Figure 2.1 The Hexicon platform with basic measurements.

The concept has had several changes to the design during the development, however the established design now is the Generation 4 H3W 18 MW, which is described here. A standard version of the concept measures 474 metres in length and 77 m in width with an operating draught of 15 metres. The size and shape enables assembly and maintenance in larger dry-docks for ship construction, as well as towing to installation site with a transit-depth of 7 m. It has three 6 MW turbines installed rating a total capacity of 18 MW. Table 1.1 includes detailed specifications. The size of the platform can be scaled to suit the capacity that is requested from the customer. Dimensioning can also be adapted to site-specific conditions. A subsea cable transmits the electricity generated from the turbines onshore. Normally several platforms would be installed together and connected to each other enabling the sharing of onshore connection.

Table 2.1 Specifications of the Hexicon platform.

Platform structure dimensions		
Length	[m]	474
Width	[m]	77
Draught (Operating)	[m]	15
Draught (Transit)	[m]	7
Weight (w/o turbines)	[tonnes]	5775
Weight (w turbines)	[tonnes]	7035
Wind turbine specifications		
Hub height	[m]	105
Rotor diameter	[m]	150
Rated power	[MW]	6
Total installed power	[MW]	18
Cut-in speed	[m/s]	3
Rated wind speed	[m/s]	11
Cut-out wind speed	[m/s]	25

The Hexicon concept can be divided into three main components: *the platform foundation*, *the wind turbines* and *the mooring system*.

The platform foundation

The platform foundation is a semi-submersible type designed using technology that has been used and proven in the oil and gas industry for almost 30 years. A key feature of the semi-submersible design is the minimal water plane area but large water displacement, which increases the structure's stability and the minimal exposure to oncoming waves letting the water pass through the structure thus reduces the forces on the platform. The platform has a number of nodes, depending on the size of the platform, upon which the wind turbines are mounted. Each node has a displacement matching the weight of the node, tower and turbine on top reducing the transferring of stresses to other parts of the platform since each node is able to carry its own load.

The wind turbines

The turbines that are fitted to the platform are not specific to any vendor, size or number of turbines. This could be customised according to site-specific demands. However, the established design uses a 5MW turbine developed by NREL scaled to 6MW as a reference turbine.[29] For specifications, see Table 2.1.

The mooring system

The platform has an innovative mooring system based where the mooring cables are connected to the platform through attachments in the corners of the platform and winches controlling the orientation. This system enables the platform to rotate to always have an optimal angle to the oncoming wind, see Figure 2.2 for illustration. The mooring system allows the platform to rotate 45° in both directions from its normal position. The turbine towers then have the ability to yaw and additional 45° in either direction, together covering a window of 180°. When wind is blowing from the opposite direction, the turbines are just rotated around and using both the platform rotation and turbine yaw covering the other 180° of possible wind angles.

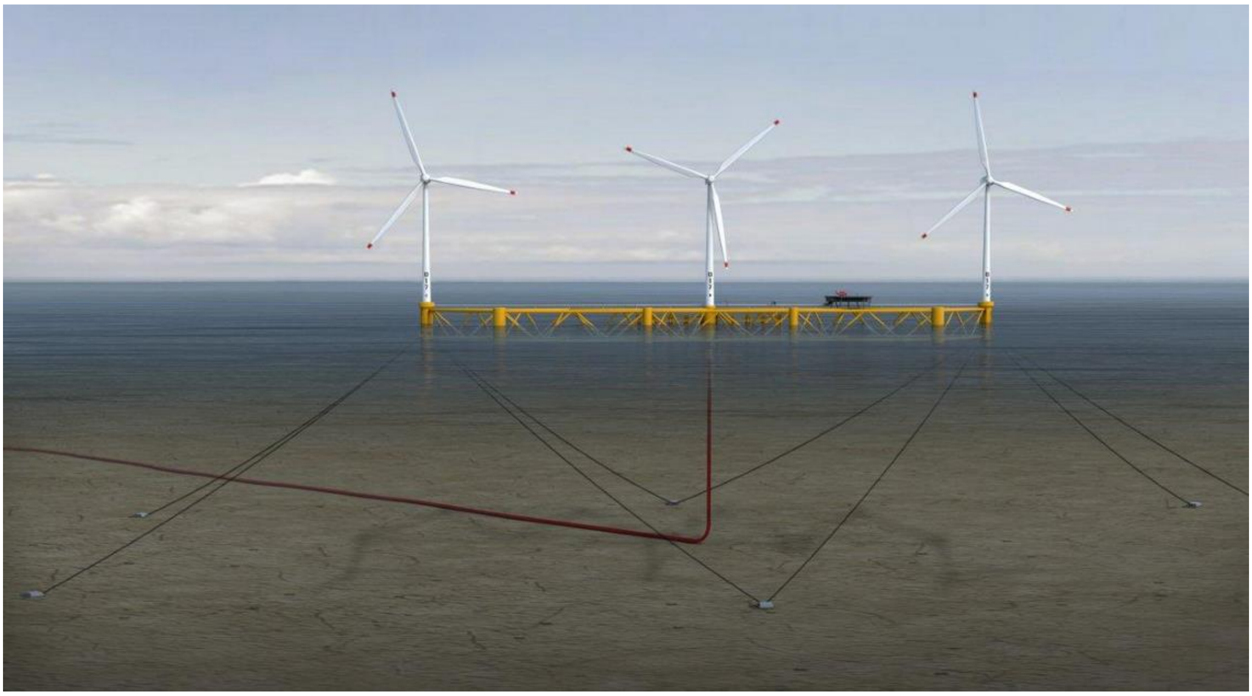

Figure 2.2 The mooring system showing the mooring lines running via the two end nodes.

2.1.5 Hexicon business strategy

Hexicon's vision is to be the world's leading designer and developer of the most cost-efficient and state-of-the-art floating solutions for the offshore renewable market. The business concept is to conduct R&D in order to promote, patent and license concept solutions with drawings and design. The services are aimed towards entities involved in energy generation, which will construct, install and operate floating wind energy platforms.

2.2 Assessment of offshore projects

An extensive protocol for equitable assessments of marine energy converters[30] has been produced by the University of Edinburgh, residing a reputable congregation of knowledge and experience within the field of offshore technology. It has been used by many when evaluating and benchmarking renewable energy technologies suited for a marine environment.[31] The protocol includes an extensive list of methodologies that might be considered in the assessment of offshore energy projects. The technical aspects of project assessment in the protocol are too complex to be used in the context of an exploratory pre-study of this kind. The level of detail of the information required to obtain a useful output is simply not viable at the stage that this study is in. However, some economic assessment tools can be useful. The protocol presents calculations of the levelised cost of energy (LCOE) as highly useful tools in an economic assessment. LCOE is considered to be the usual cost measure in the renewable energy business[32], which is further stressed by Hexicon AB.[33]

2.3 Adding qualitative aspects to the assessment

The commonly used frameworks and models for assessment of offshore projects are mainly based on quantitative measures and financial tools. However, as previously mentioned research within the field of assessing innovation project suggests a broader perspective. Simplified financial models for estimations fails to take into account all aspects of value when it comes to investments in innovation.[14]

Many articles have been published describing different project selection methods and their strengths and weaknesses. Studies comparing these methods are however more rare. One study that tries to bridge this gap presents guidelines for the choice of methods for evaluating R&D projects.[34] See Table 2.2 for a summary of the factors identified in the study.

Table 2.2 Evaluation factors for evaluating R&D projects[34]

	Strategic evaluations					Portfolio optimisation		Implementability	
	Economic return	Technological factors	Market potential	Other strategic factors	Risk level	Strategic coherence	Project interdependency	Easiness of use	Limited costs
Economic methods	++	−	−	−	+	−	−	+	++
Mathematical methods	+	−	−	−	−	++	++	−	−
Decision analysis									
AHP	+	+	+	+	+	−	−	+	−
MAUT	+	+	+	+	+	+	+	−	−
Scoring methods	+ (QI)	+	+	+	+ (QI)	−	−	++	+
Interactive methods	+ (QI)	+	+	+	+ (QI)	−	−	−	−
Strategic models	−	+	+	+	−	++	−	++	+

Only factors regarding strategic evaluations were taken into account for the purpose of this study. The factors economic return, technological factors, market potential and other strategic factors presented in the study were used. Risk level was not considered in this study to limit the scope of the evaluation process. The other factors suggested to use for portfolio optimisation and implementability analysis was also left out since they were out of the scope of this explorative pre-study. The specific methods recommended for evaluation of each factor were not used, with the exception of the economic methods recommended for evaluation of economic return. Instead literature studies and semi-structured interviews were used as a base for the evaluation, which was carried out by the authors.

2.4 Economic return

When analysing the economic return quantitative measures from the previously presented marine energy converters assessment protocol was used. The two measures that were considered to be most relevant were levelised cost of energy (LCOE) and internal rate of return (IRR). The concept of LCOE will be presented here since it is a measurement specific to the energy industry.

2.4.1 LCOE - A metric for the cost of energy

Levelised cost of energy (LCOE) is a quantitative measurement tool used for calculating the cost of producing energy. It tells the specific price the generated electricity must be sold at to generate the wanted return on capital, given by the chosen discount rate and chosen lifetime of the project. An advantage with LCOE is the non-existing relation to specific markets, their subsidies systems and electricity prices. This design makes it a convenient tool for comparing unit cost between different energy sources[35], which is important in political energy policy-making. It is also a key marker for how much it will cost to fulfil public policy objectives and goals.[36] The term grid parity is used when the cost for generating electricity for a renewable energy sources is the same or lower than conventional energy sources.[37] In Figure 2.3 typical values of LCOE are shown.

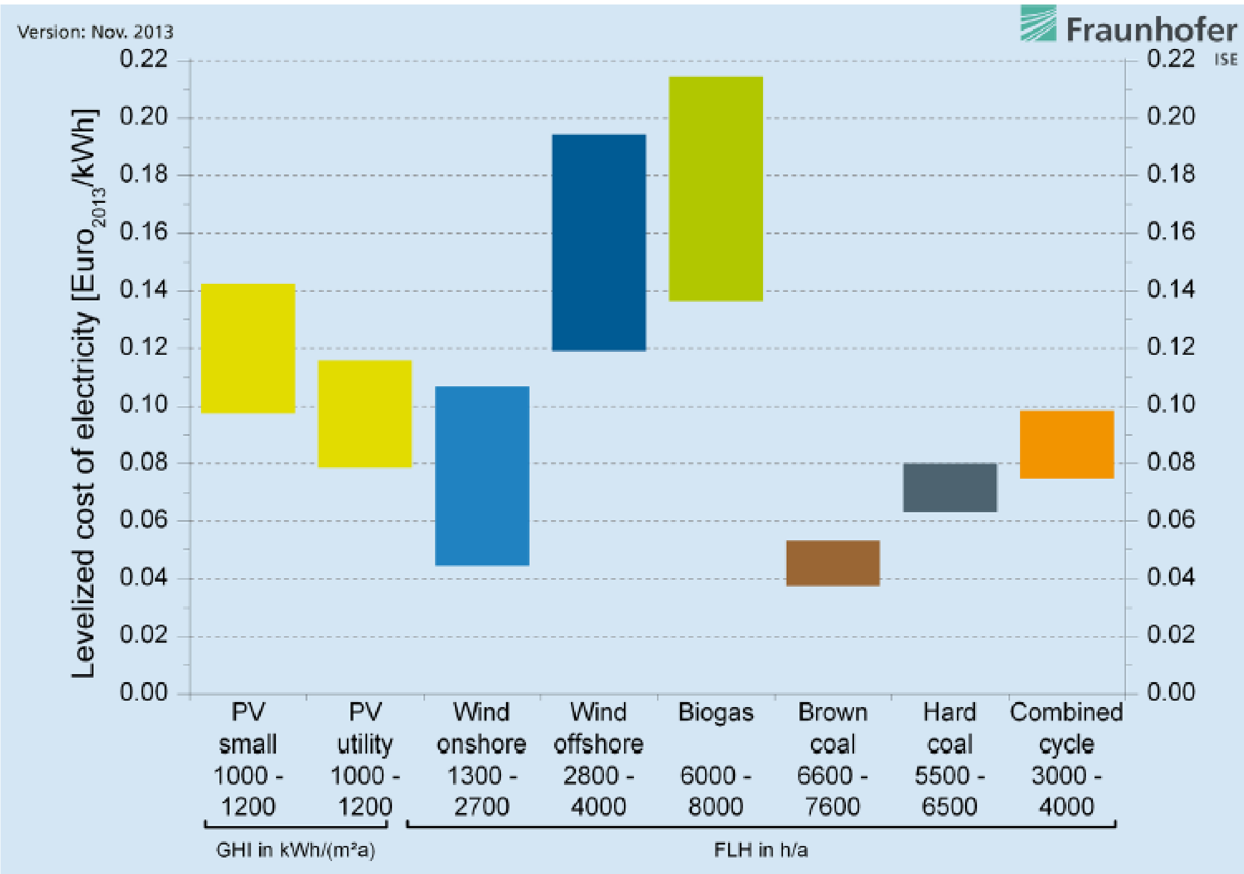

Figure 2.3 Calculated LCOE values in Germany during 2013 for renewable energy technologies and conventional power plants. The different values seen under respective energy source refers to each specific amount of full load hours (FLH), except for PV where it instead refers to insolation global horizontal irradiation (GHI) in kWh/(m²a). A minimum and maximum value for each technology has been take into consideration.[38]

As LCOE only accounts for the costs of producing energy, it does not relate to the specific market and potentially favourable systems for subsidies. Renewable energy is often incentivised on national as well as regional level with different financial support systems as feed-in tariffs (FIT) mechanism, favourable taxation or capital subsidies. In the evaluations performed in this study no beneficial financial support systems will be taken into considerations for the financial calculations.[39]

2.4 Technological factors

When looking at technological factors initial assessments of the ability to integrate the added functionality into the Hexicon platform will be performed. This includes how the add-on would be physically connected to the platform and how the additional weight and surface exposure will affect the platform and the mooring system. Possibly required re-designing of the platform and mooring system will need to be investigated. One specific technological factor that has been identified to be important is the technology readiness level, TRL, which will be discussed in the next section.

2.4.1 Technology Readiness Level

Technology Readiness Level (TRL) is a tool used for evaluating and rate developing technology and its current status.[40] It is a useful tool for comparing the maturity between various developing technologies to help support management decisions. The main purpose of TRL does not come down to the R&D process itself, but the step-by-step process of creating an innovation enabled by R&D.[41] Evaluation of TRL is used by a range of companies, organisations and governmental institutions. Often the nine different levels are defined in similar ways but with adjustment for specific technology fields. Advancement to the next TRL only occurs if all the requirements on the next level are met.[42] The strategic initiative for Ocean Energy, SI OCEAN, have developed a TRL variant of their own specifically adapted for offshore projects. The definitions and key points have been derived from US DoE Marine and Hydrokinetic database, along with discussion material gathered from SI Oceans partners. This TRL variant including definitions for each level can be seen in *Appendix A*.[52]

2.5 Other strategic factors

Other strategic factors are such that may be of importance in the evaluation of R&D projects. The integration of an added functionality to the Hexicon platform is considered to be an innovative project. The factors brought up here are proposed by Schilling[43] to be of importance when evaluating technological innovation at an early stage. Naturally there are more factors to consider, but due to the limited scope of this study only a few have been selected for evaluation.

2.5.1 Business strategy and innovation strategy

An organisation's business strategy states the overall goals for the company and how to go about to achieve these objectives. Innovation strategy is about matching the use of internal resources and skills with the opportunities and risks presented by the external environment. To create a successful innovation strategy, it is important that it aligns with the business strategy. If an innovation strategy fits well with the overall business strategy it is much more likely to be successfully implemented in the organisation.[44] If the business strategy for a company is to be a technology leader in its field, it is important to develop an innovation strategy focusing on radical and groundbreaking technology development. On the other hand one could have a strategy to be a follower, copying what others already are doing and try to make it more efficient and thus focusing more on incremental innovation as innovation strategy. [43] The concept of technology leaders and followers will be further described in the next section.

2.5.2 Timing of entry

Being first to market could mean getting an important lead, especially in a new field where similar technologies are developing parallel to each other. There are many factors determining the likelihood of a new concept’s success. A well-founded strategic decision regarding the time of entry to the market place could be important. However, research gives no clear answers to what timing strategy is the most beneficial. But there are certain factors one should be aware of when looking for the optimal timing window. [45]

First movers

Sometimes also called pioneers, face a big challenge by being first to market with a new product or service. But could potentially also generate high return due to lack of initial competition. There are many advantages to being first to market, for instance getting in the position of brand and technology leadership. First movers have the opportunity of building a solid brand image and loyalty foundation with its customers. The possibilities to get a market lead increases if a company holds key patents or protected technology. Being a technology leader also raises the chances of prolonged monopoly rent that is increased revenues or decreased costs made by a company holding a monopoly position. [45]

However, first movers often carry a substantial part of the founding research for a new technology. Emerging technologies usually require significant funding for large R&D projects. Developing distribution and suppliers channels and create customer awareness is also costly. Moreover, new technology and product development often requires unique parts that may not yet exist. Starting up or outsourcing manufacturing are often related to high costs. Some studies show that 95% of new product development does not actually lead to successful product. [46]

Early followers
Still among the early ones to market but not first as some first movers already has entered the market.

Late entrants or Followers,
Enters when the market is mature and more stable, considerably lowering the risk related to uncertainty concerning the new product or service, but are instead exposed to tougher competition as more actors has entered the market.

When to enter
Looking at the research it is not obvious which timing strategy that has highest success rates, results are mixed and definitions are defined and grouped differently.[46] One study, which grouped first movers and early followers together, concluded that followers yielded both higher returns and better rate of survival.[47] Another study that looked at product launches of more than 50 different categories, showed that first movers had a failure rate around 47%. In this study they also concluded that only 10% of the mean market share was held by first movers, consequently making early followers the outperformers.[48] However, some studies also show that the survival risk of first movers is balanced up by the higher returns it may lead to.[49] Three different older studies from the 1980s all favoured first to market. One of them showing that, at the time for the study with the chosen sample group, 70% of the market leaders were pioneers.[50]

2.5.3 Consenting processes
To establish a wind farm certain permissions need to be issued, generally known as consents. This process includes investigations of the potential effect on the environment, safety issues and many other aspects. This is a rather extensive process. Adding another functionality to the platform would may incur new aspects and require additional consents, especially if the added functionality brings new impacts on the environment. This will be discussed further for each combination concept.

2.5.4 Wind energy funding
Offshore wind projects usually have power producers, EPCI (Engineering, procurement, construction and installation companies) contractors, oil and gas companies, institutional investors, corporate investors, infrastructure funds and sovereign wealth funds as investors. Power producers are the most common investor behind offshore wind projects in the EU. The power producers constituted approximately 72% of the total cumulative investment of roughly 7 billion euro made in Europe up to 2013. Lately a growing trend of bigger wind farm projects has been seen, which has resulted in an increased attention from new kinds of financing sources. Along with this more variations in funding structures have also become more common. Commercial actors have been attracted to lend money to the sector much thanks to credit agencies and development banks. There are today more than 30 banks that have been involved in lending money to different phases of offshore wind projects.[51]

2.5.5 Grid connection
Enabling transportation of electricity to mainland, connecting to the local grid, is a key factor for supplying offshore electricity. This requires connecting an export cable from the electricity-

generating device that leads into shore. Submersible cables are used for this, which are then connected to the transmission and distribution grid network. The voltage is adjusted with transformers and substations to the right level before connecting to the grid. Sometimes the offshore energy source is not located where the highest electricity demands are. Suitable infrastructure for transporting the electricity from mainland and beyond is therefore also a requirement.[52] Necessary infrastructure for transmission is typically around 10-20% of the investment costs required for building a wind farm offshore. Historically it has been most common for developers of wind farms to take care of the construction of the grid as well.[53] In 2008 the National Grid estimated the infrastructure cost approximately 6-10 billion euro for connecting a 19 GW offshore wind park.[54]

2.6 Wind power

Wind power will be the base in all combination concepts investigated in this study. Basic theory behind wind energy generation is presented below.

2.6.1 Wind power characteristics

Driven by atmospheric pressure differences due to uneven surface temperatures, the wind is ultimately a product of the irradiation from the sun. The power of the wind flowing through a rotor disc is expressed by Equation 1[55]:

$$P = \frac{1}{2}\rho A U^3 \qquad \text{Equation 1}$$

Where:
- P is power [W]
- ρ is air density [kg/m^3]
- A is swept rotor disc area [m^2]
- U is wind speed [m/s]

For standard conditions (sea level and 15 °C) the air density is 1225 kg/m^3. From the equation one can see that the power is directly proportional to the air density and rotor area but proportional through the cube for wind speed. This reveals that wind speed is of high importance to maximise power generation.

However, a wind turbine cannot extract all energy contained in the wind. If all energy where to be extracted the wind downstream of the turbine would become stationary, hence no air would flow through the rotor and it would stop. Therefore wind has to keep flowing through the rotor and only a part of the energy can be recovered. There is a theoretical limit called the Betz limit defining the maximum achievable power coefficient, $C_{p,}$ as seen in Equation 2:

$$C_{p,Betz} = \frac{16}{27} = 0.593 \qquad \text{Equation 2}$$

The power coefficient in general for a wind turbine is expressed by Equation 3:

$$C_p = \frac{Rotor\ power}{Power\ in\ the\ wind}$$ Equation 3

Mechanical and electrical efficiencies of an actual wind turbine further limit the amount of power that can be extracted. The NREL 6 MW reference turbine used in the Hexicon concept has a maximum C_p of 0.47.

2.6.2 Wind data

Since wind resources have the greatest impact on the power production it is of great important to thoroughly investigate the wind potential of a planned site. This is normally done through wind data collection during at least a year and the result represented in a histogram displaying the accumulated time in a year where the wind was at each given speed. An example of such histogram is shown in Figure 2.4.

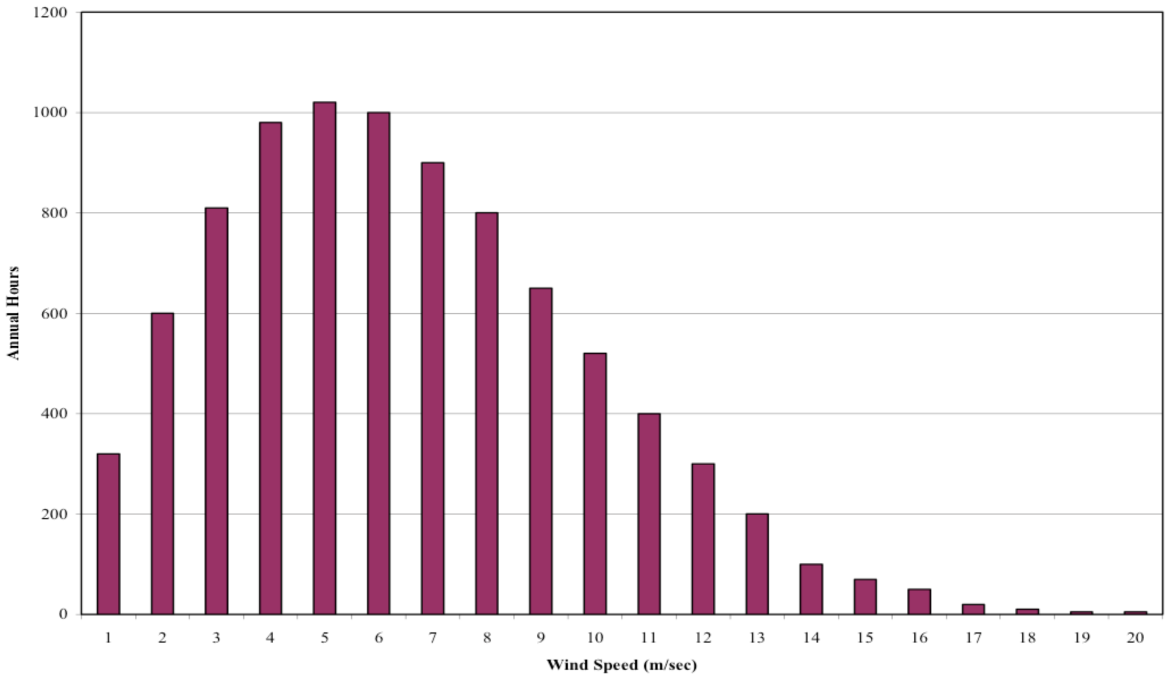

Figure 2.4 Generic histogram of annual wind speed distribution. [56]

2.6.3 Wind data manipulation

The wind data is usually collected at a height than that of a wind turbine. Wind quality and speed increases with the height over ground. To extrapolate the expected wind speeds at turbine height two mathematical methods are generally used to model the vertical wind profile over regions of homogenous, flat terrain: the log law and the power law. Both methods provide the same uncertainty due to the complexity of turbulent airflows but the power law is used by many wind energy researchers.[58] It will also be used in this study, see Equation 4.

$$\frac{U(z)}{U(z_r)} = (\frac{z}{z_r})^{\alpha}$$ Equation 4

Where: U(z) – wind speed at wanted height [m/s]
$U(z_r)$ – wind speed at reference height [m/s]
z – extrapolated height [m]
z_r – reference height [m]
α – power law exponent

If wind speed values for two heights are available the power law exponent can be calculated from Equation 4. However if only wind data on one height is available it the exponent has to be derived or estimated. The power law exponent can be derived in different ways, however researches find that these are too complicated and reduce the simplicity and applicability of the power law and recommend wind researchers to use empirical based methods to determine the exponent. In this study the method by Couniham will be used.[58] The exponent is based on surface roughness and is expressed by Equation 5:

$$\alpha = 0.096\, log_{10}\, z_0 + 0.016(log_{10} z_0)^2 + 0.24 \qquad \text{Equation 5}$$

Where z_0 represents the surface roughness, which for blown sea is empirically determined to be 0.5 mm.

2.6.4 Wind power generation

The power in the wind is proportional to the cube of the wind speed resulting in an exponential increase of power with increasing wind speed. However, the electrical power produced by a specific turbine is defined by its specific power curve. A typical power curve is shown in Figure 2.5.

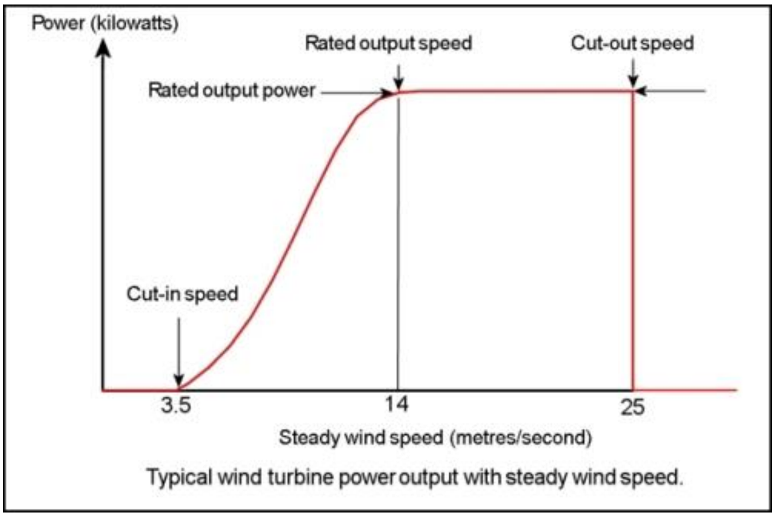

Figure 2.5 Typical power curve for a wind turbine. [57]

There are three main points along the curve: the cut-in speed, cut-out speed and rated power. At cut-in speed there is enough torque in the wind to move the turbine rotor. The power increases exponentially until reaching a nominal wind speed for which the rated power is generated and no further power is generated with wind speeds above nominal. At cut out speed the turbine stops its operation for safety reasons. To maximise energy production it is desirable to locate the turbine at a site where wind speeds are at or above nominal conditions.[58]

With the data on power for each specific wind speed and the wind data the annual production can be determined through Equation 6.

$$P_{annual} = \sum_{U=ci}^{U=co} (P_U \times H_U) \qquad \text{Equation 6}$$

The equation gives the annual power generated by a specific wind turbine. It is the sum of the product of the power (P_U) for each specific wind speed between the cut-in speed (*ci*) and cut-out speed (*co*) and the number of hours the wind speed is observed (H_U).[58]

3 Methodology

This study was divided into two stages and different methods were used to suit the different approaches in the two stages. The methodology specifically used in the two different stages will be presented further on. However, the general information gathering methods that were used in both stages are presented here.

3.1 Explorative stage

The initial, explorative stage aim was to explore many possible options for combination concepts. Hence, the methods used in this phase were of an explorative nature. The potential concepts were to be suggested and selected together with Hexicon using an idea generation and screening workshop and through discussion with representatives from Hexicon.

3.1.1 Idea generation and screening workshop

An idea-generating workshop was used to generate ideas for potential functionalities to add to the Hexicon platform. Participants were employees with different roles at Hexicon. They were chosen as participants due to the expertise and knowledge in the field of floating offshore wind. Some employees had previously worked, or still did, with cooperation's with other markets or technologies. Skills were ranging from marketing, engineering and financial competence to get a cognitive diversity to achieve a broad idea generation process.[59]

The workshop was based on traditional form of brainstorming first introduced in the book *Applied Imagination* by Osborn.[60] The method was chosen as it is a well-proven method for gathering ideas and come up with new concepts.[61]

There are many different kinds of variations and structures of brainstorming. The chosen approach, is based on the guidelines presented and used by MIT[62] and in a management guideline book written by Bhagwati[61]. There are however studies that contradicts the effectiveness of idea generation in groups and instead point to the advantage of individual idea generation.[59] Therefore the workshop was combined with individual idea generation. The individual idea generation was aimed to produce a broad spectrum of ideas that would further be discussed in a group setting. Three criteria were presented for guidance and limitation for the participants:

- The original functionality of the platform should be preserved
- The added functionality should utilise the unique features of the platform, such as the rotation, the structure design, the energy production, the offshore location, etc
- The added functionality should include additional revenues or new financing opportunities

3.1.2 Literature studies

KTH libraries search tool Primo was the main source for finding relevant books, articles, journal articles, dissertations, reports, etc. Also Google Scholar was used for similar material although most articles were accessed through KTH Primo. The sources were obtained both online as well as in printed form.

3.1.3 Other sources

Some empirical data was obtained from scientific radio programs and other online media content.

3.1.4 Semi-structured interviews

Instead of gathering and presenting quantitative data a qualitative method was chosen to get a deeper understanding of each concepts related area. This was wanted because of the importance of capturing each respondents' experience, knowledge and opinions of the related area. [63] Hence we conducted a qualitative study with semi-structured open interviews consisting of question and topics tailored to each respondent. However, the interview questions had common topics which was necessary to be addressed for each concept.

Moreover, since the gathering of information also were meant to help develop feasible concepts that could be evaluated, semi structured interviews were well suited since it facilitates the interviewee's thoughts and ideas while still maintaining the overall control while remaining open to the end goal of an interview. [64] If an unstructured approach instead would have been used, it is unlikely that the same outcome would have been reached. Structured interviews on the other hand would have limited the exploration of new ideas surfaced during the interviews, since we prior to the interview did not know in detail what information that was relevant to acquire. The material from the interviews was used to complement other sources, but also as verification of previously acquired information.

Respondents were chosen based on their experience within the field of interest. The semi-structured interviews were also used as an opportunity for guidance in the concept development. The interviews were performed in person except for one, which was performed via video conference. In addition to these interviews, many unstructured direct contacts and information gathering was performed with a number of different people and companies.

The respondents for each specific field are presented in table 3.1 below:

Table 3.1 The interview respondents

	Respondent	**Occupation**	**Motivation**
Photovoltaics	(1) Uwe Zimmermann	Senior lecturer at Department of Engineering Sciences; Solid State Electronics. Uppsala University	Has been researching photovoltaics for many years and has written a number of reports on the topic.
Aquaculture	(2) David Kristiansen, & (3) Kevin Frank	Research leader and researcher at SINTEF Fisheries and Aquaculture research institute, Trondheim	SINTEF research institute possesses an extensive competence within offshore related practices and aquaculture engineering.
Aquaculture	(4) Peter Vilhelm Skov	Associate Professor at Danish Technical University.	Researcher within the field of aquaculture at the National Institute for Aquatic Resources, Denmark.
Wave energy	(5) Rahm, Magnus	Currently Project manager at Hexicon, Previously Senior lecturer at Department of Engineering Sciences; Division of Electricity	Has been researching different kinds of wave energy technologies for over ten years and has also good insight to PV due to the broad electrical competence.

3.1.5 Information triangulation

Information triangulation was used during information gathering. It is a well-established method to try to control the reliability of information obtained, through the use of different methods and sources to verify each other.[64]

3.3 Evaluation stage

The evaluation stage aimed to create concepts based on the information gathered in the exploration stage and evaluate the concepts to create an initial understanding of the potential of the concepts. Three case studies were carried out using the floating wind energy platform under development by Hexicon as a base for the combination concepts. The evaluation was based on both quantitative and qualitative factors. It is important to understand that this is an exploratory pre-study aiming to initially investigate potential of adding other functionalities to the Hexicon platform. Hence, the methodology used and the results presented aim to give an overview perspective by analysing many aspects, both quantitative and qualitative, limiting the details of each aspect.

3.3.2 Concept creation

To be able to analyse and evaluate the combination concepts, one scenario was created for each of the three combination concepts. They were created based on a basic understanding of the added technology gained through literature studies and interviews with field experts.

Each scenario included a concept where the Hexicon platform is combined with an added functionality placed in a setting that was based on specific factors for each concept. The choice of location was also based on the availability of information relevant to the evaluation, such as the energy environment, such as wind, waves, currents and irradiation for energy extraction but also the forces working on the structure.

3.3.3 Concept evaluation

The evaluation model was based on a study on evaluation factors for R&D projects that was presented in section 2.2 *Adding qualitative aspects to the evaluation.* The economic measurements were based on factors proposed in the protocol for assessments of marine energy projects described in section 2.1 *Assessment of offshore projects*. The factors for used for evaluation in this study are presented below.

Economic return

For the estimations of economic return a spread sheet model used by Hexicon was used. This way all standard estimations for a project made by Hexicon were included and only parameters like the wind data for each specific location, CAPEX and OPEX values for the added functionalities were altered.

For energy generating concepts, the additional energy output was added to the annual production output. For concepts not generating additional energy it was assumed that it generated additional revenue. This additional revenue was added to the existing revenues in the model.

Levelised cost of energy (LCOE)

LCOE can be calculated in two ways, either the annuity method or the discounting method, where the latter is the more commonly used and also adopted in this evaluation. The discount rate is usually chosen between 5-10% and the project lifetime around 20-30 years. The equation consists of the sum of all discounted costs related to the entire system over the chosen lifespan, divided by the full amount of generated electricity, see Equation 7.[35] Related costs are such as construction, financing, possibly fuel cost, tax, insurance, Operations and Maintenance (O&M). In the denominator the sum of the electricity is determined by the energy source capacity factor; the percentage of generating ability seen over one year. [35 37]

$$LCOE = \frac{\boldsymbol{\Sigma}\mathbf{t}((\mathrm{CAPEX} + \mathrm{OPEX}) * (1 + \mathrm{r}))^{-\mathbf{t}})}{\boldsymbol{\Sigma}\mathbf{t}(\mathrm{Electtricity}\mathbf{t} * (1 + \mathrm{r}))^{-\mathbf{t}})} \qquad \text{Equation 7}$$

Where: LCOE – The cost of producing energy [EUR]
Electricity**t** - Total amount of electricity produced in year "**t**" [MWh]
(1+r)^-t - The discount factor for year "**t**" [%] with discount rate "**r**".

The Hexicon model was used for the LCOE-calculations. To estimate economic return for a concept only generating additional revenues, profit before tax was subtracted from the annual operative costs in the spread sheet resulting in a modified LCOE-value. It is emphasised that it is a modified value of LCOE that is produced, but it could provide a fair estimate how the addition would affect the cost of energy.

Internal Rate of Return (IRR)

The potential yield of each concept was measured with the Internal Rate of Return (IRR). IRR is the interest rate that makes the Net Present Value (NPV) zero. This means that the expenditures and earnings are levelled out over the project lifetime, taking into consideration the present value of future expenditures and earnings. It is typically done by trial and error, substituting higher and higher interest rate in the equation (see Equation 8) until the NPV is zero.[6]

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = 0 \qquad \text{Equation 8}$$

Where n is the period, C_n the cash flow for each period and N total number of periods, r is the interest rate, or return for each period.

It is commonly used to compare projects to invest in. If all other aspects are equal, a project with higher IRR would be considered a better investment. When comparing different investment alternatives, the IRR should be higher than a possible interest rate from another form of investment, maybe the interest rate a bank provides. Internal rate of return will be calculated for each concept. This will be based on the scenario that is chosen for each concept.

Sensitivity analysis

A sensitivity analysis is a method for showing how different variables affect the outcome, for instance commonly used for different financial models.[65] For the three concept cases, the CAPEX and OPEX are based on varying degree of uncertainty. To reflect the effect of this data, a sensitivity analysis has been done for the estimation of economic return. The CAPEX and OPEX were set to 10% more to represent a higher cost scenario and to 10% less as a lower cost scenario. The production in each case was not altered since those calculations were based on weather data that were considered to be relatively reliable, at least in comparison to the cost estimates.

Technological factors

To create a brief evaluation of the impact of the added integrated functionalities, a few factors that were considered of importance from a technical perspective have been analysed. This constituted a brief feasibility study from a technical perspective. These factors have been identified, in consultation with Hexicon engineers and the field experts for each concept, as the most important ones to consider as part of a basic research stage. Other factors would be interesting to analyse at a later stage but are outside the scope of this study.

Added loads on platform

As part of the evaluation of how the platform would be affected by an added functionality, additional loads on the platform were estimated. This might result in a need for redesigning of the mooring system, or other structural elements of the Hexicon platform. Depending on the type of functionality that is added and what kind of forces that can be expected to arise, specific calculations will be carried out in each case.

Additional weight

Additional structures on the platform will add weight to the structure and therefore increase the need for buoyancy. Unless the additional structure is partly submerged and self-buoyant the displacement of the structure has to be increased. Increased displacement would normally be created by increased volume of the nodes in the platform and therefore increase the material costs. The need for additional volume is determined by the simple relation that 1 000 kg added mass requires 1 m^3 of extra displacement volume.

Interference with existing structure and mooring system

The added functionality may interfere with the existing platform. This could be in a physical way with structural elements colliding or other systems that could interfere.

Impact from the offshore environment on the added functionalities

An evaluation of how well suited to an offshore environment a potential add-on is was carried out. This evaluation was be based on available information on the subject.

TRL

An attempt to determine the TRL of each of the added functionalities was made. To do this, the definitions presented in the previous chapter *Frame of reference* and in Appendix A were used.

Market potential

Estimation of market potential is very important for evaluating the future success of a concept and to be able to present appealing numbers for potential investors. Since this study was looking into concepts with different functionalities, the markets were unique for each one of the concepts with varying value offerings, features and customers. When investigating the merging of different technologies or businesses one must consider if the added technology or business would open up new interesting markets or market segments, or if it actually may decrease the ability to attract potential investors by confusing market strategies. A brief assessment of the market for a potential added functionality were performed. This assessment focused on a global market to show the bigger potential of the concept. The authors used screening questions to structure the discussion, as proposed by Schilling.[13] The screening questions are presented below.

-How big is the market?

-Who is the most likely investor of the new product?

Other strategic factors

These other factors were evaluated using a subjective approach. For each concept a discussion was made regarding the factors discussed in the *Frame of reference* and presented here. Also here screening questions were used, with the focus of the combination and the added technology function, leaving less focus on turbines.

Business strategy and innovation strategy

- How well does the potential concept align with the Hexicon business strategy?

Timing of entry

- Is the firm likely to be first to market? Is that a desirable strategy?

- Is the market ready for the product; are enabling and complementary technologies well developed?

Consenting processes

- Will the added functionality result in additional requirements on environmental assessments, which could make the overall consenting process more difficult?

4 Results from explorative stage

4.1 Idea generation, screening and choosing of concept

The workshop generated a wide range of ideas for functionalities to add. It started with an individual idea generating process. Ideas where then shared openly on a white board and further discussed, which also led to the generation of some new ideas. This process generated a total of 36 unique ideas.

The later part of the workshop contained an evaluation and screening process, which aimed to narrow down the alternatives to the final three ones. As screening method each workshop participant had to divide a total of six points each to the ideas they considered having most potential based on these three criteria which was presented to them:

- The technical feasibility of the combination
- The economic feasibility of the combination
- The market potential of the combination

The ideas that got more than one point, were further openly discussed and jointly marked with green for being very interesting and red for being less interesting, see Table 4.1.

Table 4.1 Screening process results from workshop

Added functionality/concept	**Points**	**Colour grade**
Wave energy	8	Green
O&M service station for wind farms	6	Green
Photovoltaics	3	Green
Tidal energy	3	Green
Aquaculture	7	Green
Desalination or water purification	5	Green
Pressure-based energy storage	4	Red
Battery-based energy storage	3	Red
Pressurization of oil wells	2	Red
Platform for oxygen generation for waters with limited circulation, i.e. the Baltic Sea.	2	Red

Lastly a finalising discussion was carried out with the green marked alternatives, which lead to the final three concepts. The concepts that were chosen were:

- Photovoltaics
- Wave energy
- Offshore Aquaculture

The basis for the final choosing of the three concepts can be concluded with the following key point of each of the green marked ideas:

Photovoltaics
Mature technology that has large potential and could be a relatively easy integration. Has the potential of making the platform a less intermittent energy source.

Desalination or water purification
There is an increased demand for desalination plants and it could potentially be a good fit. However an on-going project at Hexicon concerning this combination made it less interesting since there was a desire to focus on new unexplored areas.

Wave energy
Has a large potential and it was found feasible to identify a suitable technology to integrate in the structure in a not too complicated way. Moreover, it has the potential of making the platform a less intermittent energy source.

Tidal energy
Same advantages as for wave energy, but complications with finding a suitable technology to integrate with the platform was addressed. As well as the likelihood of increased demands on the mooring system if the platform was to be located at places with the needed strong currents, which could further complicate such a concept.

Aquaculture
The offshore aquaculture concept scored high due to the interest of looking at other possibilities than merely energy generating additions, thus be used as a reference concept that could illustrate how a non energy generating addition could affect a multiuse platform.

O&M service station for wind farms
Was found to be a practical option and potentially much needed concept, but was in comparison to the other alternatives found to be less interesting. One major drawback with an integration of a manned service station is that it increases the requirements on the platform due to health and safety aspects.

5 CONCEPT BACKGROUND STUDIES

The selection of three functionalities to integrate in three different concepts was followed by background studies of each technology. It is presented in this chapter. The background studies followed a similar model, but the level of detail in the information varied due to availability.

5.1 Photovoltaics

Photovoltaics (PV) has long been used to convert solar power to electricity in areas or environment unable to access grid connection. As early as 1839 Alexandre-Edmond Becquerel discovered the photovoltaic effect, but it was not until 1958 as the first silicon solar cell was invented.[66] Since the turn of the century the most common use has shifted to grid connected PV-systems, which now dominate the market. Other common application areas are lighthouses, radio stations, space applications, boats, outdoors equipment, etc. Since the 1970 there has been a growing market for smaller PV systems outside the grid. Grid connected PV are often installed on house roofs or in big fields on mounting structures.[67] The currently biggest PV power station in operation is Desert Sunlight Solar Farm found in Riverside County, California, USA, and has a capacity of generating 550 MW from a total of 8 million panels.[68]

The absence of moving parts during the energy generation means little wear and maintenance and a long lifespan. This also result in zero emission as well as any noise during operation. They can be designed very compact or scalable to enormous proportions just by adding them up. To protect the solar cells from getting damaged by weather and wind they are encapsulate in a protective modules, e.g. laminated between two glass sheets.[69]

5.1.1 Market

In 2013 the world reached more than 130 GW of worldwide cumulative installed PV capacity, as seen in Figure 5.1.[70] Although the total installation is still only in the scale of about 3-4 nuclear power plants. This is related to the still relatively high manufacturing costs, but production improvements and research are continuously pushing the prices down.[71] Every time the production volume has doubled, the price has dropped with approximately 20%.[72]

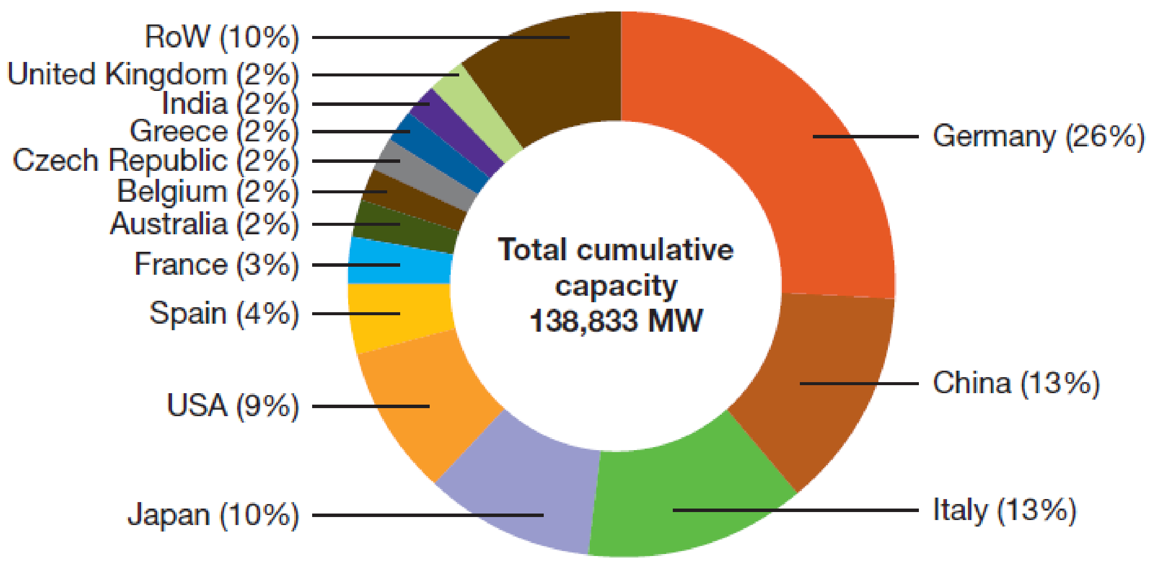

Figure 5.1 The total worldwide cumulative PV capacity, where RoW stands for Rest of the world (Middle East and Africa).[79]

Besides costs for solar panels there are Balance Of System cost (BOS) which is comprised of the additional costs related to a PV installation setup, usually ranging from 20% (simpler grid-connected setup) up 70% (complex off-grid setup) of the total cost. Included in BOS are usually all other components needed, for instance: [73]

- Inverter (sometime not included in the BOS cost)
- Transformer
- Mounting components
- Combiner box and various necessary components
- Installation and site preparations
- Management, design of system, installer overhead, fees for permits and up-front financing expenses
- Battery packs/battery charger if needed

The Solar energy market has a growth rate of approximately 40-50% yearly and is today the fastest globally growing energy source. However, in Europe the market has stagnated some lately due to the earlier very generous subsidies and tariffs system that has been reduced significantly. Subsidies have, and still do, play a major role in market growth as PV in many countries still is a more expensive source of electricity in relation to conventional energy sources. Although lately the prices on PV have dropped significantly due to scaled and more efficient production but also subsidized production in china. This has resulted in grid parity on a number of places. [74]

Worldwide the market has continuously increased as a result of a global, as well as local needs. Rapidly growing top markets are mainly China, South-East Asia, followed by Latin America, the MENA-countries and India. Moreover. There is a big potential for the sun-belt region (66 countries based within 35° of the Equator[75]) which according to market estimations prospects a range from 60 to 250 GW installed cumulative capacity for 2020 and 260 to 1100 GW for 2030. There are still many markets that have not embraced solar power as an energy source yet, meaning there is a untapped potential.[70] One study pointed to solar power being the least expensive energy source for many countries in the coming future (scenario analysis with a timespan reaching to 2050).[73]

Looking at a global average LCOE scale, the cost for PV generated electrify has decreased by half over a four-year period.[76] As LCOE calculations are directly related to what input is chosen, as discount rate etc, the values can differ a lot. An LCOE prognosis reaching to 2050 can be seen in Figure 5.2.

LCOE, in EUR_{2014}ct/kWh																								
Year	2015						2025						2035						2050					
WACC	5%		7,5%		10%		5%		7,5%		10%		5%		7,5%		10%		5%		7,5%		10%	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Argentina	5,5	12,5	6,6	15,1	7,8	17,9	4,1	10,0	4,9	12,1	5,7	14,3	3,0	8,6	3,5	10,4	4,1	12,4	1,9	6,9	2,2	8,5	2,6	10,2
Australia	4,6	8,9	5,5	10,8	6,5	12,8	3,4	7,1	4,1	8,6	4,8	10,2	2,5	6,1	3,0	7,4	3,5	8,9	1,6	4,9	1,9	6,1	2,2	7,3
Brazil	4,7	8,2	5,7	9,8	6,7	11,7	3,5	6,5	4,2	7,9	4,9	9,3	2,6	5,6	3,0	6,8	3,6	8,1	1,6	4,5	1,9	5,5	2,3	6,7
Canada	5,8	10,4	7,0	12,6	8,3	14,9	4,3	8,3	5,2	10,0	6,1	11,9	3,2	7,2	3,8	8,7	4,4	10,3	2,0	5,8	2,4	7,1	2,8	8,5
China	4,8	8,2	5,8	9,8	6,9	11,7	3,6	6,5	4,3	7,9	5,1	9,3	2,6	5,6	3,1	6,8	3,7	8,1	1,7	4,5	2,0	5,5	2,3	6,7
France	5,5	9,4	6,6	11,3	7,8	13,4	4,1	7,5	4,9	9,0	5,7	10,7	3,0	6,4	3,5	7,8	4,1	9,3	1,9	5,2	2,2	6,4	2,6	7,7
India	4,6	6,7	5,5	8,1	6,5	9,6	3,4	5,4	4,1	6,5	4,8	7,7	2,5	4,6	3,0	5,6	3,5	6,6	1,6	3,7	1,9	4,5	2,2	5,5
Korea, South	6,3	7,2	7,5	8,7	8,9	10,3	4,7	5,8	5,6	7,0	6,6	8,3	3,4	5,0	4,1	6,0	4,8	7,1	2,2	4,0	2,6	4,9	3,0	5,9
Morocco	4,6	6,3	5,5	7,5	6,5	9,0	3,4	5,0	4,1	6,0	4,8	7,2	2,5	4,3	3,0	5,2	3,5	6,2	1,6	3,5	1,9	4,2	2,2	5,1
Russia	5,5	11,0	6,6	13,3	7,8	15,8	4,1	8,8	4,9	10,6	5,7	12,6	3,0	7,6	3,5	9,2	4,1	10,9	1,9	6,1	2,2	7,5	2,6	9,0
Saudi Arabia	4,5	6,1	5,4	7,3	6,3	8,7	3,3	4,8	4,0	5,8	4,7	6,9	2,4	4,2	2,9	5,0	3,4	6,0	1,5	3,3	1,8	4,1	2,1	4,9
South Africa	6,5	9,4	7,8	11,3	9,3	13,4	4,8	7,5	5,8	9,0	6,8	10,7	3,5	6,4	4,2	7,8	4,9	9,3	2,3	5,2	2,7	6,4	3,1	7,7
Spain	4,5	6,9	5,4	8,4	6,3	9,9	3,3	5,6	4,0	6,7	4,7	7,9	2,4	4,8	2,9	5,8	3,4	6,9	1,5	3,8	1,8	4,7	2,1	5,7
Thailand	5,3	6,9	6,4	8,4	7,5	9,9	3,9	5,6	4,7	6,7	5,5	7,9	2,9	4,8	3,4	5,8	4,0	6,9	1,8	3,8	2,2	4,7	2,5	5,7
Turkey	4,8	6,9	5,8	8,4	6,9	9,9	3,6	5,6	4,3	6,7	5,1	7,9	2,6	4,8	3,1	5,8	3,7	6,9	1,7	3,8	2,0	4,7	2,3	5,7
Uganda	4,8	6,5	5,8	7,8	6,9	9,3	3,6	5,2	4,3	6,2	5,1	7,4	2,6	4,4	3,1	5,4	3,7	6,4	1,7	3,6	2,0	4,4	2,3	5,3
United Kingdom	7,4	11,7	8,9	14,1	10,5	16,8	5,5	9,4	6,5	11,3	7,7	13,4	4,0	8,1	4,8	9,8	5,6	11,6	2,6	6,5	3,0	8,0	3,5	9,6
United States	4,3	6,9	5,2	8,4	6,2	9,9	3,2	5,6	3,9	6,7	4,5	7,9	2,4	4,8	2,8	5,8	3,3	6,9	1,5	3,8	1,8	4,7	2,1	5,7

Figure 5.2 Projections of LCOE values for large scale solar for different countries and discount rates (WACC). [73]

5.1.2 Technology

Photovoltaics uses a technology that transforms light to electricity without any mechanical moving parts. The first generation PV is still the most common type and uses crystalline silicon semiconducting material. It uses a pn-junction to transform solar power to energy, which is an interface for connecting two semiconducting materials with each other. The solar cell works like a semiconductor diode and consists of a thin plate of semiconducting materials with an electrical contact on each side. The contact on the topside, the one facing the sun, is designed so the light can penetrate into the semiconducting material and an electrical voltage (approximately 0,5 V per cell) occurs between the layers, which can be utilized through an external circuit to get a current flowing. As long as the sun keeps shining the current will keep flowing, and when it stops the charge evens out between the two layers. When connecting a solar panel to the grid there is need for an inverter, which can transform direct current to alternating current.[78] [77]

Second generation PV is called thin film solar cells. It is much thinner than conventional silicon solar cells, but the basic light absorbing principle is the same. There are three major thin-film technologies: thin film silicon (TFSI), cadmium-telluride (CdTe) and copper, indium, gallium and selenide (CIGS).[78] The thin film solar cells are made out of a few millimetres thin film on a glass- or steel surface with the light-absorbing layer consisting of the active elements.[79] The thin film layers usually range from tens of micrometres down to just a few nanometres, in comparison to conventional silicon based PV, which usually has a thickness of up to 200 micrometres.[80] Naturally it means they thin film solar cells carry less weight, but also that they can be manufactured and designed in a flexible way enabling more variations in the mounting procedure.[81]

Third generation PV uses nanostructured solar cells, also called Grätzelcells, are still in research stage. It is based upon advanced chemistry and copies the basic principles of the photosynthesis found in green plants. Solar energy is absorbed by a dye and a charge transport is then taking place through a titanium dioxide membrane, which generates energy that could be transformed to electricity, the present world record reached an efficiency rate at 11%. The plans for mass commercialisation are very real and lucrative as they have great potential in becoming very cost effective. However there is still much development to be done before fully reaching this stage.[82] The efficiency ratio between the generated electrical energy and the incoming solar energy is determined by the properties of the semiconductor material. Typically the efficiency ratio is ranging from approximately 7-8% up to 17-18% for different commercially used techniques.[67]

Solar panels specific peak power or nominal power [kWp] is measured under Standard Test Conditions (STC), with a solar irradiation value of 1 000 W/m^2, spectrum AM 1,5 and at a cell temperature of 25 °C. This means it is not the actual theoretical limit of how much electricity a specific solar panel can generate, but only the given output for the STC specified conditions.[83]

5.1.3 Solar Energy

Solar irradiance
Solar irradiance is a measurement used for quantifying the amount of electromagnetic radiation (sunlight) which a specific surface area is exposed to, see Equation 9.

$$G_T = \frac{\partial \Phi e}{\partial A} \qquad \text{Equation 9}$$

Where: G_T - Solar irradiance [W/ m^2]
Φe - Radiant flux [W]
A - Exposed area [m^2]

Power output
The actual power output [W] that can be obtained from solar panels is determined by Equation 10.

$$ActualP_{out} = G_T * p * A * \eta * L_M \qquad \text{Equation 10}$$

Where: $ActualP_{out}$ – Power output [W]
p - Packing ratio of solar cells for total surface area of panels [%]
G_T - Incoming solar radiation [W/ m^2]
A - Total surface area of panels for the installation [m^2]
n - Efficiency rate of the solar cells [%]
L_M - The different losses obtained in the whole system [%]

The total peak power/Nominal effect for whole PV-system is calculated with equation 11.

$$R = \dot{R} * y \qquad \text{Equation 11}$$

Where: R - Total amount of installed capacity [kWp]
$\dot{R}$- Specified peak power/Nominal effect for the solar panel [kWp]
y - Amount of panels installed

Capacity factor

A commonly used metric for calculating the effective utilization rate is the capacity factor, CF, see Equation 12. It tells the ratio of the electricity which has been produced during a given timespan, in this case one year in relationship to the installed nominal effect with a 100% utilization rate over the same time period. [84]

$$CF = \frac{ActualP_{out}}{NominalP_{out}} = \frac{G_T * p * A * \eta * L_M}{R * 8760} \qquad \text{Equation 12}$$

Where: CF – Ratio of actual power output and the installed nominal effect [%]

5.1.4 Technical considerations

Solar irradiance is the number one factor affecting the solar cell's instantaneous power output, which in turn are dependent on number of factors such as position of the sun, shading, clouds and pollution.[92] The angle of incidence of the solar beams hitting the panel has a direct correlation to the instantaneous power output. A flat mounted panel loses approximately 18% efficiency compared to a panel that angles itself towards the sun.[85] In Figure 5.3 the average annual irradiation for Europe between 2004-2010 be seen.

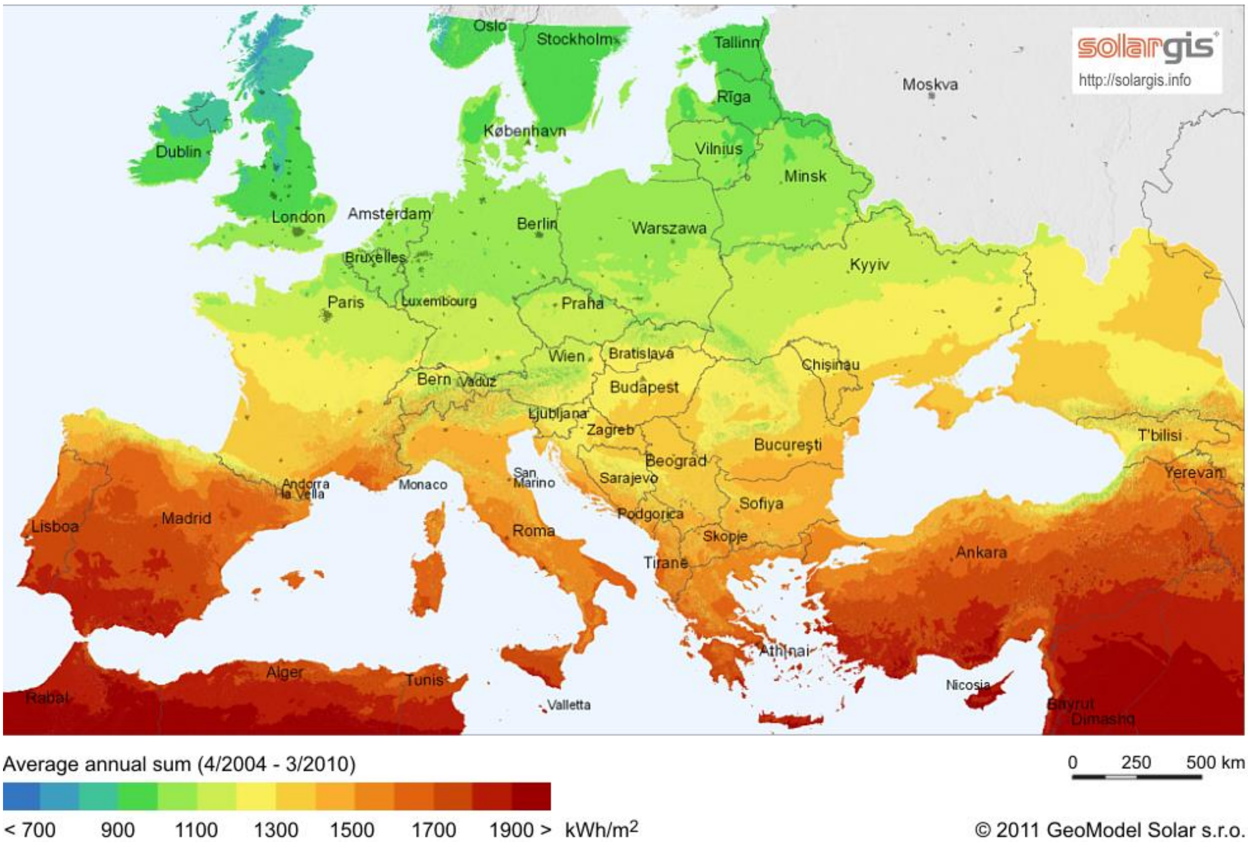

Figure 5.3 Global solar irradiation between 2001-2010.[86]

When parts of a solar panel are covered by shadow, the power output reduces. But the negative effect is greater than just the solar cells that are shaded since they are connected in series. For one panel where only 1 out of 36 solar cells are totally covered, the efficiency loss is approximately 80%. However now days, most of the panels are adapted to partially prevent this phenomenon by integrating bypass diodes in the panel to enable the current to pass through cells if an area is shadowed.[87]

Temperature also has a great impact on the power output as photovoltaics works better in lower temperatures. Overheating solar cells due to high ambient temperatures and solar radiation results in a decreased efficiency.[88] The power reduction output can be as much as 10-20% for a 40 °C temperature difference which is not that uncommon for certain areas. [88] However, the sun is usually positioned low at locations with lower temperatures, resulting in a less irradiation. Consequently, generally less electricity is generated a sunny day in the winter compared to a sunny day in the summer.[78] Also, in a marine environment with solar panels very exposed to cooling winds and good ventilation could result in a few percent efficiency difference.[92] However, when this matter was discussed with an associated Professor with a Ph.D. in thermodynamics, he did not think this would have a too big impact. There are currently on-going research investigating this phenomena.[89]

Unprotected solar cells are affected by environmental factors such as temperature, moisture, illumination and are therefore encapsulated to make sure it has a great longevity. Usually panels have a guaranteed lifespan of around 20 years, ensured by a specific certification protocols. But even when properly encapsulated the environmental factors results in an overtime decreasing efficiency rate, contamination and particles preventing the sunbeams from reaching the solar cells. When cover glass are exposed to a harsh marine environment it could easier results in corrosion, wear, deterioration and contamination. Two Hong Kong based smaller studies both confirmed this. The first was performed using special toughened glass for solar cell panels to research the optical transmittance dependency in a simulated marine environment. By submerging the cover glass in varying degree of tap water mixed with artificially prepared seawater, they concluded that the spectral transmittance of the cover glass decreased and was directly related to the submerging time and/or the concentration of seawater. The second study exposed actual solar panels to simulated marine environments similar the first study; submerging panels in different salt solutions and compared to the same type of panels that were not submerged. The conclusion was that during the same solar radiation intensity, marine solar cell cover glass transmittance is lower than the transmittance for same type but stationed on land, which resulted in a lower power output as seen in Figure 5.4.[90 91]

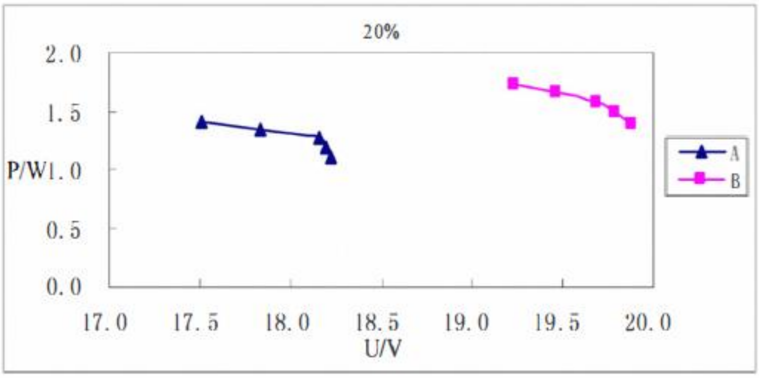

Figure 5.4 Characteristics curves for the output curves of panel A (the surface of its cover glass immersed in a 20% salt solution) and B.[91]

However, another study investigated variations between different types of panels and how they were affected by factors considered to reduce the power output; temperature coefficients, shadowing, pollen and snow. This was however not done in a marine environment. The result only showed very small differences between different types of solar cells. [83] Moreover, there is probably an increased positive self-cleaning effect of the solar panels with water and wind washing the panels when more weather exposed in an offshore environment.[92]

5.1.5 Proof of concept

There are positive synergy effects from a wind/solar system with sun shining when there is no wind and the other way around, making the generating capacity of the whole system less intermittent. A study performed in Hong Kong examined the complementing characteristics of PV in combination with wind power. The results concluded that solar and wind generating units have the ability to complement each other in a favourable way.[93]

One techno-economic study investigated the possibilities of using floating solar panels on a platform offshore and connect it to Malta's existing electricity grid. The study was performed by doing a cost analysis based on Malta's monthly trend consumption data, capital expenditures and operating costs for a floating PV installation, cost savings from decreased use of fossil fuels and CO2 reductions. The results concluded that an overall cost reduction could successfully be accomplished if such a solution where to be implemented.[94]

5.1.6 Consent and siting

Little information is available on specific requirements for PV installations in an offshore environment. However, it was reasoned that the requirements regarding environmental impact would be less than for a wind turbine installation mainly due to much less visual impact.

5.2 Wave energy

Waves are the result of wind blowing over a sea surface for a long enough distance, called fetch. Wave rich environments contain a lot of energy and ocean energy is considered to be one of the most dense renewable energy sources dependent on location. The oil crisis in 1973 resulted in an increased interest in wave energy and development really took off in the 1980s and 1990s, now with more concepts stretching further than the theoretical stages. In 1991 the European Commission (EC) included wave energy in their R&D program for renewable energies, which really changed the situation for the European developers, and since the over 30 projects in Europe have been funded by the EC. There is also a growing interest in other countries like USA, Canada, South Korea, Australia, New Zealand, Brazil, Chile and Mexico.[95]

Having been on-going for decades, the development of wave energy devices is still considered to be in the R&D phase. That being said over 100 concepts in over 30 countries have been or are under development. Some developers have even had grid-connected devices for several years, but the sector as a whole is not considered to have any commercially available devices at present.[52]

The wave energy field can be divided into three categories: near shore, intermediate offshore and deep offshore.[52] The categorisation is based on the difference in water depth, which affects the type of mooring technique, but they also differ in how the water particles behave which could have an influence in how a wave energy converter (WEC) is designed. The deep offshore category is the one that is of most interest to add to the Hexicon platform as it shares the same type of deep-water slack mooring. Therefore, the background research will mainly focus on technologies and concepts within this category.

5.2.1 Market

The market for wave energy devices is a market under development. It is considered to have immense potential, yet developers are struggling to create commercially viable products. A major setback lately is the Pelamis project[96], which was considered to be very promising, having reached a high level of TRL, which went bankrupt[97].

However organisations like Portuguese-based WavEC drives multiple projects supporting the development of various developing concepts across Europe. They also run a shore based wave energy plant on the Azores, which delivers electricity to the grid.[98] Other projects with tested prototypes are the Scottish Aquamarine[99] and two Swedish developers; Seabased[100] and Corpower Ocean[101].

As for all energy generators, it is of interest to lower the cost of energy produced. A recent report from SI Ocean[52] finds current values of LCOE ranging between 0.33 and 0.63 EUR/kWh for a 10 MW farm. These values are significantly higher than for other renewables, including offshore wind energy and tidal energy. This is due to most concepts being in an early stage of development. However, projections show a drastic reduction in LCOE-levels with increased installed capacity as a result of deployment of commercially viable installations. Figure 5.5 shows the expected cost variation following future installed capacity.

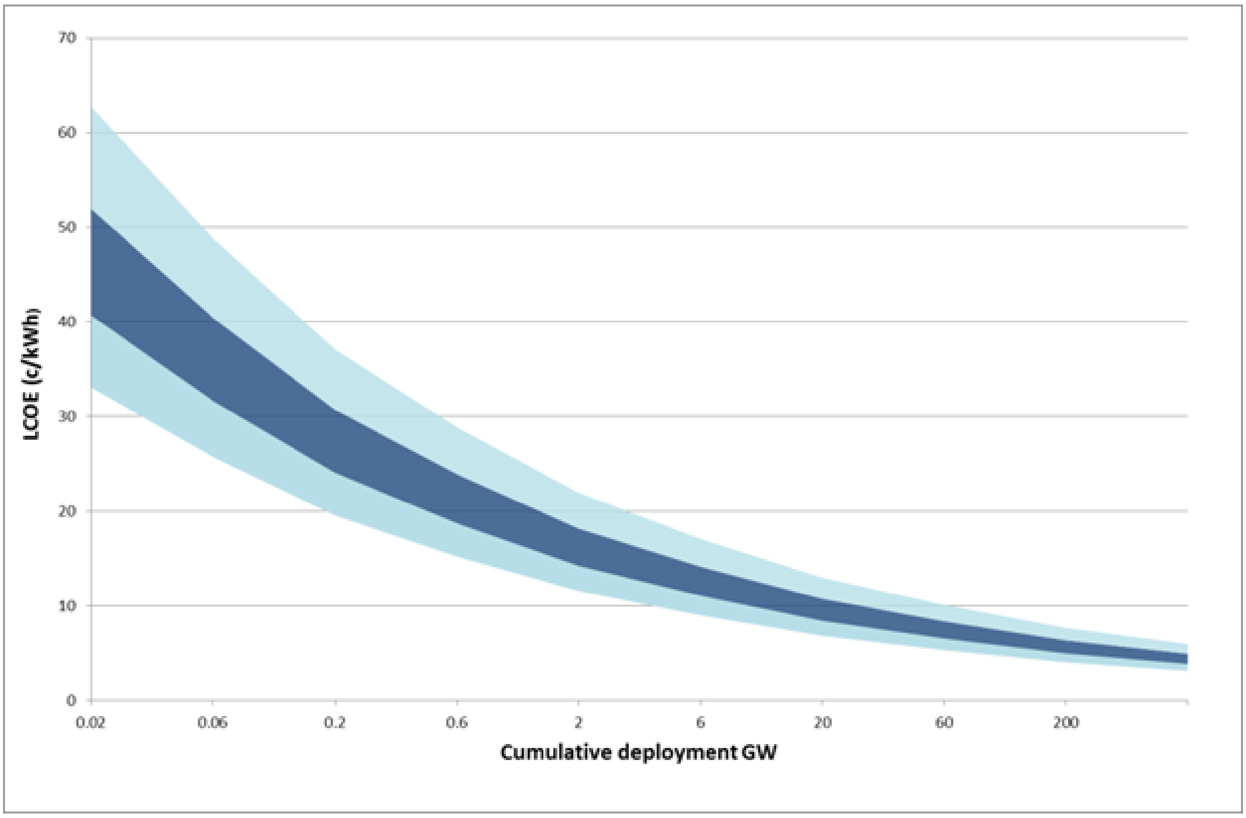

Figure 5.5 The effect of LCOE value in relation to expected future installed capacity. [52]

5.2.2 Technology

A WEC has a power take-off (PTO) system that converts the energy from the waves that are affecting the device into electricity. There are different types of PTO systems including mechanical, hydraulic or direct drive using permanent magnet generators. The most common ones can be categorised into turbines, hydraulic and linear electrical generators.

Turbines

A turbine PTO system generally uses air as a fluid being pushed through a turbine by the fluctuating water level in a chamber as a result of wave motion. One can also utilise the fluctuating hydrostatic pressure due to the fluctuating wave height over a submerged device to draw in or exhaust air from a chamber through a turbine. These systems are normally integrated in an onshore installation, where air chambers can be built on the shoreline, which enables easier O&M. But it can also be used in an offshore platform, moored to the seabed.

Hydraulic
A hydraulic PTO system requires some kind of mechanical movement that can be transferred into a stroking motion pumping high-pressure fluid through a hydraulic motor generating electricity. This movement can for example be created by a floating buoy moored to the seabed creating a vertical linear movement when the buoy is raised and lowered by the waves. A floating bridge can be mounted to an offshore construction moving up and down creating a stroking motion as well.

Linear electrical generators
A linear electrical generator requires a linear motion of two bodies in relation to each other. When a magnet (in one of the bodies) moves back and forth along an electrical coil (in the other body) an electric current is induced. This method eliminates the use of some kind of linkage to transfer the linear motion into rotational motion to drive a rotating generator.

5.2.3 Wave energy
The energy contained in waves is normally presented as power per meter wave crest width for a single wave, P_w. It is generally known as energy transport or power density. Equation 13 shows a simplified expression of energy transport based on group velocity, which is the velocity at which the energy of the wave is propagated.

$$P_w = \frac{1}{2}\rho g A^2 c_g$$ Equation 13

Where: P_w – power per meter of wave crest [W/m]
ρ – water density [kg/m^3]
g - gravitational force [m/s^2]
A – wave amplitude [m]
c_g – group velocity [m/s]

By using relationships specific for deep water, $c_g = \frac{g}{2\omega}$, $\omega^2 = gk$ and $= \frac{2\pi}{T}$, the equation can be written as Equation 14[102 103]:

$$P_w = \frac{\rho g^2}{64\pi} H_s^2 T_e$$ Equation 14

Where: H_s – significant wave height [m]
T_e – wave energy period [s]

The most commonly used method for describing the energy in a sea state is an energy spectrum, which presents the wave energy at a given location as a function of wave frequency. Since the energy in the sea state changes constantly, this is the best way to describe the energy distribution over time. Significant wave height, H_s, and wave energy period, T_e, can then be obtained through Equations 14 and 15.

$$H_s = 4\sqrt{m_0}\ ,\ H_s = \frac{m_1}{m_0}$$ Equation 14 & 15

Where m_0 is the zeroth spectral moment, $m_0 = \int_0^\infty S(\omega)\, d\omega$ and m_1 the first spectral moment, as seen in Equation 16: [103]

$$m_1 = \int_0^{\infty} \omega S(\omega) d\omega \quad \text{Equation 16}$$

To be able to evaluate the energy potential of wave power plants and also to establish design criteria a characterisation of the wave climate at the site of deployment is of importance. Today this can be achieved in many areas due to an extensive network of wave buoys used for ocean monitoring, See Figure 5.6. [52]

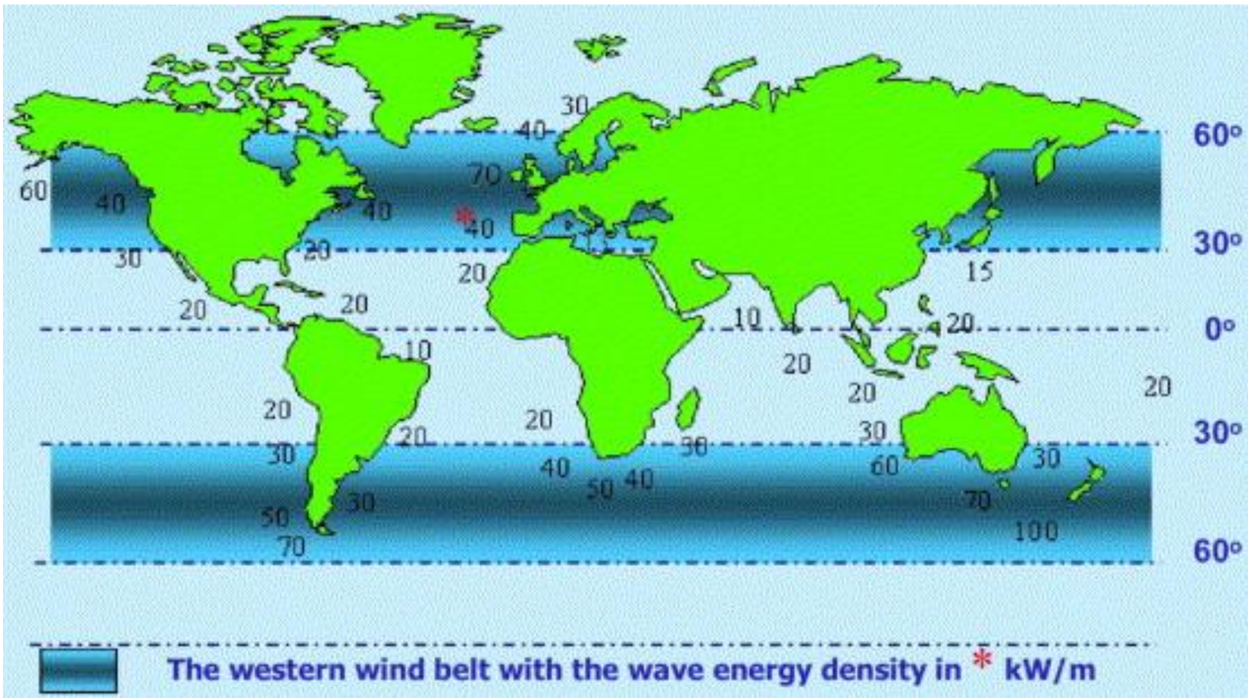

Figure 5.6 Map illustrating the power density, or energy transport, in the world's oceans. [104]

5.2.4 Technical considerations

A vital part of the development of a WEC is to design the PTO to suit the energy spectra. Since the energy contained in the waves is fluctuating so much a challenge lies in the development of the PTO system to get an optimal energy output.

Another part of that challenge is to create a WEC that is designed for optimal energy conversion in design conditions, which is in most cases a rather mellow wave environment that is also capable to withstand the extreme forces of severe storms.

Further difficulties occur in the testing phase. For a concept to prove itself it needs to be tested in real sea conditions. Since almost all systems involves some kind of resonance for optimal wave energy absorption, the size of the structure is directly linked to wavelength why the structure has to be made in large scale, close to full scale, to be tested and analysed in open sea conditions.[104]

5.2.5 Proof of concept

A few concepts where wind and wave energy is combined already exist. The W2Power by Norwegian Pelagic Power[105] is a hybrid platform designed to harvest both wind and wave energy. The platform combines two 3.6 MW wind turbines with arrays of buoys working on a water pump system elevating water thus creating potential energy. The water is then released through a singular

Pelton turbine generating energy. The platform is rated to 10 MW in total. Another concept is Danish project Floating Power Plant[106]. This concept has been under development since 1995, the current design being an 80 metres wide semi-submersible platform with a single 5 MW wind turbine mounted and a wave power take off (PTO) system consisting of floaters creating a rotational force on a hydraulic system with a rated capacity of 2.6 MW. A 1:50-scale model has been tested in combinations of wind and waves conditions in 2013 and 2014 and the company behind the project claims it is proven stable in appropriate conditions for a commercial-scale device.

5.2.6 Consent and siting

The planning and deployment of wave energy projects have similar demands as offshore wind energy projects.[107] Generally, a wave energy park affects the environment in the same way and has the same high safety standards. In the UK two types of environmental assessments are used for marine renewables, however as per today both of them are only needed for offshore wind and not wave energy[107], meaning an easier consent process for wave energy projects.

5.3 Aquaculture

Aquaculture comprises all kind of farming of fish, shellfish and other aquatic creatures. The farming takes place both on land in ponds and tanks, in lakes and in open water along coastlines. Over the past three decades the production of seafood has more than doubled, from 65 million tonnes in 1970 to 142 million tonnes in 2008, 90 million tonnes being from wild fish. These numbers are expected to grow further but there is little belief that the production from wild stocks will increase much more since many fishing areas are overfished.[108]

Since this study aims to investigate the possibilities to combine aquaculture with an offshore structure (the Hexicon platform), open water aquaculture is what is of interest. Although the majority of types of fishes farmed are done so in freshwater ponds or tanks or coastal environments less exposed to wind, the market for salmon and other fishes kept in coastal cage farms is still considerable holding 9% of the total market by value. For this study a combination with salmon farming will be concept of choice.

5.3.1 Market and industry trends

Some countries focus more on farming in the ocean, along the coast. This is for example in Norway a very large industry, it is the second largest industry after the oil industry and with an uncertain future for oil, aquaculture is a top candidate to what the Norwegian economy will rely on if the oil industry loses it strength.[109] [110] The total value for farmed fish in Norway alone reached over 40 billion NOK in 2014.[111] Statistics from the Norwegian Directorate of Fisheries show a relatively steady number of farm sites over the past years but a steady increase of produced volume of fish.[112] A restriction in the allowance of total biomass farmed in the sea is the main limitation for a more extensive expansion. The salmon farming industry in Norway expects a production that is five times bigger than today. To be able to meet these expectations there is a general belief that the aquaculture industry has to move further offshore due to lack of space in near-shore locations hindering the expansion of fish farms in these locations.[110]

An important issue holding back a more expansionary development of the industry are problems with salmon lice and the risk of fish escape. The problem with lice, if a site is contaminated, lies within the risk of contamination of neighbouring sites as well as wild salmon in the surroundings. By moving further offshore this risk is considered to be reduced significantly due to greater diffusion of sites, more water circulation and the fact that wild salmon do not inhabit waters too far offshore. [110]

Another issue is pollution of the water and the seabed below fish cages due to that the water flowing through the cages carry excessive nutrients, bacteria, faeces, antibiotics or other medical substances, etc.[113] The problems with polluted water and seabed is often more evident in shallower and less circulated water why moving the farm sites further out in the ocean could have a positive effect and be part of a solution to this problem. Not only problems related to restricted circulation would decrease by moving further offshore, but also issues with visual impact, competition with tourism and inshore fisheries.[108]

This incurs more capital-intensive investments and large scales to become economically feasible, but the world's largest salmon producer Marine Harvest has already started their development of open ocean fish farms.[114] Another major company, SalMar, is working on the development of open ocean farms. [110]

5.3.2 Technology

Fish farms can vary a bit in size. Today most sites placed a bit out at sea constitutes of six to 12 fish cages. The size of the cages also varies, but they can be up to 50 metres in diameter. At each site also a feed barge is located for feed supply and to accommodate staff working at the farm.[115] Figure 5.7 shows a 3D-model of how a typical fish farm is set up with fish cages and feed barge with accommodation facilities. Energy is required to run the feed supply, supervision systems and for the accommodation facilities. Figures from a study in 2010[115] of the energy consumption at the fish farm Masterholmen was used to get an appreciation of the consumption. This farm consists of 10 fish cages and feed barge. The total energy consumption was 607 MWh during one year.

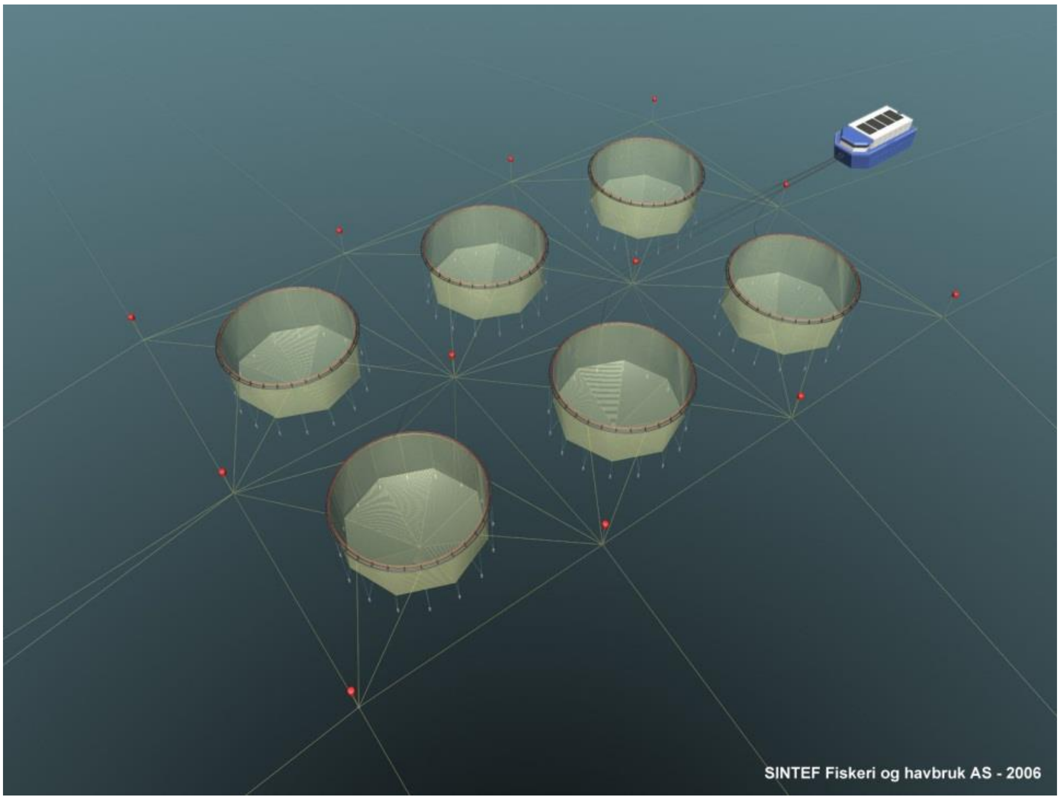

Figure 5.7 3D-visualization of how a fish farm could look like. [116]

Today most farm sites are manned to monitor and to perform daily operations such as removing dead fish. The personnel is accommodated on a service platform, which usually also contains the feed silos. One platform, or feed barge, can normally cover the need for a whole site, if the distance to the fish pens is not too far. The feed is distributed with airflow in hoses to each pen. In some cases monitoring and feeding is carried out by a service boat with an integrated feeding system.[139]

5.3.3 Technical considerations

Moving offshore not only entail benefits but also creates problems related to the reduced accessibility and increased exposure. In 2012 a report was produced by Norwegian research institute SINTEF[117] investigating many aspects considered in the development of fish farms in exposed locations. This report was based on a workshop, study visits, interviews and a survey with participants from the industry. It provides one of the most comprehensive analyses of the area of offshore fish farming.

A survey regarding the most crucial aspects with more exposed farming sites was carried out with 20 representatives from different parts of the industry answering. The results are presented in Figure 5.8.

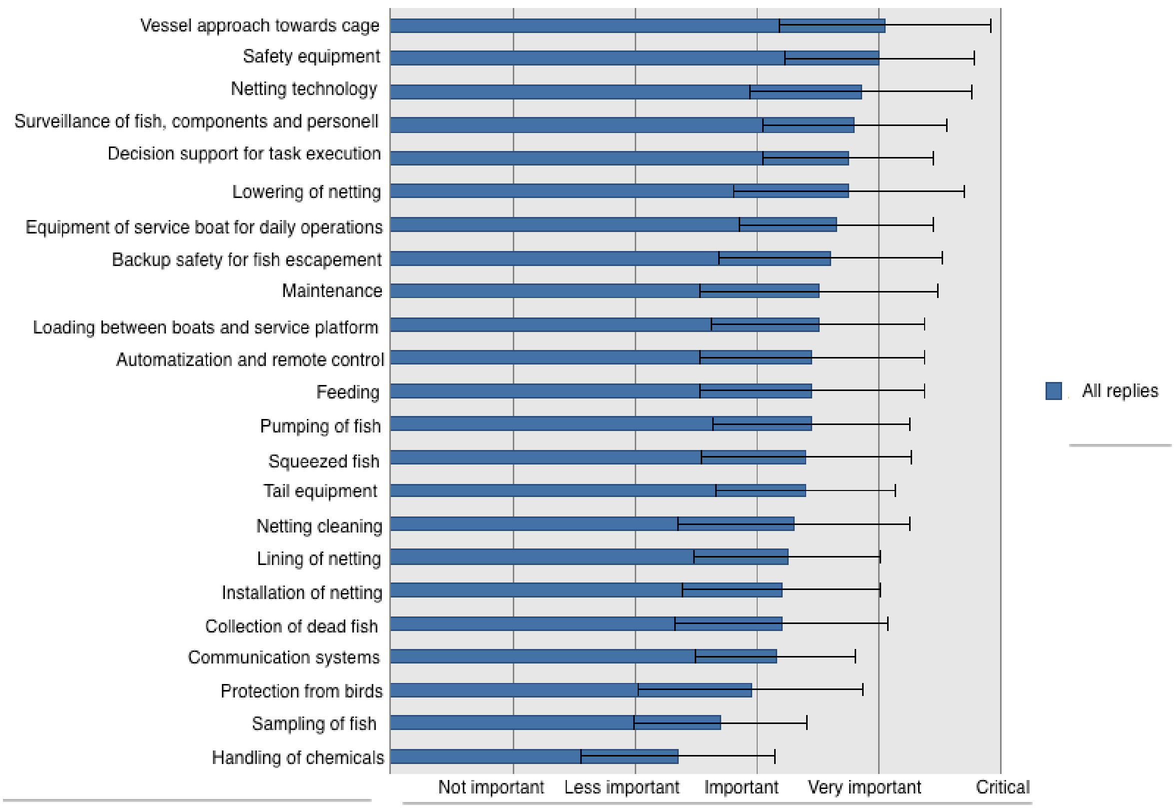

Figure 5.8 Survey regarding important aspects for fish farming sites.

Conclusions from the SINTEF report are that safety aspects, both for personnel and equipment, are crucial. Problems with boats close to the cages today are much related to the unpredictable movements of the cages top floating ring and the difficulty to approach and stay close to it during operations.

Moving to more exposed sites increases the forces that affect the structure. The risk of cages breaking leading to fish escapement is a crucial problem.[117] Not only does fish escapement cause financial losses but also the more serious problems are related to effects on wild populations through disease and dilution of locally adaptive gene complexes.[113]

Despite the fact that feeding is done automatically and the sites are being monitored by numerous cameras. Current regulations demand daily monitoring to be able to detect potential faults and dead fish which needs to be removed.[110]

Since the Hexicon platform is designed with an interior consisting of a triangular framework of beams, the most evident solution to create fish cages would be to utilise this framework to carry the cages. The cages would then be attached to the beams in the platform and extend down to a suitable depth. Conventional cages are cylindrical shaped, but there are different concepts under development using spherical and diamond shaped cages such as the Aquapod[118] and KZO Sea Farms[119]. What needs to be considered is the behaviour of the fishes, particularly they tend to swim in a circular pattern, favouring a shape that enables this.[110] Another important aspect when it comes to cage design is how well proven the design is and conventional cylindrical net cages are by far most common in coastal farming.

The fact that the fish cages would be hanging underneath the platform results in a potential interference with the mooring system with lines or wires attached to the platform extending to the seabed. Calculations need to be carried out estimating the available space underneath the platform, if this is the preferable placement.

5.3.4 Environmental aspects on fish health

Studies have been made investigating the effects of noise from wind farms on different fish species. In a study by Thomsen et al.[120] the operational noise from a 1.5 MW wind turbine was found to be heard up to 4 kilometres by cod and herring and up to 1 km by dab and salmon. However the noise from the wind turbine is partly masked by ambient sound, for example from wind. One study[121] estimates the distance to which fish could be scared away from a wind turbine, to 4 metres. When it comes to habituation by fishes to continuous sound some claim little or no habituation[122] while others have observed habituation to continuously emitted sound[123]. Hawkins[124] made observations that support the fact that fishes can rapidly assess the importance of a particular stimulus, like a continuous sound, which indicates a possible habituation to wind turbines. Thomsen et al.[125] concludes that it is unlikely that the sound from wind farms would cause physical damage to fishes with the limitation that themed study was performed on 1.5 MW turbines with the coming standard being 5-6 MW turbines obviously creating higher sound levels.

5.3.5 Consent and siting

To establish a fish farming site there are numerous aspects that are being considered when issuing a consent. The most important ones include studies of environmental impacts on the aquatic environment and the seabed underneath and how the structure will handle forces from waves and currents at the specific site. [110] There are no specific demands for offshore sites to this date.

6 CONCEPT CREATION

The background study on the three areas of concept was followed by creation of three concepts, each integrating one of the selected functionalities. The three concepts are presented in this chapter. As the level of detail in the information varied, also the level of detail in the concept description varied accordingly.

6.1 Photovoltaics

An outlook in the photovoltaic field through research, interviews[92], and consultation with employees at Hexicon, suppliers and manufacturers has given a deep insight and highlighted important factors, which have been the foundation for the creation of the final concept.

For the choice of specific solar panel a number of different solar panels were evaluated. First generation single or multi crystalline solar panels with an efficiency rate around 15-18% were chosen due to its good power output to price ratio and well proven history record of durability.[92] The type of encapsulation of panel had to be suitable for a marine environment, the warranty should cover the whole lifespan of the project. Hence the range of panels to be considered was limited. The panels should also have a good resistance to power degradation over time and be as maintenance free as possible. Since there are three turbine towers potentially shadowing the panels, the choice of panels should include at least three bypass diodes to limit the negative shadowing effect.

When it comes to platform integration, an important factor is how the panels are mounted. The choice is either an easier static flat mounted setup or a more advanced setup, which can optimise the angle of the panel against the incoming radiation. Flat mounted panels are cheaper and makes the installation part much simpler, with the downside of losses in power output. Also, it requires more maintenance and there is a greater chance of things to break due to a more complex mounting structure. When located offshore on a platform it is harder and more expensive to service. Another important factor is that flat mounted panels would cause considerably less stress on the structure and the panels themselves during high wind loads compared to inclined panels. Hence the panels will be flat mounted in this concept.

6.1.1 Concept layout

The total surface area allocated for panels have been set to 29 000 m^2, included are subtractions for necessary electrical equipment, some spacing between module sections of panels, helicopter pad and part of its estimated shadow, walking bridge and wind turbines. The platform's original approximated surface area seen from above is 31350 m^2.

The following solar panel has been identified as a good fit according to the specified criteria: Canadian solar CS6K-260P-PG Double-Glass, (Poly-crystalline, Nominal Max Power (Pmax) 260 W, module efficiency: 15,88%, size: 992 * 1650 * 11.8 mm and Weight: 23 kg).[126]

Resulting in a total Nominal Max power of 4,57 MWp for a total of 17575 solar panels covering a surface of 29 000 m^2. For illustration see Figure 6.1 and 6.2.

Figure 6.1 Visualisation of the PV-concept seen from the front of the platform.

Figure 6.2 Visualisation of the PV-concept seen from the backside of the platform.

Costs
All CAPEX and OPEX costs used in the calculations can be seen In Table 6.1. Following the tables are the sources and motivations for the used costs described.

Table 6.1 CAPEX and OPEX costs for PV-system[73]

CAPEX		
Solar panels	[EUR/kWp]	700
Inverter	[EUR/kWp]	110
Mounting structure	[EUR/kWp]	75
DC-cabling	[EUR/kWp]	60
Grid connection	[EUR/kWp]	60
Installation costs	[EUR/kWp]	50
Infrastructure	[EUR/kWp]	40
planning and documentation	[EUR/kWp]	35
Transformers	[EUR/kWp]	20
Switch gear	[EUR/kWp]	5
Total	[EUR/kWp]	1155
Total CAPEX for 4,57 MW installed capacity	**EUR**	**5 278 350**

OPEX		
Operations & Maintenance	[EUR/kWp]	20
Total yearly OPEX for 4,57 MW installed capacity	**EUR**	**91 400**

Panel price for this specific panel were given directly by Canadian solar at 0,65 EUR per watt for a large scale order of approximately 17 000 units, with the possibility of reaching further discounted price if a deal came to be realistic. Another solar panel with very similar specifications and also suited for an offshore environment, was offered from a Swedish supplier at 0,75 EUR per watt for the roughly the same quantity. The average price at 0,70 EUR per watt will be used to give a direction of a realistic price for a solar panel suitable for intended environment.

A study performed to estimate the costs for future PV systems[73] also established a suggested current total cost per watt of 450 EUR/kWp for all BOS costs, including inverter. This is based on a ground mounted PV system of approximately 1 MW covering an area of 14280 m^2 with 15 % efficiency. The figures are conservative estimates meant to represent a mature market in Germany 2013/2014. This information was validated as representative data in agreement with Respondent 5. The studies specified module price was 550 EUR/kWp. However the chosen higher cost at 700 EUR/kWp should be more representative due to the higher requirements on solar panels suitable for an offshore environment.

Typical cost for necessary inverter, no specified equipment is chosen. Mounting structure figures are hard to estimate exactly, but it should be fairly representative as mounting structure for ground based PV plants are quite solid. Also, there is a simpler flat mounted structure on the platform compared to the inclined used for plants which needs to be raised up in the air. The DC-cables represents cables between modules and necessary equipment. Grid connection cost is approximated to cover the extra cost of upgrading the originally intended connection for the Hexicon platform. Installation is done in docks prior to the platform is placed at sea. Hence the installation cost should roughly be equal to ground based installation. Since the panels will be flat mounted it should also make it easier compared to an inclined installation. Infrastructure cost usually accounts for all costs related to the site, as fencing, preparing of ground etc. This is not directly related to this case, but it could cover unforeseen expenses not accounted for, for instance possible more expensive grid connection then expected etc. Remaining BOS components, which are costs for Planning and documentation, Transformers and Switch gear are assumed to be fairly the same. Even if some of the BOS costs end up being far from the used costs, it would still have relatively small effect on the overall expense of the PV system as the solar panels are the major cost.

Efficiency & Losses
System efficiency losses due to miscellaneous factors has been estimated to 15%, this varies some but is a value used in other studies for calculating the power output.[31] The average performance ratio on new well designed PV plants in Germany are commonly between 80-90%.[73]

The chosen solar panels have an efficiency rate of 15,88%. However, there are efficiency decreases on a yearly basis, according to the panel specifications it is 2.5% degradation the first year and each subsequent year 0.5%.

There is a negative shadowing effect from the wind turbines, however it is difficult to estimate the amount of time and area the panels will be shadowed by these since it depends on how the platform is oriented, which will be dependent on the wind direction. The potentially positive effect of cooling winds which can result in a more efficient working temperature for the solar cells[92], may compensate some for the efficiency loss due to shadowing. Hence it is estimated that the two factors is balanced out by each other.

The efficiency loss due to horizontally mounted panels are accounted for in the irradiance solar data. Packing ratio of solar cells for the panels has been estimated to 99%. No downtime of the system will be taken in to account in the calculations.

6.1.2 Location
Malta was chosen as a suitable location for the combination of PV and wind due to its beneficial resources in terms of irradiation, demands of increase renewable energy sources and the big interest in sea based PV there. Moreover, discussions have earlier been held between Hexicon and the Maltese government and they have shown interest in the platform, making good wind data available for thorough calculations. Although wind conditions are not ideal on Malta, the location was still chosen due to many benefits for a PV installation to highlight its potential. The chosen site location is seen in Figure 6.3.

Malta is a small island with limited areal and demands of increasing their renewable energy production. All electricity is generated in fossil fuelled power plants located on the Island, with a total capacity of 571 MW. By 2020 the Maltese government has entered an agreement, which commits them to have a minimum of 10% sourced from renewable energy sources.[127] Also, the University of Malta launched phase one of three in a 200,000 EUR sea floating solar panels research project in December 2014. Part of the aim is to investigate the technical aspects and factors affecting the output of the panels in a marine environment, but also prototyping to find working setups both economical and financially. Malta is currently seen as one of the leaders in development of sea floating PV.[89]

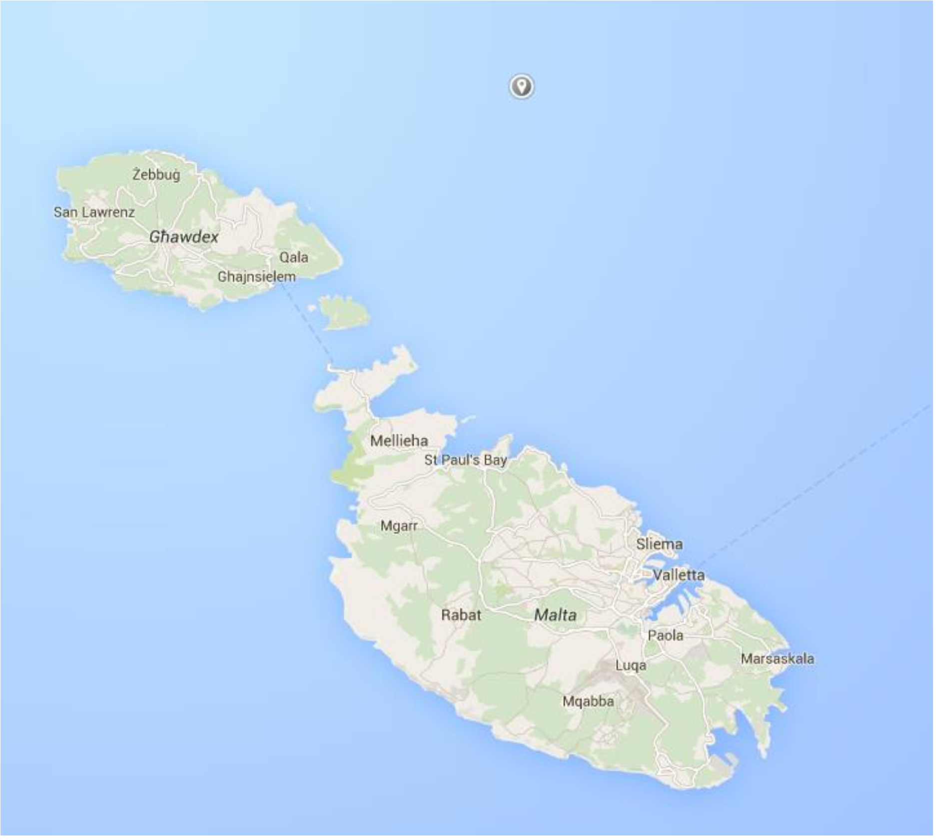

Figure 6.3 The chosen location for the PV-concept on Malta.

A key presumption for the location is that there is a satisfying exposure to solar radiation. There are many databases with solar irradiation data, which makes it possible to estimate potential yield from a setup of solar panels. PVGIS is one organisation supplying such data base for areas focused around Europe and Africa. In Table 6.2 Malta's irradiation on a monthly basis over a year is displayed together with wind data. The irradiation data comes from PVGIS tool with the specific radiation database Climate-SAF PVG.[128] It is clear that Malta has a well-suited radiation exposure, making the location very suitable for PV. The capacity factor, CF, for this location is calculated to 11,53%.

Table 6.2 Site data for the Aquaculture concept.[129 130]

GPS-coordinates		
N 36,1000°		
E 14,4300°		
Wind conditions		
Reference speed 123 m	[m/s]	7
Extrapolated mean wind, 105 m	[m/s]	6.8

Month	Hh	TD
Jan	2710	14.2
Feb	3600	13.5
Mar	5270	14.5
Apr	6280	16.1
May	7360	18.8
Jun	8030	22.3
Jul	8150	25.4
Aug	7320	26.0
Sep	5630	24.6
Oct	4230	22.3
Nov	2920	19.2
Dec	2350	16.1
Year	5330	19.4

Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Hh: Irradiation on horizontal plane (Wh/m2/day)

TD: Average daytime temperature (°C)

6.2 Wave power concept

Based on the information gathered from literature and from interviews a few types of WEC have been considered. The selection of a representative concept to combine with the Hexicon platform was based on suitable WEC technology. When looking at which WEC technology that would be most suitable the conclusion was that a point absorbing WEC would be most suitable. This was based on discussions with Respondent 5.

6.2.1 Concept layout

The concept layout was developed in collaboration with a developer of a point absorber WEC, though a case study of their concept, and regards to their input on a feasible integration were taken. It should be noted that a requirement that was predefined in the study was that an additional structure should utilise the actual platform structure, as opposed to just utilising the same sea area. A solution was produced that was considered to best fit the criteria of utilising the platform structure and also to get as much effect out of the concept as possible.

The WECs will be mounted in the K-joints along the horizontal lower beam in the platform structure. This solution would result in an installation of 20 WECs. The concept is shown in Figure 6.4 and 6.3. The WECs that were considered has a power rating of 300 kW per WEC with a capacity factor estimated to 0.29. The total added capacity rates 6 MW.

Figure 6.4 Visulaisation of the wave energy concept seen from above.

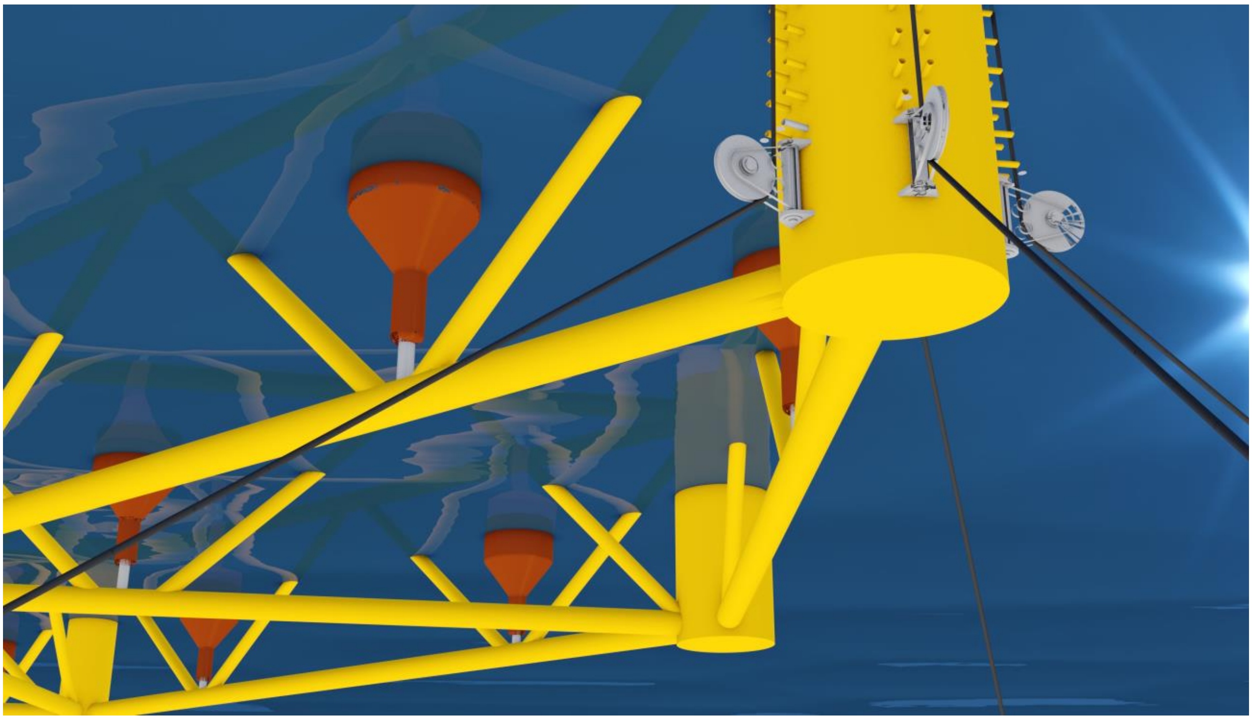

Figure 6.5 Visulaisation of the wave energy concept seen from underneath.

The reason why the WECs were chosen to be mounted in the K-joints along the lower horizontal beam is the proximity to the diagonal beams connecting the lower and upper horizontal beam, taking up vertical forces. How the WECs would affect the structure in terms of additional loads is presented in the evaluation section.

The concept fulfils the requirement of an integration of the WECs in the platform structure. There are two main benefits from this. First of all, the costs for mooring of each WEC are eliminated apart from the cost of attachment to the platform, which was taken into consideration when in a cost evaluation. But also components that normally adjust the mooring line's length to compensate for tidal differences can be eliminated. Since the platform, to which the WECs are attached, follows the water level the need for a water level adjuster is eliminated.

Costs
The costs that the integration of the WECs would result in are presented in Table 6.3. The costs were obtained from a cost breakdown for a 10 MW project planned by the developer. The project included a little more than double the amount of what could be integrated in the Hexicon platform. A cost per unit was calculated for each item in the project cost breakdown and then multiplied with the 20 units in the combination concept. The estimated costs for the addition of WECs are presented in Table 6.3.

Table 6.3 Costs for integration of WECs

Cost breakdown 6 MW WEC addition		**Costs**	**Excluded costs**
Device CAPEX 6 MW	[EUR]	12 810 800	
Moorings & anchor	[EUR]		2 162 200
On-shore grid connection	[EUR]		270 300
Offshore grid conn.	[EUR]		4 324 300
Spare parts(%)	[EUR]	270 300	
Siting and permits (%)SUM	[EUR]		864 900
GHG investigations (%)	[EUR]	21 600	
Installation cost	[EUR]	1 081 100	1081100
Management cost	[EUR]	4 324 300	
Decommissioning	[EUR]		4 324 300
Total CAPEX		**18 508 100**	
O&M (5% of platform CAPEX/year)	[EUR]	6 405 400	6 405 400,00
20 year project total cost	[EUR]	**24 913 500**	**19 432 500**

As seen in the cost breakdown some costs were excluded from the estimated costs for the project. These are costs that were considered to be eliminated in an integration concept since the components were considered already existent in the Hexicon platform. The cost for O&M was split in half as a rough estimate to take into consideration O&M costs specifically tied to the WECs.

6.2.1 Location

The choice of location for the wind and wave concept landed on a site in Dounreay in Northern Scotland in the UK where Hexicon is planning deployment of a demonstration platform. The site is located 9 km from the coast as shown in Figure 6.6. One of the main reasons for the location was available data on both wind and wave conditions and that the consent process for a demonstration platform was well underway. The likely deployment of a demonstration platform would also open up for the possibility to test an integrated WEC.

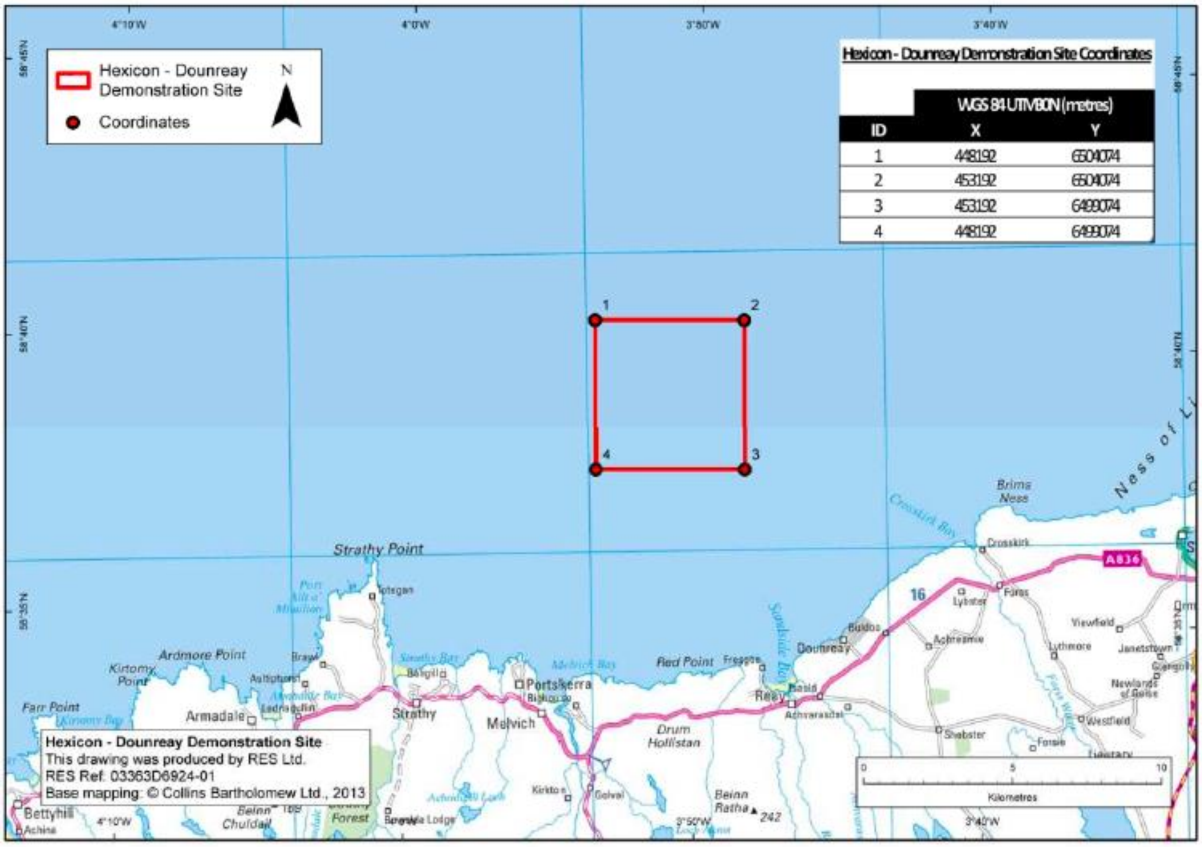

Figure 6.6 Location for the wave energy concept. [131]

The location is rich in wind resources and has reasonable wave resources. Wind and wave data as well as coordinates for the location are presented in Table 6.4. Wind and wave data is obtained from a report ordered by Hexicon.[158]

Table 6.4 Site data for the Wave power concept.

GPS-coordinates		
N 65.04074°		
E 004.48192°		
Wind conditions		
Annual mean wind, 80 m height	[m/s]	9.5
Extrapolated value for 105 m hub height	[m/s]	10.1
Wave conditions		
Operational wave height, mean annual Hs	[m]	2,0
Corresponding mean period, Tp	[s]	10.0
Mean wave energy climate	[kW/m]	23.5
Extreme wave height, 50 year return, Hs	[m]	12.1
Currents	[m/s]	0.71
1-year current, surface	[m/s]	0.71
1-year current, bottom	[m/s]	0.71

6.3 Aquaculture concept

As mentioned in the background study of aquaculture it is believed that the type of aquaculture most suitable to combine with the Hexicon platform is Atlantic salmon farming. This is based on recommendations from field experts from SINTEF research institute[110] and DTU Aqua[132], a marine research institution at the Danish Technical University. This type of fish farming is considered to be suitable for open ocean conditions, where the wind resources also are rich.

6.3.1 Concept layout

The concept that will represent the combination concept of offshore aquaculture and the Hexicon platform is based on conventional cage technology with circular rings, one floating and one sunken, holding the net between them. A cage from Musholm will be used as representative cage.

Four cages will be installed the triangular spaces created by the cross beams on the Hexicon platform. The cages are 122 m in circumference having an approximate diameter of 39 m. The vertical distance between the rings is 10 m with a cone shaped bottom to collect sunken dead fish and debris in a collector in the centre extending an additional 4 m. This is almost equivalent with the operating draught of the platform, 15 m. Figure 6.7 and 6.8 illustrates the installation of the Musholm cages in the Hexicon platform.

Figure 6.7 Visualisation of the aquaculture concept with four cages integrated in the platform.

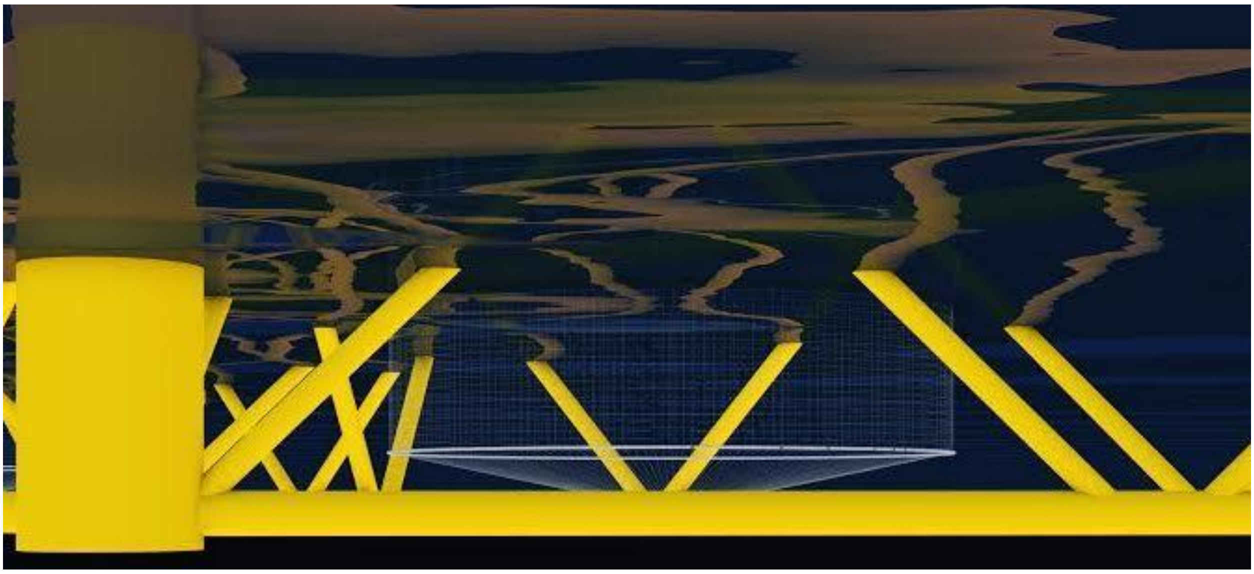

Figure 6.8 Visualisation from an underwater view of one of the cages integrated in the platform.

The floating ring could be attached with lines from the three nodes in each corner of the triangle. It is common practice that one mooring- or attachment line is split into three lines extending to the ring to spread the forces around the ring. To hold the shape of the bottom cone a cone shaped sinker weighing approximately 4 tonnes is placed in the bottom ensuring the shape is retained even in strong current or wave induced motions.

Since each platform will be located at a considerable distance from each other to ensure optimal wind conditions it is impossible to have a mutual feed barge servicing several platforms. An option would be to have one feed barge per platform, but this is a rather large investment per platform. However, the chosen option for this study was to have a service vessel with an integrated feeding system. This vessel would service each platform in a farm each day carrying out feeding and monitoring. Since these systems are placed outside the platform, the cages would not consume any energy.

Costs

The costs related to CAPEX used in this study were based partly on information from DTU Aqua[132] (for the cost of cage) and from a study on investment costs for offshore fish farming projects[133]. The operational costs, OPEX, were based on statistics from Fiskeridirektoratet[134] based on the entire Norwegian fish farming industry. The costs are presented in Table 6.5.

Table 6.5 CAPEX and OPEX cost for aquaculture concept based on four cages.

CAPEX		
Fish cages, 122 m (4 pcs)	[EUR]	402 000
Nets	[EUR]	228 000
Net cleaning system	[EUR]	114 000
Installation and supervision	[EUR]	68 400
Freight	[EUR]	36 000
Work vessel with feeding system	[EUR]	1 080 000
Offshore transport boat	[EUR]	120 000
OPEX		
Fry costs	[EUR]	254 350
Feed costs	[EUR]	1 335 630
Insurance costs	[EUR]	12 780
Salaries	[EUR]	209 060
Depreciation	[EUR]	142 850
Other maintenance costs	[EUR]	648 070
Financing costs	[EUR]	32 520
Slaughtering	[EUR]	306 610
Total OPEX (annual)	[EUR]	**2 941 875**
Total CAPEX	[EUR]	**2 048 400**

6.3.2 Location

For the evaluation of the aquaculture concept a location was chosen along the coast in the municipality of Bjugn in Mid-Norway. At the location today a fish farm is situated that is used as a research site by ACE, Aquaculture Engineering. The site was used in the SINTEF study[135] as a representative for a wind and wave exposed location, which it is reasonable to believe a site for the combination concept with the Hexicon platform would be. In Figure 6.9[136] the location is marked with a red cross.

Figure 6.9 Location for the aquaculture concept.

GPS-coordinates and wind data is presented in Table 6.6. The wind data is provided by Windmap[137], a wind resource map based on data from the Norwegian energy consultancy Kjeller Vindteknikk. Annual mean wind speeds at 50, 80 and 120 m height are provided at desired locations.

The wave climate is defined as "significant exposure" for fish farm sites according to a report where extreme wind, wave and current conditions were evaluated for this specific site[138]. The combined wave conditions considering swell and wind waves with a 50-year return period is presented in Table 6.6. The significant wave height, H_s, and peak wave period, T_p, is presented. Maximum wave height is estimated with an estimation used for a Rayleigh distributed wave spectrum that says $H_{max} = 1.86H_s$

Table 6.6 Site data for the site aquaculture concept.

GPS-coordinates		
N 63.52137°		
E 009.37224°		
Wind conditions		
Annual mean wind, 80 m height	[m/s]	8.26
Annual mean wind, 120 m height	[m/s]	8.5
Extrapolated mean wind, 105 m	[m/s]	8.4
Wave conditions, 50 y return		
Wind waves	H_s [m]	2.9
	T_p [s]	7.9
Ocean swell	H_s [m]	1.6
	T_p [s]	10.8
Combined wave height	H_s [m]	3.1
Combined max wave height	H_{max} [m]	5.8
Currents		
1-year	[m/s]	0.3

7 CONCEPT EVALUATION

Based on the three different concepts background studies evaluations of each concept were performed. A holistic evaluation approach was adopted, including qualitative as well as quantitative factors as described in the method section.

7.1 Base Case

Basic conditions for the Hexicon platform were established and assumed equal for all three concepts. The main assumptions were based on production and operation in a similar type of economic environment resulting in the same costs for these. Assumptions used for all concepts were:

- Identical platform setup with three wind turbines, 18 MW total capacity
- Currency: EUR
- Discount rate: 10%
- Insurance cost: 1,5% (of CAPEX)
- Inflation rate: 2%
- Project lifetime: 20 years of operation
- CAPEX and OPEX for the Hexicon platform without added functionality are estimated by Hexicon and apply to a generic platform designed for average site conditions.
- For calculations of revenues a wholesale price for electricity produced from estimations of a previous potential project at Hexicon, which was built in the calculation model, was used. The price used was 0.172 €/kWh. It should be noted that this price does not necessarily reflect the actual wholesale prices at each specific location, since these vary a lot between different countries. This was considered sufficient since the focus was on investigating the differences in the economic outcome between the original platform and the combination concepts.

Further assumptions
The grid connection cost was equal for the base case and includes cable and installation of connection and were based on an averaged 5 km distance between platform and offshore cable landfall. Onshore cable was not included.

Additional expenditures were added to each specific case, e.g. structural improvement of the platform, grid connection improvement, insurance, etc. Added costs for grid connection were taken into account to handle the theoretical peak capacity for the combined concept. The Increased insurance cost are based on 1,5% of the total CAPEX.

Energy generation
The energy generation from the turbines was based on wind data for each location and included in the calculations for each concept.

7.2 Photovoltaics

7.2.1 Economic Return

Energy production
The annual energy production was estimated for the PV addition and for the wind turbines based on the data on wind resources and solar irradiation at the chosen location. The production from the solar panels is a mean value of the annual production over 20 years, considering the assumed decrease in efficiency of 2.5% after one year and 0.5% the following years. It is presented in Table 7.1.

Table 7.1 Annual mean energy production over 20 year

PV-system only	[GWh]/year	7.1
[GWh]/year	[GWh]/year	52.3
Total energy production	[GWh]/year	59.1

The energy output turned out to be relatively low for the scenario investigated, due to mediocre wind conditions at the location for the PV concept. Therefore the total output dependent on both wind and irradiation resources was calculated for combinations between 6.5 and 11 m/s and annual mean irradiation between 900 and 1800 kWh/m^2. It is presented in Table 7.2. The highlighted cell shows where the concept based on the Malta location is approximately located. The table illustrates that a relatively small increase in wind speed can compensate for a significant decrease in irradiation. Obviously a windy site with lots of sun would be preferable.

Table 7.2 Total output of PV concept dependent on wind and irradiation resources.

		Total energy output dependent on wind and irradiation [GWh/year]										
Mean wind speed [m/s]	**11**	96,0	96,4	96,8	97,2	97,5	97,9	98,3	98,7	99,1	99,3	99,5
	10,5	93,1	93,5	93,9	94,3	94,6	95,0	95,4	95,8	96,2	96,4	96,6
	10	89,7	90,1	90,5	90,9	91,2	91,6	92,0	92,4	92,8	93,0	93,2
	9,5	85,7	86,1	86,5	86,9	87,2	87,6	88,0	88,4	88,8	89,0	89,2
	9	81,2	81,6	82,0	82,4	82,7	83,1	83,5	83,9	84,3	84,5	84,7
	8,5	76,1	76,5	76,9	77,3	77,6	78,0	78,4	78,8	79,2	79,4	79,6
	8	70,6	71,0	71,4	71,8	72,1	72,5	72,9	73,3	73,7	73,9	74,1
	7,5	64,5	64,9	65,3	65,7	66,0	66,4	66,8	67,2	67,6	67,8	68,0
	7	58,1	58,5	58,9	59,3	59,6	60,0	60,4	60,8	61,2	61,4	61,6
	6,8	55,4	55,8	56,2	56,6	56,9	57,3	57,7	58,1	58,5	**58,7**	58,9
	6,5	51,2	51,6	52,0	52,4	52,7	53,1	53,5	53,9	54,3	54,5	54,7
		900	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1750**	**1800**
		Annual mean irradiation [kWh/m2]										

LCOE

In Table 7.3 below the calculated LCOE value is presented.

Table 7.3 LCOE for PV concept including sensitivity analysis

			Sensitivity analysis	
			+10%	-10%
LCOE for base case w/o PV for Malta	[EUR/kWh]	0.215		
LCOE with integrated PV for Malta	[EUR/kWh]	0.191	0.191	0.191
Calculated change	[%]	11	11	11

As shown in Table 7.4, the concept with integrated PV on Malta resulted in an 11% decrease of the LCOE value. A 10% increase or decrease in CAPEX and OPEX costs did not affect the LCOE, up to the third decimal.

IRR

The rate of return for the PV concept for the chosen scenario is presented in Table 7.4.

Table 7.4 IRR for PV concept including sensitivity analysis

			Sensitivity analysis	
			+10%	-10%
IRR for base case w/o PV for Malta	[%]	9.78		
IRR with integrated PV for Malta	[%]	11.92	11.91	11.94
Calculated change	[%]	+22	+22	+22

7.2.2 Technological factors

A brief summary of the result is presented in Table 7.5 below. Analysis and explanation in more detail then follows.

Table 7.5 Summary of Technological factors

	Results
Added loads on platform	Added weight by approximately 1129 tons.
Additional weight	
Interference with existing structure and mooring system	Potentially affecting structural behaviour.
Impact from the offshore environment on the added functionalities	Potential salt cover of panels may cause efficiency decrease. Cooling winds may result in efficiency increase.
Technological Readiness Level	9

Impact from the offshore environment on the added functionalities
The use of panels in more or less harsh environments dates long back and the background study points to this not being a major concern. Performance guarantees on the panels provide some kind of assurance of the durability.

Although there are research saying there is a decreased efficiency for solar panels in marine environment, the consequences observed are moderate. However, it is reasonable to expect a need for some kind of system that can take care of salt covering caused by salt mist. Alternatively performing regular cleaning maintenance manually.

One technical aspect of solar panels in an offshore environment are the potentially positive benefits with exposed solar panels to cooling winds which should decrease the panel temperature resulting in a higher efficiency. How big this effect is, is still unclear.

Added loads on platform
Extra wind loads on the solar panels potentially affecting the platform is not considered due to the insignificant horizontal area exposed to wind.

Additional weight
The added weight approximately sums up to 1129 tons for mounting structure and solar panels. Other necessary associated equipment has been neglected due to its relatively small contribution. Roughly estimated weight can be seen in Table 7.6

Table 7.6 Added weight for PV system

Mounting structure[139]	[kg/m^2]	25
Panels[126]	[kg/unit]	23
Total	[tons]	1129

The total added weight of the PV-system will approximately increase the original weight with 16%. This would result in need for increased displacement with 1129 m^3.

Interference with existing structure and mooring system
Installation of solar panels and necessary equipment requires added support structure across the platform. This stiffening of the structure may result in a change in oscillation behaviour of the platform. However, with a relatively flexible mounting structure this may be avoided.

Technological readiness level
The technological readiness level for first generation solar panels has long since reached the end of the TRL scale. However, there is still development occurring and new technologies may be more relevant in a near future.

7.2.3 Market potential
It is difficult to estimate how big the market is since a specific market for offshore PV/Wind combination platforms does not yet exist. However, the step from offshore wind is perhaps not that big. As shown in the background studies, there is a globally increasing demand for renewable energy sources in combination with decreasing prices and an increased efficiency. With regards to the calculated LCOE value, it is shown that a combination of PV and Wind would lower the cost of electricity in comparison to the original concept. This is something that are highly attractive on the market place, as LCOE is a fundamental comparison value when looking into potential energy source to invest in.

There is also an availability factor concerning limited land areas suitable for wind, PV or other energy generating sources. Which is the case for a small island like Malta, and an offshore-based alternative is a beneficial option. That is also why a lot of development and research on floating PV is carried out on Malta. Both PV and wind energy are today two very fast growing markets, which is positive for a combination of the two from a market perspective.

The basic deliverable and function of this unique combination is not that different from an energy source with only wind, part from still being in an early phase and hence are very prone to high risk. That aside, in the perspective of what the product delivers the main customers should be the same as the ones investing in green energy sources today. The typical investors that were mentioned in the background study for offshore wind funding (power producers, EPCI contractors, oil and gas companies, institutional investors, corporate investors, infrastructure funds and sovereign wealth funds as investors), should therefore be potential investors. In addition to this it is likely to assume additional interest from typical investors in conventional PV plants.

7.2.4 Other strategic factors

A brief summary of the result is presented in Table 7.7 below. Analysis and explanations in more detail then follows.

Table 7.7 Summary of Other strategic factors

	Results
Business strategy and innovation strategy	Hexicon’s original strategy fits relatively well with an additional solar power functionality
Timing of entry	Being first to market would presumably be favourable
Consenting process	The comprehensive consenting process for offshore wind should not result any additional permits for the PV-system.

Business strategy and innovation strategy
On paper the present business strategy for Hexicon aligns well with the combined PV/wind concept, as the basic function of the added solar panels only delivers more of what the intend original aims to; developing state-of-the-art floating solutions for the offshore renewable market. Of course if affects the business in terms of time, focus and money, which translated to the need for allocating new resources, expanding the business capabilities and establishing new collaborations. But the end goal remains the same. Hence, the overall business strategy should be good match between the new and the original concept.

Timing of entry
As far as the background research shows it does not exist any real competition in terms of projects with a PV/wind setup in an offshore environment of equal capacity. There are some land-based concepts that combine wind and PV in one system.

As written in the technological evaluation, *Impact from the offshore environment on the added functionalities*, the added PV technology is well proven and should not substantially raise the perceived risk compared to original platform without PV. Also, solar energy popularity is on the rise as grid parity is reached in more and more places. Popularity of a technology should help in the process of attracting investors and is a timing opportunity that could prove helpful. Waiting for the technology to mature even more would make the numbers look better, if assumed prognosis presented in the background are realised. However the price to power output performance is already today at a desirable level as is shown in the financial calculations. Hence there is little argument for delaying market entry unless better numbers are targeted.

The launch of a large-scale PV/wind platform should have potential to draw a lot of attention. Media exposure that could prove highly advantageously for marketing and branding purposes, and being first out would definitely result in greater media and public notice than second, third or fourth.

Certain offshore locations also have limited sea territory available, and depending on country there are different ways of distributing sea areal. Being first to market should give a big lead in accessing hotspots and key locations with the greatest conditions in both climate and financial terms; advantageously substitutes or investment support for certain countries or beneficial infrastructural models.

When it comes to enabling technologies, solar panels with an encapsulation adapted to a marine environment are a presumption to cope with the tough offshore environment. There are still some uncertainties to whether the current models can cope well enough, where decreased transmittance capabilities of the glass are one concerning factor. Although much point to this not being a crucial factor, especially not since manufacturers of solar panels leave warranties guaranteeing efficiency specific rates up to 30 years. Hence, current technology level should not be a reason to avoid entering the market. Conclusively, being first to market is in this case considered more valuable than being a follower or late entrant.

Consenting process
In the context of installing PV on an offshore wind platform, additional permits should, as far as the background study has shown, not be needed due to the already very high requirements for offshore wind turbines. Although this must be further investigated in each specific location, as it is highly dependent on a regional and local level.

7.3 Evaluation of wave power concept

The evaluation of the wave power concept is based partly on the literature review on the subject carried out, but also based on input from discussions with a developer of a point absorber WEC, regarding possible solutions of integration and the effects that these solutions would imply. The information from literature research was mainly used for evaluation of qualitative aspects, in particular market potential and timing of entry. Information to evaluate the technical and economic factors was mainly supplied by the WEC developer.

7.3.1 Economic Return

Energy production
Since energy output of a WEC is highly dependent on the specific wave pattern at the site in question calculations has to be made on based on a so called wave scatter diagram, a table describing the accumulated time each chosen sea state occurs. The calculation of the yearly output for the WEC units used in the study was performed by the developer of the WEC used. This was added to the output from the wind turbines. The annual energy production was estimated for the WEC addition and for the wind turbines based on the data on wind resources and a wave scatter diagram for the chosen location. It is presented in Table 7.8.

Table 7.8 Energy production from wave energy concept.

Energy production WEC addition	[GWh]/year	15.3
Energy production wind turbines	[GWh]/year	86.7
Total energy production	[GWh]/year	102.0

It was suspected that the outcome of the calculations on the Dounraey might be modest due to modest wave energy resources. Therefore a test was made using WEC output values calculated for another site with a slightly higher energy climate as reference (26.5 kW/m instead of 23.5 kW/h as for Dounraey). This test resulted in an energy production of 17.42 GWh/year. This was based on a calculated yearly output of 871 000 MWh per unit. Table 7.9 shows how the total output varies with different yearly output per unit and the mean wind speed at a potential location. The output from a WEC can not be calculated in a similar way as with wind energy due to the fact that the wave energy climate can not be generalised the same way during one year as wind resources. Therefore values of actual output that needs to be produced are used to describe the wave energy climate. The approximate value for the concept created is highlighted.

Table 7.9 Total output of WEC concept dependent on WEC-unit output and mean wind speed.

		Total energy output dependent on wind and wave energy output [GWh/year]									
Output per unit [kWh/year]	**1150000**	70,7	77,6	84,0	90,1	95,6	100,7	105,2	109,2	112,6	115,5
	1100000	69,7	76,6	83,0	89,1	94,6	99,7	104,2	108,2	111,6	114,5
	1050000	68,7	75,6	82,0	88,1	93,6	98,7	103,2	107,2	110,6	113,5
	1000000	67,7	74,6	81,0	87,1	92,6	97,7	102,2	106,2	109,6	112,5
	950000	66,7	73,6	80,0	86,1	91,6	96,7	101,2	105,2	108,6	111,5
	900000	65,7	72,6	79,0	85,1	90,6	95,7	100,2	104,2	107,6	110,5
	850000	64,7	71,6	78,0	84,1	89,6	94,7	99,2	103,2	106,6	109,5
	800000	63,7	70,6	77,0	83,1	88,6	93,7	98,2	102,2	105,6	108,5
	764000	63,0	69,9	76,3	82,4	87,9	93,0	97,5	**101,5**	104,9	107,8
	750000	62,7	69,6	76,0	82,1	87,6	92,7	97,2	101,2	104,6	107,5
		6,5	**7**	**7,5**	**8**	**8,5**	**9**	**9,5**	**10**	**10,5**	**11**
		Mean wind speed [m/s]									

LCOE

In Table 7.10 the calculated total LCOE value is presented:

Table 7.10 LCOE for Wave power concept

			Sensitivity analysis	
			+10%	-10%
LCOE for base case w/o WEC for Dounraey	[EUR/kWh]	0.13	-	-
LCOE with integrated WEC for Dounraey	[EUR/kWh]	0.135	0.139	0.134
Calculated change	[%]	3.9	6.9	3.1

As shown in Table 7.10 the integration of the WECs from the WEC developer results in an increase of the cost of energy by almost 4% compared to the base case for the test site at Dounraey. Since the result did not show any positive impact on the Hexicon platform it was of interest to see the gain for the WEC developer to integrate the units to the Hexicon platform and therefore reduce costs associated with installation, mooring and O&M. The costs of energy for an installation with 20 units separately installed was estimated to be 0.27 EUR/k. This cost was reduced to 0.15 EUR/kWh for the WEC units when integrated, assuming exclusion of shared costs as presented in Table 6.3.

IRR
The estimated IRR is presented in Table 7.11. A slight decrease of the project IRR was seen.

Table 7.11 IRR for Wave power concept

			Sensitivity analysis	
			+10%	-10%
IRR for base case w/o WEC for Dounraey	[%]	19.58		
IRR with integrated WEC for Dounraey	[%]	18.34	17.93	18.76
Calculated change	[%]	-6	-8	-4

7.3.1 Technical factors

A brief summary of the result is presented in Table 7.12 below. Analysis and explanation in more detail then follows.

Table 7.12 Summary of Technical factors for wave power.

	Results
Added loads on platform	Lift force for one bouy: mean 2 090 kN; fully submerged 3590 kN; maximum lift force 5980 kN. Working on point of attachment.
Additional weight	Since the buoys are self-buoyant, there is no considerable amount of additional weight.
Interference with existing structure and mooring system	Maximum surge motion of the wave buoy needs to be analysed to ensure that collision with structure is not possible. The draught on the platform needs to be increased to 20 m.
Impact from the offshore environment on the added functionalities	Of no concern.
Technological Readiness Level	5

Added loads on platform
The integration concept builds on an attachment of the WECs to the Hexicon platform. This type of integration would incur significant additional loads on the platform structure. Values of these additional loads were reported by the WEC developer and estimated for a typical Atlantic wave climate with an energy density of 25-30 kW/m. A 300 kW unit was estimated to have a mean lift force of 2 090 kN, when fully submerged 3590 kN and a maximum lift force of 5980 kN in extreme conditions.

Interference with existing structure and mooring system.
Since the WECs are attached to the lower beam, there is no interference with the mooring of the platform. What needs to be considered is the fact the buoy can move horizontally as well due to surge movement in the water. It would therefore be necessary to verify the maximum surge motion

of the wave buoy, making sure that the distance to the diagonal beams is sufficient for that range of movement so no collision can occur.

A requirement for the concept to be feasible is that the draught of the platform is increased. This is due to a required depth of 20 m for the WECs to have enough vertical room from its attachment point to the water surface.

Impact from the offshore environment on the added functionalities.
Being a marine construction designed to operate in a wave energy rich climate, it is assumed that the WEC can handle more extreme conditions than the Hexicon platform, thus the impact from the offshore environment should be of no direct consideration. The chosen WEC has a 20-year design life.

Technology Readiness Level
Basic components have been manufactured and tested in simulated environments to verify subsystem and system level functionality. This places the project on TRL 5. Preparations are being made to perform scale model tests in a relevant environment that will take the project to TRL 6 within the next year.

7.3.2 Market potential

It is difficult to estimate the size of the market for concepts combining offshore wind and wave energy. The demand for renewable energy is an increasing demand and many indicators are pointing towards an exploitation of offshore wind and wave resources. An offshore energy platform also has the strength of not using land area in heavily populates coastal regions where the available land is very expensive or already fully utilised.

The basic deliverable and function of this combination is not significantly different from the original Hexicon platform. However, adding a component not fully developed from a technical perspective, such as the WECs, should increase the level of uncertainty and risk in the project. That aside, in the perspective of what the product delivers, the main investors are the same as the ones today. The typical investors that were mentioned in the background study on offshore wind funding, will therefore properly also be interested in this concept; power producers, EPCI contractors, oil and gas companies, institutional investors, corporate investors, infrastructure funds and sovereign wealth funds as investors.

7.3.3 Other strategic factors

A brief summary of the result is presented in Table 7.13 below. Analysis and explanation in more detail follows.

Table 7.13 Summary of Other strategic factors

	Results
Business strategy and innovation strategy	Hexicon's original strategy fits relatively well with an additional wave energy functionality.
Timing of entry	Being an early follower was assumed favourable.
Consenting process	The comprehensive consenting process for offshore wind should not result any additional permits for the WECs.

Business strategy and innovation strategy

The concept of combining wind and wave energy aligns with the business strategy of developing cost-efficient and state-of-the-art solutions for floating offshore renewable energy. The added functionality would provide more of the originally intended output, electricity, and therefore the addition does not differ too much. It would not necessarily involve extensive amounts of additional engineering if the concept would be based on collaboration with an external developer of the WEC solution.

Timing of entry

Other companies (see Proof of concept - combinations with wind energy) have been developing concepts combining wind and wave energy for a few years. No concept has yet become commercially viable and it can be assumed that this will not happen for a few years as well. Two scenarios were identified for this case. Since at least two concepts already have undergone a few years of development they are considered to have a lead towards being first to market. On the other hand the challenges presented for these two concepts to become commercially viable may be too difficult to overcome resulting in a prolonged development process, leaving room for other competitors, such as Hexicon, to catch up in the development towards a commercially viable concept. Furthermore, the difficulties presented and lessons learned for a development leader in this market might be beneficial for following developers, who might be able to avoid them. This implies that being a follower could possibly be a desirable strategy on this market.

There is certainly a market ready for concepts combining wind and wave energy. The biggest uncertainty can be considered to lie in the development of a WEC concept efficient enough to significantly contribute to a wind energy platform. The results in this study indicate that the chosen WEC has a high potential to live up to this requirement due to its high efficiency rating in comparison to other WECs.

Consenting processes

The addition of WECs to the Hexicon platform would most likely not complicate the consenting processes. The requirements on wave energy projects require the same environmental analyses as wind energy projects in the UK to date. However, a second certificate will become required for wind energy projects, but not initially for wave energy projects.

7.4.4 Economic Return

Energy production and revenues from fish farming
The annual energy production was estimated for the wind turbines based on the data on wind resources at the chosen location. The results from the estimation of the fish production is also presented here in Table 7.14 below.

Table 7.14 Energy production and revenues from fish farming

Energy production wind turbines	[GWh]/year	71.8
Fish produced and sold	[kg]/year	743 462
Estimated wholesale price	[EUR/kg]	3.87
Revenues from fish farming	[EUR/year]	2 874 082

LCOE
In Table 7.15 it the modified LCOE values are presented:

Table 7.15 LCOE – Aquaculture concept

			Sensitivity analysis	
			+10%	-10%
LCOE for base case w/o aquaculture for Tristein	[EUR/kWh]	0.158	-	-
LCOE with integrated aquaculture for Tristein	[EUR/kWh]	0.153	0.157	0.149
Calculated change	[%]	-3.2	-0.6	-5.7

Table 7.15 shows a slight decrease of the modified LCOE value when adding aquaculture to the platform.

IRR
Table 7.16 below shows the results of the IRR-calculations. A very small positive change in IRR can be seen in the results.

Table 7.16 IRR of the aquaculture concept

			Sensitivity analysis	
			+10%	-10%
LCOE for base case w/o aquaculture for Tristein	[%]	15.51		
LCOE with integrated aquaculture for Tristein	[%]	15.74	15.51	16.30
Calculated change	[%]	+1	0	+5.1

7.4.1 Technological factors
A brief summary of the result is presented in Table 7.17 below. Analysis and explanation in more detail then follows.

Table 7.17 Summary of Technological factors

	Results
Added loads on platform	Relatively small added load calculated to 437 kN
Additional weight	Since the cages are self-buoyant, there is no considerable amount of additional weight.
Interference with existing structure and mooring system	The depth of the fish cages is adapted to avoid all possible interference with mooring system.
Impact from the offshore environment on the added functionalities	Assumed challenge to develop cages to withstand more demanding wind and wave conditions.
Technological Readiness Level	9

Added loads on platform

Estimations of forces induced by water flow will be performed using the drag component of Morison's equation. Morison's equation is a semi-empirical equation used to determine the inline forces on a body in oscillatory flow. The equation is normally used to calculate forces on solid cylinders but it has been used in several studies[140] [141] [142] to estimate forces on netting cylinders, by looking at the twines in the net as cylinders. The area is estimated by the projected area of the total length of twine, both front and back of the net cage. Equation 16 determines the drag force.

$$F = \rho C_d A u^2 \qquad \text{Equation 17}$$

Where: ρ – water density [kg/m$^{3]}$
C_d – drag coefficient [-]
A – cross-sectional area of body [m^2]
u - flow velocity [m/s]

In this study only the drag component will be estimated to limit the scope of the calculations and it is assumed that the drag forces have greater impact than the inertial forces due to very small diameters of the cylinders, which in this case is the net twines.

The flow velocity is incurred by constant currents and oscillating flow from the waves. Only horizontal flow will be considered. The constant flow can be obtained from data on currents at the site. The oscillating velocity, u_x, however is determined by Equation 17[143.]

$$u_x = \frac{H}{2}\omega e^{kz}\sin(\omega t - kx) \qquad \text{Equation 18}$$

With H being the wave height, ω the wave frequency also expressed as $\omega = \frac{2\pi}{T}$, k the wave number determined by $k = \frac{2\pi}{L}$, *t* the time, *x* the direction of propagation, *z* the depth below surface and *L* the wavelength determined by $L = \frac{gT^2}{2\pi}$. For maximum speed $\sin(\omega t - kx) = 1$, further simplifying the expression by substituting ω resulting in $u_x = \frac{\pi H}{T} e^{kz}$.

The velocity is calculated at significant wave height at the thought location.

The drag coefficient was found through the empirical formula developed by Milne[144], see Equation 18.

$$C_d = 1 + 2.73\left(\frac{d}{l}\right) + 3.12\left(\frac{d}{l}\right)^2 \qquad \text{Equation 19}$$

The estimated loads from waves and currents, based on the data previously presented, are shown in Table 7.18.

Table 7.18 Drag forces for the Aquaculture concept

Drag force (from waves)	[kN]	424
Drag force (from current)	[kN]	13
Total drag forces	[kN]	437

Additional weight
The cages will not add any additional weight to the platform since they are self-buoyant. Since the feeding is proposed to be carried out with a service vessel no weight is added from feeding systems either.

Impact from the offshore environment on the added functionalities.
Naturally, the components added in the aquaculture concept is proven to withstand sea conditions but most farm sites are located with some kind of sheltering from open ocean conditions. It is reasonable to assume that locations with better wind resources will result in more demanding conditions when it comes to water movement. An attempt to briefly estimate the drag forces induced by wave motions that could be expected at the chosen location was made in the study. However, the background research indicates that the increased exposure due to more extreme environment is the most difficult challenge and further research will have to be carried out in this area.

Technology Readiness Level
The technology readiness level is very high for the added functionality in the aquaculture concept. If considering the use of conventional fish cages the technology is very mature. Looking at the TRL-scale the technology can be considered to fulfil the criteria of the highest level, 9, which is “Actual system proven through successful mission operation”.

7.4.2 Market potential

Atlantic salmon farming is extensively farmed along the Norwegian coastline, mostly in fjords but also a little bit offshore, if some kind of sheltering is provided. It is an important contributor to the Norwegian economy, with a 40 billion annual turnover, and there is a need for expansion of the industry to meet growing demands on farmed fish partly due to declining wild fish stocks.

An expansion is restrained today by limitations in the volumes of fish that can be farmed in Norwegian waters. This is due to the fact that the suitable sheltered waters are limited. Therefore there are strong incitements to develop farms that can be located further offshore. A strong indication on this is the development of concepts for exposed locations by actors like Marine Harvest.

7.4.3 Other strategic factors

A brief summary of the result is presented in Table 7.19 below. Analysis and explanation in more detail then follows.

Table 7.19 Summary of Other strategic factors

	Results
Business strategy and innovation strategy	Considerable sidestep from Hexicon's core strategy. May cause complications due to different type of stakeholders.
Timing of entry	Being first to market would presumably be favourable.
Consenting process	Fish cages placed further offshore than current could benefit from assumed less strict environmental assessments.

Business strategy and innovation strategy

An important issue when it comes to business strategy is that the aquaculture concept involves a whole new set of stakeholders. Primary additional stakeholders that were identified are seafood companies, fish industry and environmental authorities and buyers of fish. An obvious problem is who the customer of such a concept is. It is difficult to believe that an energy company is able to operate an aquaculture business in a successful way and vice versa. When it comes to ownership there are three way that has been identified: an energy company as a main owner letting a seafood company operate fish farming on the platform generating lease revenues for the energy company; a seafood company as main owner producing the energy needed for the fish farming operations and sell the rest of the electricity; a joint ownership where the energy production is operated by an energy company and the fish production by a seafood company.

Timing of entry

Some aquaculture companies are already developing concepts for offshore aquaculture. However the challenges that come with increased exposure have been holding the realisation of concepts, at least off the coast of Norway. Not being a company in the aquaculture industry originally, collaborations with relevant actors in the industry would be crucial for possible development. Considering this, it is likely that a company solely focusing on fish farming as its core business would be the first to the market. This was considered as a positive thing, since there are many challenges and better to let someone else take the lead. Being an energy producing platform, also gives the possibility to offer something new to the offshore aquaculture market even if not being the first to commercialise a product.

The aquaculture industry is in great need of taking the farming further offshore. However studies on the development of offshore farming sites highlights many problems that need to be solved. The basic technologies for farm sites in locations with a moderate exposure to difficult wave conditions are however available.

Consenting processes

It is reasonable that a site further offshore will imply less strict requirements on the impact on the seabed since a greater depth would mean increased diffusion of fish waste. However this is not known since no permissions have been issued for open ocean locations.

Another scenario is that the platform would need to be located in somewhat more sheltered due to possible limitations caused by the net cages ability to withstand the same forces as the platform itself. This scenario is represented in this study. However it has not been taken into consideration here which difficulties may arise with the consent to install a large turbine platform relatively close to land. The challenge clearly lies in finding locations providing rich wind resources and limited exposure far enough from inhabited coastal areas.

8 DISCUSSION

8.1 Method discussion and source criticism

The frame of reference for this study was mainly based on articles published in scientific journals with high reliability. When it comes to the field of floating offshore energy, it is a rather narrow and relatively immature field resulting in a limited amount of relevant studies and other publications.

Research on processes for qualitative evaluation methods for offshore wind related projects, were quite limited as well, if not non-existent. Naturally this resulted in a lack of reference material for evaluative case studies in the specific area, applying qualitative evaluation methods. This was solved by studying and using evaluative methods for more generic innovation projects as well as incorporating semi-structured interviews with relevant experts for each field.

For information regarding the specific case studies, the use of information and other input from several sources was an attempt to increase the reliability of the gathered information. The differences in the fields that the three concepts represent, with varying level of technology readiness naturally result in a difference in the level of detail of the information that could be obtained. It should therefore be noted that there is a relatively high uncertainty in information regarding costs and potential outcomes. Then again, this is one of the reasons for highlighting the need for incorporating qualitative factors for innovation projects like these.

A high involvement of employees on Hexicon may have influenced the outcome of some parts of the study. This was a risk that was considered necessary since much of the input needed to carry out the study had to be obtained from Hexicon. The idea generation and screening workshop was also carried out only with employees from Hexicon, which may have created limitations in the idea generation. However, in the evaluation process Hexicon employees have mainly acted as a support and help with technical aspects, which enabled the evaluation and should hence not have affected the final outcome too much. An object evaluation of the three concepts was in their interest as well.

8.2 Results discussion

The estimations of economic impact did not indicate any significant differences when adding fish farming equipment or wave energy converters compared to the base cases for each scenario. The results showed a negative impact on the cost of energy when adding WECs. It should be noted that the test site for the wave energy concept is optimised for wind energy testing and therefore not having the most optimal wave conditions. A location with more suitable wave environment would affect the output generated from the WECs integrated in the concept and possibly contribute to lowering the cost of energy instead of increasing it, as was the case in this study. Due to the lower TRL, compared to the other concepts, there is greater uncertainty when it comes to estimations of energy output. This needs to be considered when looking at this alternative. With reference to the estimations of cost of energy for WECs in general presented in the report from SI Ocean (see section 5.2.1) it should be expected to decrease significantly with future development and increased installed capacity, making this a more promising technology to integrate in the future.

The output from the fish farming is very much dependent on the capacity of the cages integrated. It was considered not possible to integrate more cages due to risks for oxygen depletion in downstream cages. But with a greater draught of the platform, the depth of the cages could be increased as well with an increased production volume as result. It should however be noted that the number of cages to limit the risk of oxygen depletion is based on assumptions and if estimated through simulations it could possibly show a possibility to integrate up to three additional cages, almost doubling the production.

The addition of PV resulted in a more evident change in a positive way, by lowering the cost of energy and increasing the internal rate of return. This can partly be explained by lower installation costs compared to the WECs for similar installed capacity. It can also be linked to relatively low wind resources on the chosen location, resulting in a greater impact of another energy source such as solar irradiation. This result could motivate the addition of PV for locations with lower wind penetration.

The addition of a PV system as well as equipment for aquaculture resulted in rather limited additional loads and interferences with the platform structure. The additional load induced by waves and current on the aquaculture cages, based on values for 50-year return period, is relatively small. It should be noted that the wave induced forces increases proportional to the square with increased wave particle speeds, a result of increased wave height. The chosen site for this concept is relatively protected and should not be considered as an offshore site per definition. It was chosen due to its relatively large exposure to waves with fair to good wind resources.

The addition of WECs in the proposed way however resulted in significant demands on the platform’s ability to handle vertical forces in the attachment points for the WEC buoys. However it is very difficult to estimate how the lift forces from each unit works simultaneously. This is something that would need to be simulated to make more accurate estimations of the affecting forces. The wave energy concept also required an increased draught of the platform for the WEC buoys to have enough space in large wave heights. A suggestion was to create a concept where additional structure was to be added below the lower beam of the platform. However, the load requirements that this additional structure would have to fulfil seemed difficult and costly to live up to. Also, an additional structure under the main one would most likely involve negative aspects for construction in a dry dock as well as transportation to installation site. Therefore, a solution requiring an extension of the nodes and other vertical structural elements seemed like the best option.

The technology readiness level (TRL) for the PV and aquaculture addition was identified as very high, being developed technologies at TRL 9. An uncertainty still lies in how performance of the PV-panels might be affected by the environment, due to limited research available on the area. The wave energy addition was clearly the least developed, however determined to TRL 5.

A big challenge that was identified with the combination with aquaculture is the need for monitoring and daily operations since the concept used in this study did not include a service and feed barge, which is common practice with most conventional fish farms. The daily monitoring and feeding becomes dependent on weather conditions and there might be days when servicing and feeding is not possible. Current regulations demand daily monitoring of farm sites. A solution could be to have a service boat accommodating the staff and making it possible to visit all platforms in a park each day. However there are sites that are fully monitored and controlled from land via video surveillance and remotely controlled operations and it is reasonable to believe that these regulations will change with more advanced and more reliable control systems.

Input from potential owners and operators was left out in this study due to scope limitations. However it was identified to be an important step in further evaluation of the concept. This has been identified as a probable next step for further development. The results from this study, however, may be a good foundation for discussions with potential stakeholders.

As presented in the background research, there are cases with combination of solar and wind energy that are beneficial as it makes the overall energy generating capacity of the system less intermittent. This also applies to the combination of wind and wave energy, since the wind and waves not necessarily act on the platform. The benefits of different energy sources to reduce intermittency in the system was not estimated in this study, still it is an important factor that could be further investigated and potentially increase the motivation for having a platform with multiple energy sources.

8.3 Suggestions for future work

There is a future need for detailed analyses of certain technical aspects, in particular the following areas are necessary to address:

- The added loads caused by the integration of WECs
- The structural behaviour of a Hexicon platform due to the potential stiffening the mounting structure of a PV-system may cause
- The effects on efficiency due to salt covering of the solar panels

Due to the relatively small increased capacity of the PV and WECs in particular, investigate options for up scaling of the capacity of both PV and wave energy for a larger contribution to total capacity. Another option would be to evaluate the potential of co-located wind and wave farms, using only the offshore grid connection cable as common component.

Moreover, finding optimal sites where conditions provide an optimal mix of energy resources to maximize yield will highlight specific areas of interest to further investigate market entry into and may result in concepts becoming highly attractive,

To further develop the aquaculture concept, collaboration with a company within the Norwegian fish farming industry would be necessary to gain valuable input regarding design of such a concept and to investigate models for ownership and operational aspects.

Quantify the benefits of harvesting energy from different renewable energy sources, thus making the system less intermittent.

9 CONCLUSIONS

The calculations of LCOE suggest that added functionalities of the extent used in the investigated scenarios only have limited impact on the cost of energy. The most significant impact was seen with the addition of PV to the platform. It was considered to be a result of the limited added capacity as well as mediocre energy resources at the chosen locations.

The results from the evaluation of technical aspects show varying impact from the three concepts. The integration of PV seems to have least impact from a technical perspective and when it comes to demands for redesign of the original platform. This is followed by the aquaculture concept, based on the assumption that an external feeding and service system can be used. The integration of WECs has the highest demand on redesign, requiring an extended draught of approximately 5 metres.

Investigations of qualitative factors indicated aspects that would be of importance to further analyse. One important aspect would be potential difficulties with ownership and target markets when considering a multiple use platform. This is increasingly evident for functionalities that are not generating energy, such as the aquaculture concept. The overall conclusion regarding the aquaculture concept was that there is great potential, but also great challenges, not only technical but also businesswise due to the need for connection of two distant industries.

Looking at the alternatives, conventional energy sources must sooner or later be replaced by sustainable ones. To combine two renewable energy sources with a viable financial model in a relatively maintenance free set up, the concept theoretically have the potential to be attractive on the energy market.

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10 APPENDIX

Appendix A: TRL definitions adapted for a marine environment[52]

TRL	Description	Indicative Ocean Energy Device
1	Basic principles observed and reported	**Discovery/Concept Definition;** Scientific research begins to be translated into applied research and development where basic principles are observed and reported. Technology concept and application are formulated and investigated through analytic studies and in-depth investigations of principal design considerations. This stage is characterised by paper studies, concept exploration, and planning. **Scale Guide 1:25 – 1:100 (Small Scale)**
2	Technology concept and/or application formulated	
3	Analytical and experimental critical function and/or characteristic proof of concept	**Early Stage Development, Design and Engineering;** Active research is initiated, including engineering studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. **Scale Guide 1:25 – 1:100 (Small Scale)**
4	Component and/or partial system validation in a laboratory environment	**Proof of Concept;** Early stage proof-of-concept system or component development, testing and concept validation. Critical technology elements are developed and tested in a laboratory environment, and computer simulation of the device will be carried out. **Scale Guide 1:10 – 1:25 (Medium Scale)**
5	Component and/or partial system validation in a relevant environment	**Technology Laboratory Demonstration;** Basic technological components are fabricated at a scale relevant to full scale and integrated to establish and verify subsystem and system level functionality and preparation for testing in a simulated environment. Subsystem level interfacing testing demonstrated at model scale. **Scale Guide: 1:2 – 1:5 (Large Scale)**
6	System/subsystem model validation in a relevant environment	**System Integration and System Technology Laboratory Demonstration;** System level interfacing/integration testing demonstrated at model or prototype scale. At this level, representative model or prototype system at a scale relevant to full scale, which is beyond that of TRL 5, is tested in a relevant environment, such as a test facility capable of producing simulated waves/currents and other operational conditions, while monitoring device response and performance. Furthermore, the devices foundation concept shall be incorporated and demonstrated. This stage represents a major step up in a technology's demonstrated readiness and risk mitigation and is the stage leading to open water testing. **Scale Guide: 1:2 – 1:5 (Large Scale)**
7	System prototype demonstration in an operational environment	**Open Water System Testing and Demonstration;** Testing may be initially performed in water at a relatively benign location, with the expectation that testing then be performed in a fully exposed, open water environment, where representative operating environments can be experienced. The final foundation/mooring design shall be incorporated into testing at this stage. **Scale Guide: 1:1 – 1:3 (Large Scale)**
8	Actual system completed and service qualified through test and demonstration	**Open Water System Operation;** The prototype in its final form (at or near full scale) is to be tested, and qualified in an open water environment under all expected operating conditions to demonstrate readiness for commercial deployment in a demonstration project. Testing should include extreme conditions. Production of GWh scale electricity, operating continuously for at least one year. **Scale Guide: 1:1 – 1:2 (Pre Commercial Demonstrator)**
9	Actual system proven through successful mission operation	**Commercial Scale Production / Operation;** Final commercial unit, economic deploymentwhen the technology is ready for mass production and has proven to operate as designed for several years. Array scale projects. **Scale Guide: 1:1 (Full Scale[1])**