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Abstract

The demand for oil & gas resources is forecasted to continue increasing in the next decades. And, since most of the potential onshore areas for exploration are already under production, most of the new discoveries to be done are offshore, in deeper water depths and longer step-outs from land.

Subsea located equipment for control and monitoring of the oil & gas production require supply of electrical power for remote operation of control valves, monitoring of fluid pressure, temperature and flow. Power is typically supplied from an offshore platform or from a land based facility through a subsea umbilical. One alternative configuration is the installation of the power generation equipment close to the consumers, avoiding the use of long and expensive umbilicals and reducing the area needed for power generation equipment in the platforms, among other advantages that can save capital and operation costs.

By reviewing the available power generation technologies for powering subsea production equipmant, ranking them according to a set of parameters, selecting the most feasible concepts and evaluating the cost of these concepts in different subsea cases; this thesis identifies the power generation technologies most suitable for the subsea application. Energy storage technologies are also briefly screened for the subsea application and recommendation is done on the use of a specific one.

The Levelised Cost of Electricity (LCOE) is used to define the most cost effective technology for four different subsea cases (operation of a SSIV, operation of a single subsea well, operation of 8 subsea wells and operation of a subsea boosting station).

It is observed that there is technology available, with high readiness level, that can power subsea equipment, as an alternative to powering from the topside facilities of the platform or from onshore facilities, with considerable cost saving, also solving some other technical challenges faced in long tie-backs and in platform space management.

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List of Abbreviations

AC	Alternating Current.
AUV	Autonomous Underwater Vehicle.
CAPEX	Capital Expenditure.
CO_2	Carbon dioxide.
CSP	Concentrated Solar Power.
DC	Direct Current.
E2P	Energy to Power.
EMEC	European Marine Energy Centre.
EPU	Electric Power Unit.
EUR	Euro.
EV	Electric Vehicle.
GWh	Gigawatt hour.
IMR	Installation Maintenance and Repair.
IRENA	International Renewable Energy Agency.
kW	Kilowatt.
kWh	Kilowatt hour.
LCOE	Levelised Cost of Electricity.
MW	Megawatt.
MWh	Megawatt hour.
NCS	Norwegian Continental Shelf.

NOK Norwegian Krone.

OPEX Operating Expenditure.

OTEC Ocean Thermal Energy Conversion.

OWC Oscillating Water Column.

OWSC Oscillating Wave Surge Converter.

O&M Operation and Maintenance.

PLEM Pipeline End Manifold.

PSP Passive Solar Power.

PTO Power take-off.

PV Photovoltaics.

ROV Remotely Operated Vehicle.

SCM Subsea Control Module.

SDU Subsea Distribution Unit.

SSIV Subsea Isolation Valve.

SURF Subsea Umbilica Flowlines and Risers.

TRL Technology Readiness Level.

TUTA Topside Umbilical Termination Assembly.

TW Terawatt.

UiS University of Stavanger.

UPS Uninterruptible Power Supply.

UTA Umbilical Termination Assembly.

WEC Wave Energy Conversion.

XT Christmas Tree.

1 Introduction

This chapter describes the demand for power in the subsea oil & gas production equipment and the challenges with the power distribution to the subsea equipment. The scope of this thesis, goals, methodology used, limitations and structure of the thesis are also described in this section.

1.1 Problem description and background

The demand for energy resources is expected to continue growing worldwide in the next decades due to the forecasted increase in the world's population and in the standard of living in developing countries, with oil & gas resources dominating the global energy matrix.

Most of the existing potential onshore areas for oil & gas exploration are already under production, leaving most of the new discoveries to be done offshore in deeper waters and longer step-outs from land, where the industry faces new technological challenges.

Deep water oil & gas exploration requires the installation of subsea located equipment for control and monitoring of the production from each well and for assurance of the produced fluids transport to offshore platforms or to land located facilities. Supply of electrical power to the subsea equipment is required for remote operation of production control valves, produced fluid pressure measurement, temperature measurement and flow measurement, and condition monitoring of the subsea equipment itself. This power is most commonly supplied from an offshore platform or from a land based facility through a subsea power and communication umbilical.

The installation of the power generation equipment close to the subsea power consumers, which is the main subject of this thesis, has the following potential advantages:

- To avoid expensive platform modifications for installation of additional power generation in case of new tie-backs to platforms already in operation;
- To reduce the area needed for power generation equipment in new built platforms;

- Shorter umbilical distance from power source to consumers, which can be very beneficial in long step-out cases;
- Reduced fuel costs;
- Reduced CO_2 emissions.

1.2 Scope and objectives

The scope of this thesis is to review the available power generation technologies that can be used for powering subsea oil & gas production equipment locally, and to evaluate the most cost effective technology for four subsea cases with different power demand.

The main objective of this thesis is to identify the power generation technologies that most suit the subsea application and identify the most cost effective technology in specific cases.

1.3 Methodology

This thesis is based on the research methods listed below:

- Literature research for familiarization and understanding of the available power generation and power storage technologies;
- Discussions with UiS supervisor;
- Author's experience in the oil & gas industry;
- Inquiries to power generation equipment manufactures.

And the following activities were defined to achieve the objective of this thesis:

- Survey and review of the current technologies and solutions for powering subsea equipment;
- Survey and review of the available power generation technologies with potential for use in subsea application;
- Survey and review of available power storage technologies to be used as backup power source to the subsea consumers;
- Selection of most relevant power and storage technologies;
- Cost evaluation in different equipment configurations.

1.4 Limitations

For the analysis performed in this thesis, the following delimitations were considered:

- The main focus is on the power supply to the subsea equipment, the communication towards the onshore operators is only briefly described in Section 2 and is assumed to be available through use of fiber optic cables or satellite communication;
- All-electric subsea control system, i.e, valve actuation with use of electrical actuators, is assumed for simplification of the system, with the elimination of all hydraulic components;
- Average annual values are used for wind velocity, tide velocity, solar radiation yield and wave propagation characteristics in the levelised cost of electricity (LCOE) analyses.
- A subsea system offshore Norway, with water depth of 300 m is assumed in the analyses performed in Section 5.

1.5 Structure of the thesis

This thesis is structured as described below.

Section 1 provides the problem description and background, scope and objectives of the thesis, the methodology used and limitations of the work performed.

Section 2 describes the typical subsea production and processing systems, and common practices in the industry for powering subsea equipment for oil & gas production. Challenges with the current solutions are also presented.

Section 3 describes the different types of power generation technologies, with literature study focused on the subsea application, including their main characteristics, cost and considerations. The literature reviewed includes academic books and papers, lectures notes from UiS, technical reports, master and PhD theses and websites from companies and regulation agencies.

Section 4 describes the technologies for power storage currently available and the recommendations for subsea application.

Section 5 describes the subsea topologies used as study cases; the qualitative concept selection methodology used for ranking the most suitable power generation technologies; the quantitative cost estimation for the selected technologies, using the levelised cost of electricity (LCOE) methodology; and the sensitivity analysis performed.

Section 6 provides the conclusive remarks of the work performed in this thesis and describes suggestions for further work that can improve the concept selection of power generation technologies for subsea application.

2 State of the art

This chapter describes the typical subsea production and processing systems needed for oil & gas exploration, with focus on the power distribution to these equipment. The challenges faced by the industry in that respect will also be discussed.

2.1 Subsea production and processing systems

The subsea production system is responsible for operation and control of the oil & gas wells located under the sea water. The complexity can vary from a single satellite well to several wells connected to a manifold, which transfer the produced fluids to a fixed or floating facility or directly to onshore facilities (subsea-to-beach field layout) [2].

A typical subsea production system layout is shown in Figure 1, and is comprised of the following equipment:

- Drilling system;
- Wellhead system;
- Subsea Christmas Tree (XT);
- Subsea Umbilical, flowlines and risers (SURF);
- Manifolds and tie-in system;
- Control system;
- Installation and workover system;
- ROV tools.

In addition to the equipment mentioned above, some subsea fields require the implementation of subsea processing technologies with the objective of handling and treating the produced fluids for mitigating flow assurance issues prior to reaching the platform or onshore facilities [2]; or for boosting the production from the well due to low reservoir pressure.

Figure 1: Typical subsea production system layout

Subsea processing systems can include the following equipment:

- Pump;
- Compressor;
- Separator;
- Sand handling equipment;
- Heat exchanger.

The introduction of subsea processing in the field development may bring benefits, such as: reduction in topside processing equipment, enable marginal field developments (especially at ultra-deepwaters and/or long tie-backs) extend production from existing fields with decreasing reservoir pressure, improve flow management and reduce environmental impact [2].

Figure 2 shows the subsea processing system that includes subsea separation, boosting and re-injection of bulk water into a non-hydrocarbon reservoir [1] for Statoil's Tordis field in the North Sea, that is in operation since 2007 and has increased the field recovery factor from 49% to 55% [20].

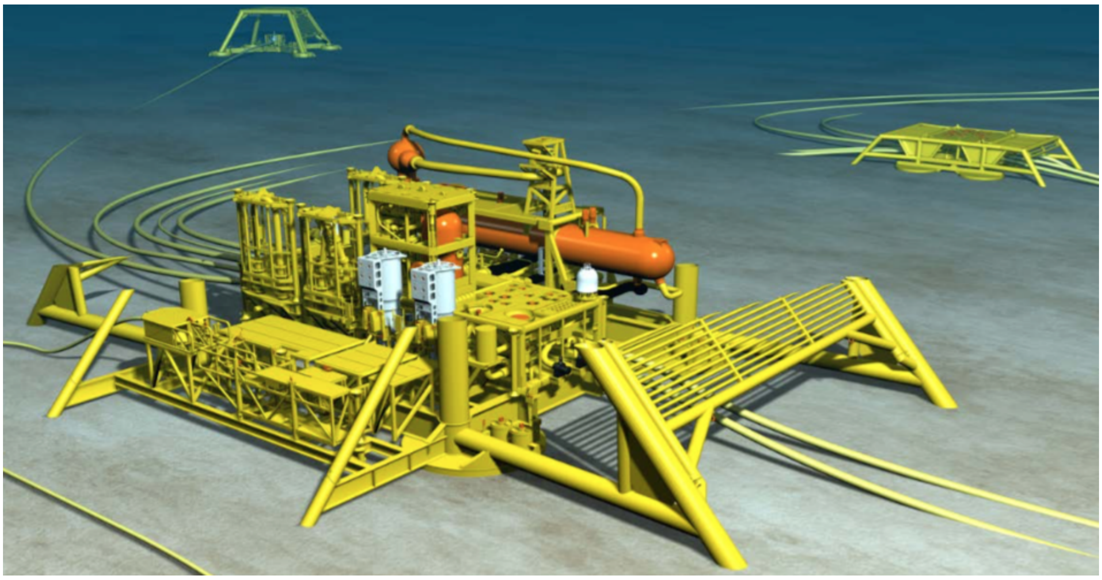

Figure 2: Tordis subsea separation [1]

2.2 Subsea power distribution

The electrical power supply to the subsea production equipment is needed for powering the control equipment responsible for opening and closing of flow control valves and safety valves, and for monitoring pressure, temperature, flow rate in the subsea christmas trees, manifolds and installation and workover systems.

Availability of power supply is also a key factor in subsea processing systems [2], since the amount of power required by subsea motors, which run pumps and compressors, are much greater than what is typically required for a subsea production system.

Power is generated either on the topside facilities of the platform (gas turbines) or onshore and, typically, an uninterruptible power supply (UPS) is used to protect the system from electrical power surges and blackouts [2].

Figure 3 shows a typical subsea control system with power distribution to the final consumers (i.e, actuators in the subsea XTs and manifolds) from the topside power supply through umbilicals. Additionally, Figure 3 shows the subsea distribution system comprised of topside umbilical termination assembly (TUTA), subsea distribution unit (SDU), umbilical termination assembly (UTA) and Flying Leads. A typical electrical actuator for subsea use is shown in Figure 4

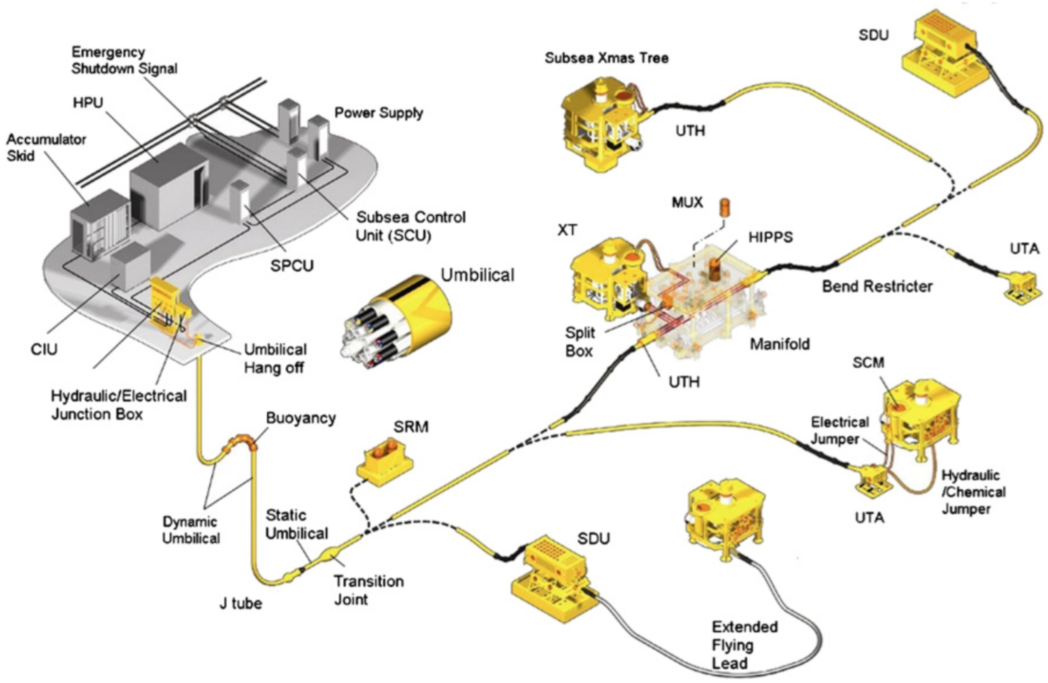

Figure 3: Typical subsea control system [2]

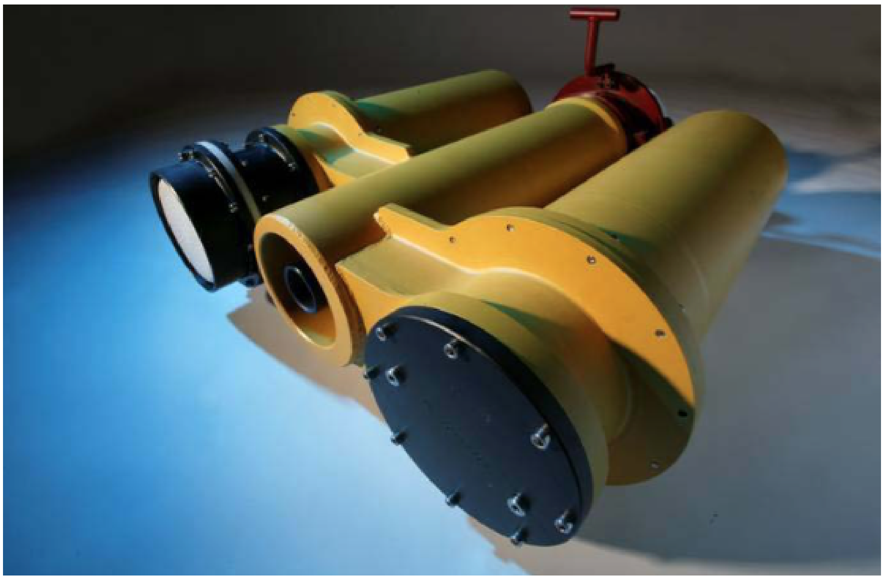

Figure 4: Subsea electrical actuator from FMC [3]

Electrical power to the subsea equipment is supplied by a Electrical Power Unit (EPU), located in the control room of the topside production facility or in the onshore facility. The power transmission is done with the use of subsea umbilical, which has its length varying in the kilometer range, and subsea electrical distribution systems, comprising of electrical jumpers, connectors and distribution boxes.

The UPS can be located in the production facility (offshore or onshore) or subsea, in some cases where there is need to reduce fault sources due to the implementation of safety functions.

The communication from the topside or land based facility to the subsea control equipment is done by use of copper cables or fiber optics, which are also included in the subsea umbilical in a typical configuration.

Figure 5 showns an example of the cross section of a subsea umbilical that includes:

- High voltage power cables;
- Low voltage power and signal cables;
- Fiber optic cable;
- Hydraulic control tubing;
- Chemical injection tubing.

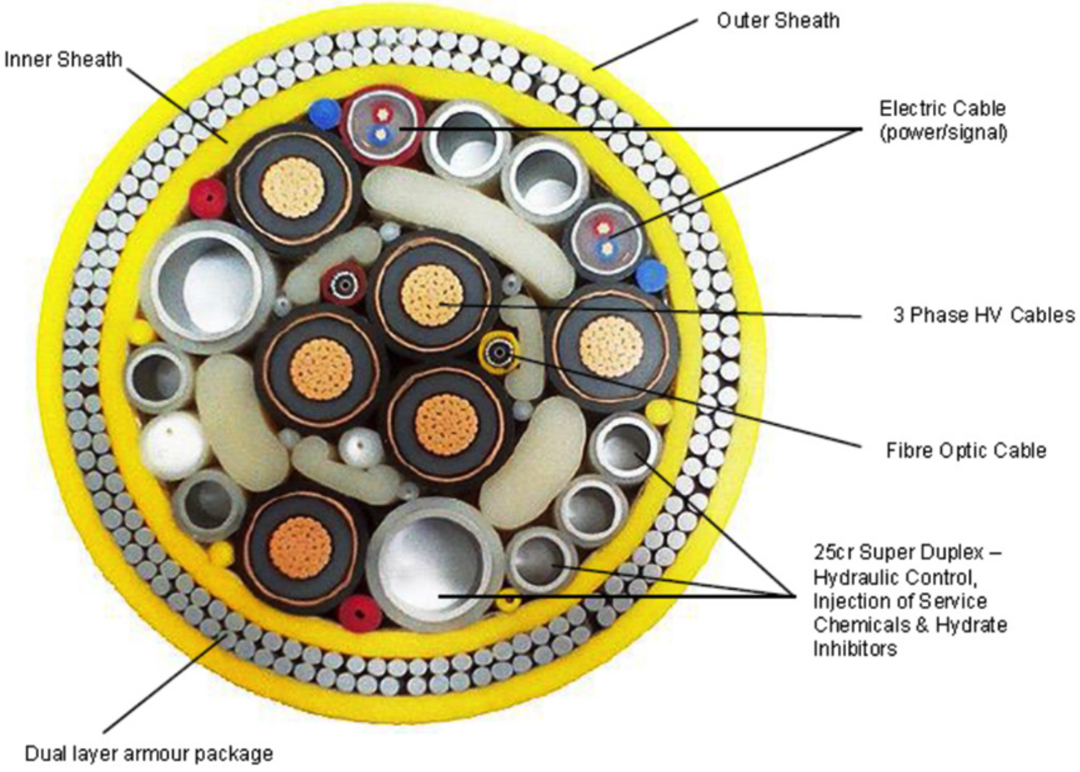

Figure 5: Umbilical cross section example [4]

2.3 Challenges

The supply of power to the subsea equipment from a topside production facility or from an onshore facility has some known design and operational challenges:

- Need of platform modifications for installation of additional power generating equipment (gas turbines) in case of new tie-backs to existing production facilities. These modifications can be considerably costly and, in some cases, there may not exist enough space for installation of new power generation equipment.
- Costly umbilicals in long step-out cases, especially when developing satelite wells with lack of infrastructure nearby.
- Long umbilicals may not be feasible, in cases where tie-back to an onshore facility is needed, due to the high power losses in the AC lines.

Figure 6 and Figure 7 show that only the umbilical can represent between 8-10% of the subsea field development cost, depending on the water depth. The umbilical share in the total cost can also be considered higher since it also takes part of the total installation cost.

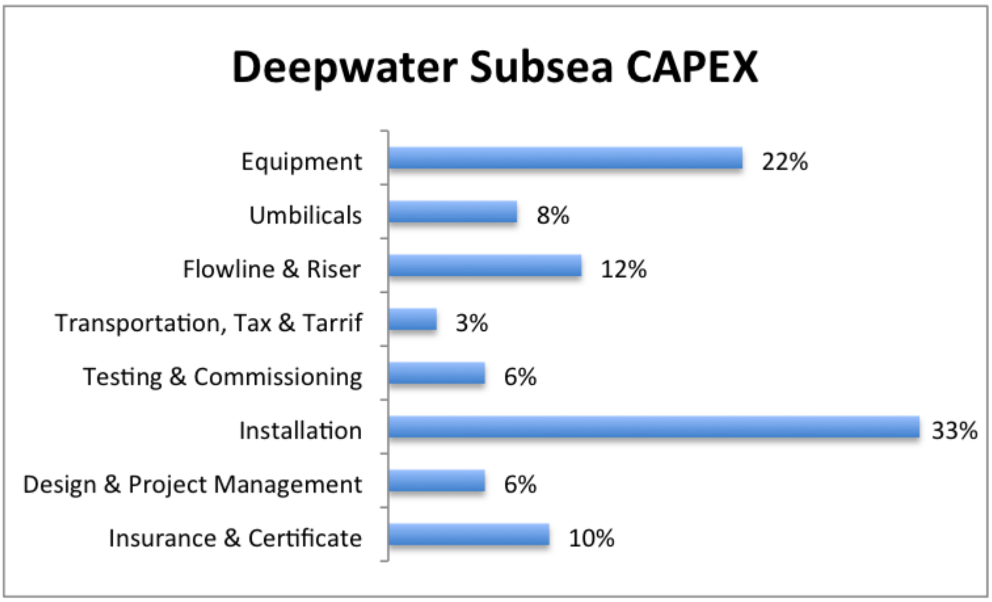

Figure 6: Deepwater subsea CAPEX breakdown [2]

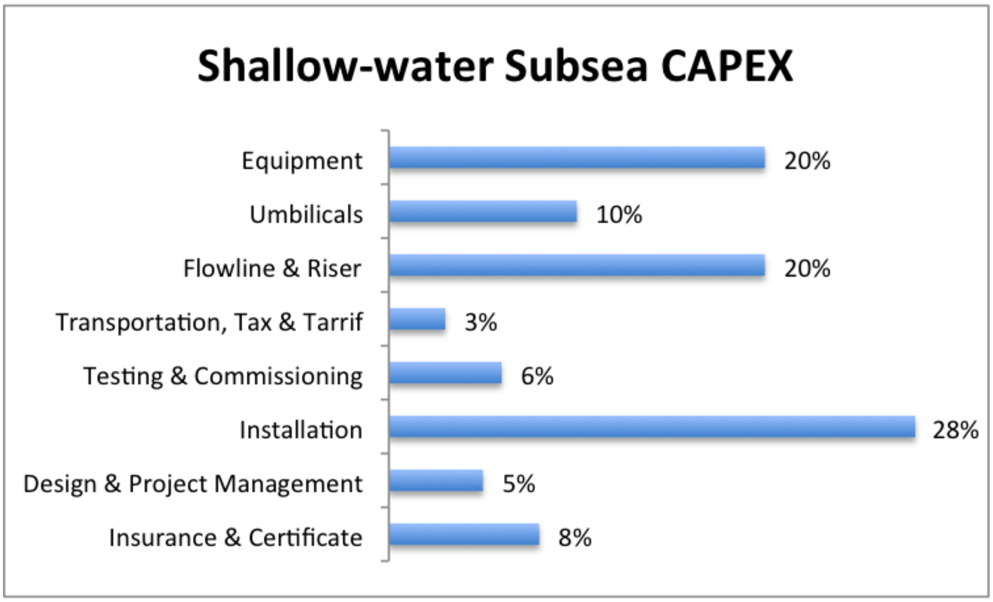

Figure 7: Shallow-water subsea CAPEX breakdown [2]

Figure 6 shows that the efficiency of AC power transmission has exponential decrease with the umbilical lenght. DC power transmission has better efficiency than AC power, but there are no DC components available for subsea operation since subsea DC power is still a technology under development.

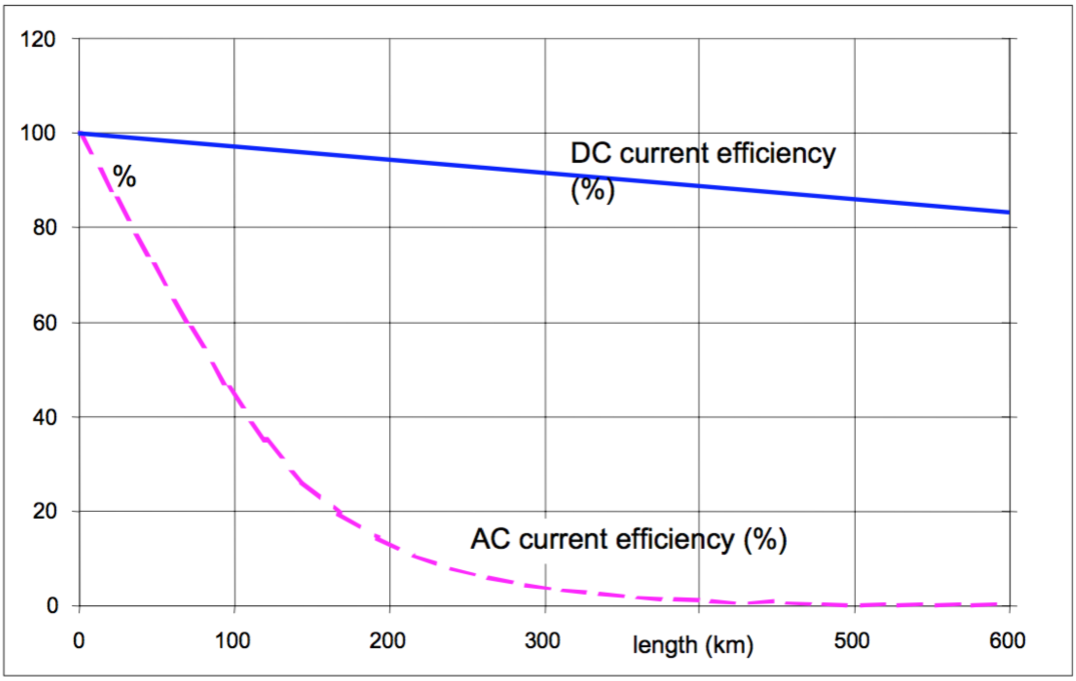

Figure 8: AC and DC power transmission [3]

Alternatively, power can be generated close to the subsea equipment, both on the sea surface or subsea, with the potential of significant cost reduction for connecting the subsea equipment to the power generation equipment. This reduction is possible by the shorter power cable distance and by the elimination of power generation needs on the topside production facility or onshore facility for the subsea production system equipment. This alernative can also make projects with very long step-outs to shore feasible.

Having the power generation equipment close to the subsea consumers may also increase the total subsea production system reliability since the amount of components for power distribution is reduced. But this needs to be analysed in conjuction with the reliability of the new power equipment introduced into the system.

The feasibility and associated levelised cost of electricity with the alternative of having the power generating equipment on the sea surface or subsea will be evaluated as part of this thesis.

3 Technology assessment

This section describes the most relevant ways of generating power offshore and subsea to supply electricity to subsea equipment for oil & gas production. The working principle, type of devices, associated costs and considerations about the power generation concepts are described.

3.1 Solar

Solar energy can be described as the driving force for almost all types of renewable energy, inputing 175,000 TW to the outer atmosphere of Earth. This exceeds the current global energy need per unit time of about 15 TW by four orders of magnitude, having the theoretical potential of providing the primary energy demand of the world [12, 21].

Mainly, three processes are used to transform the solar radiations into energy: solar photovoltaics (PV), passive solar power (PSP) and concentrated solar power (CSP). In PSP and CSP, the solar radiation energy is transformed into heat for increasing the temperature of a working fluid (e.g. water). The heated working fluid is then used for direct heating, in the case of PSP, or for running an electricity generating turbine, in the case of CSP [12]. PV converts light directly into electricity at the atomic level due to the photoelectric effect of some materials that causes them to absorb photons of light, with an intensity distribution given by the Planck curve, and release electrons. Capturing these free electrons creates an electric current that can be used as electricity.

PSP is not relevant for subsea application since the main need in the subsea installed facilities is electrical power, not heating. CSP technique uses mirrors to head the incoming radiation towards a concentrated spot containing the working fluid. The use of floating mirrors offshore may bring many practical challenges due to their fragility and the oscillatory characteristics of the ocean, making CSP also not attractive for powering subsea facilities.

PV is the most relevant for offshore application, and the PV material is the main driver for the efficiency of PV cells. The two most common types of PV cells are silicon-wafer-based and thin-film. Silicon-wafer-based PV cells have higher efficiency rates than thin-film ones but are more expensive. The efficiency of different commercial solar cells are shown in Figure 9. Several types of thin-film PV technologies exist, using semiconductors like Silicon (Si), Cadmium (Cd) and Tellurium (Te) or metals like Copper (Cu), Indium (In) and Gallium (Ga) [12]. It is observed that the efficiency of PV cells, in general, is increasing over time due to the better understanding of the physical processes and enhancements in production techniques [12].

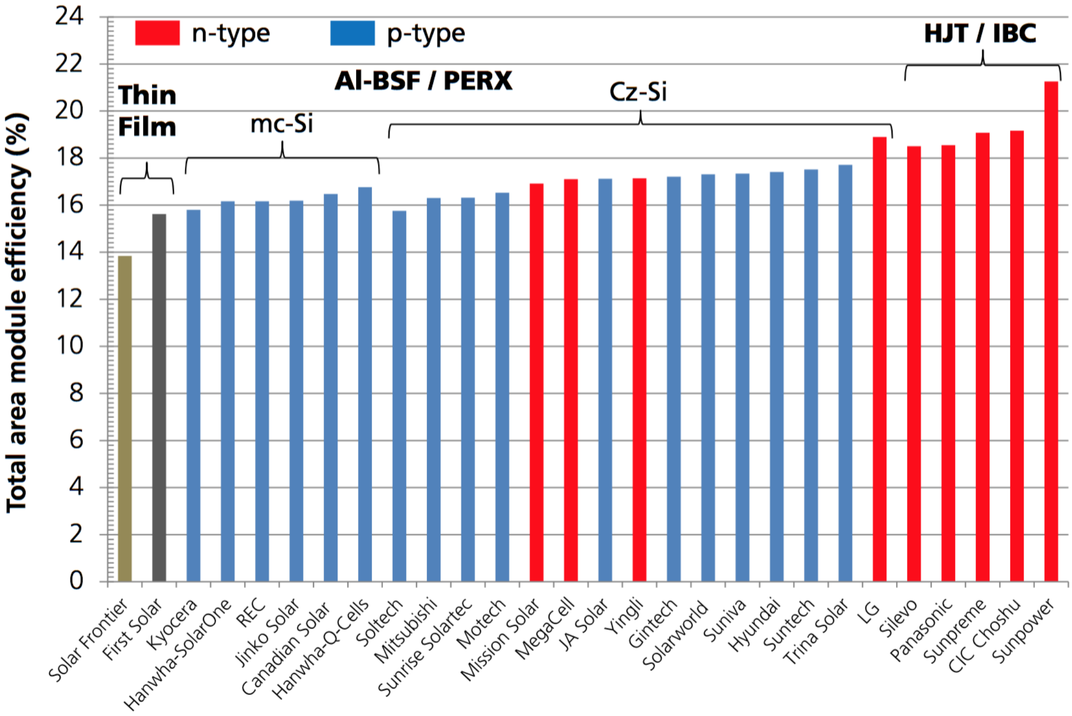

Figure 9: Current efficiencies of selected commercial PV modules [5]

In the analysis performed in Section 5, a solar cell with efficiency of 10% is considered in the LCOE calculations.

Solar energy conversion is limited by the amount of incoming radiation on the location, varing from 200 kWh/m^2.y in Norway to 2600 kWh/m^2.y in Saudi Arabia [22].

Since solar power doesn't require any fuel for operation, the main costs are the capital cost of the solar panels installation (80-90%) and the O&M cost (10-20%) [12]. The capital cost can vary between 2,000-5,000 EUR/kW [12]. O&M costs cover the cleaning of the panels, non-scheduled maintenance and replacement of inverters, which have lower life time than the PV cells. The levelized cost of solar PV, according to [12], is between 128 EUR/MWh and 389 EUR/MWh.

DNV GL developed in 2012 a concept called SUNdy, shown in Figure 10 below, for a large-scale dynamic floating offshore solar field. The concept featured a hexagonal array which floats on the sea surface, totaling 4,200 solar panels and capable of generating 2 MW of power. SUNdy uses thin-film 560 W solar panels which allow them to ondulate with the ocean's surface [23].

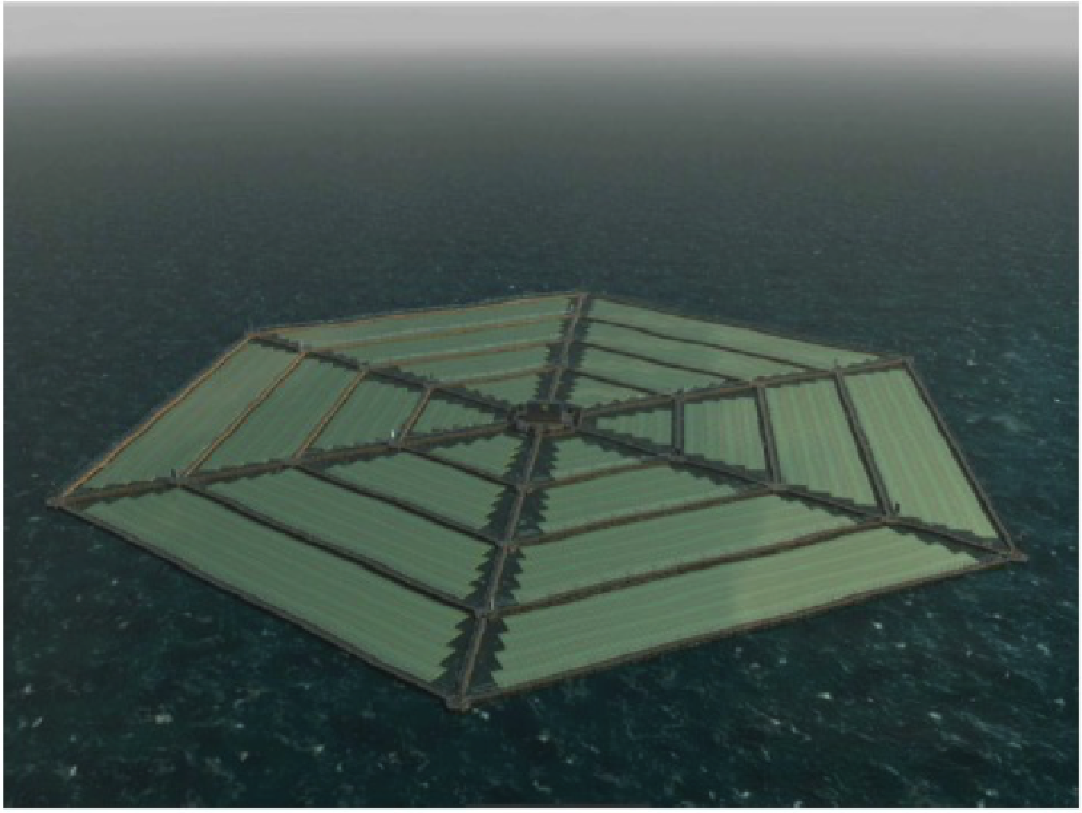

Figure 10: SUNdy concept from DNV GL [6]

There are some floating solar projects under operation and under construction in Japan, in Brazil [24] and in the UK [25], with capacity varing from 1.7 MW to 13.7 MW, but all of them are located in dam reservoirs, which do not see the same weather conditions as in sea waters.

3.2 Offshore wind

The Earth's surface being unevenly heated by the sun, where the poles receive less solar radiation than the equator, combined with the rotation of the planet and the distribution of land and sea areas, create air flows where less dense warm air rises while more dense cooler air flows, taking the place of the warm air and creating winds patterns. Electricity is produced by wind turbines converting the kinetic energy of the wind into electrical power by placing rotor blades in a position that allows wind to blow past them, making the blades to rotate and drive a shaft connected to a generator. Wind energy is considered a second generation solar energy, having theoretical potential of 130 TW of available power, but considering 2% of the Earth's area and offshore wind power, could reach around 5 TW [12].

The wind speed is the most crucial factor influencing the power output of a wind turbine, because the wind speed contributes by a cubic dependence to the output [12]. Wind speeds are generally higher offshore (5-7 m/s in average) than on land (3-5 m/s in average), making offshore wind turbines attractive in the power output perspective, but a specific spot location can have large variations in wind speeds over time and, as highligheted in [12], is a key factor in defining the economic viability of wind power.

Wind turbines can have horizontal or vertical axis, but horizontal ones are the most common, both onshore and offshore, due to their better aerodinamic efficiency. The maximum efficiency of a single wind turbine, independent of the wind velocity is about 60%, according to Betz's theory [12, 26], but considering the conversion process from mechanical to electrical energy, total efficiency of wind turbines is around 30-40%. Direct drive generators, eliminating the need for the gearbox, are being developed and may improve the efficiency and reliability of wind turbines.

Offshore wind is more feasible with the use of large-scale wind turbines, from 2 MW to some lager units with capacity of 5-7 MW, but too large wind turbines can be very expensive due to the much higher installation costs [12]. Most of the offshore wind turbines in operation are located in shalow waters, between 10 and 50 meters of water depth [27] with fixed foundation structures, such as the ones used in the Horns Rev 1 offshore Denmark [28], the London Array [29] and the Sheringham Shoal Offshore Wind Farm [30] in the UK. However, there are some concepts under development with floating wind turbines, as the Hywind concept from Statoil that had a pilot project installed in 2009 in the south-west coast of Norway in a water depth of 200 meters [31] and a pilot wind park off the Scottish coast in a water depth of 100 meters that is planned to final commissioning in 2017 [32], and the WindFloat installed in 2011 off the Portuguese coast [33].

As wind power depends only on wind for electricity production, it doesn't require any fuel for operation, the main costs are the capital cost of the wind turbines, foundations and installation (70-94%) and the O&M cost (6-30%) [12]. The capital cost can vary between 2,000-5,000 EUR/kW for offshore wind turbines due to the lower maturity compared to onshore wind turbines and their challenging and expensive installation [12]. The levelized cost of offshore wind power, according to [12], is between 95 EUR/MWh and 124 EUR/MWh.

Most of the wind turbines in operation up to today are generating electricity which is connected to the grid [12]. DNV GL has launched a JIP called WIN WIN for development of a pilot project of a wind powered subsea water injection system. The main concept diagram of the WIN WIN is shown in Figure 11.

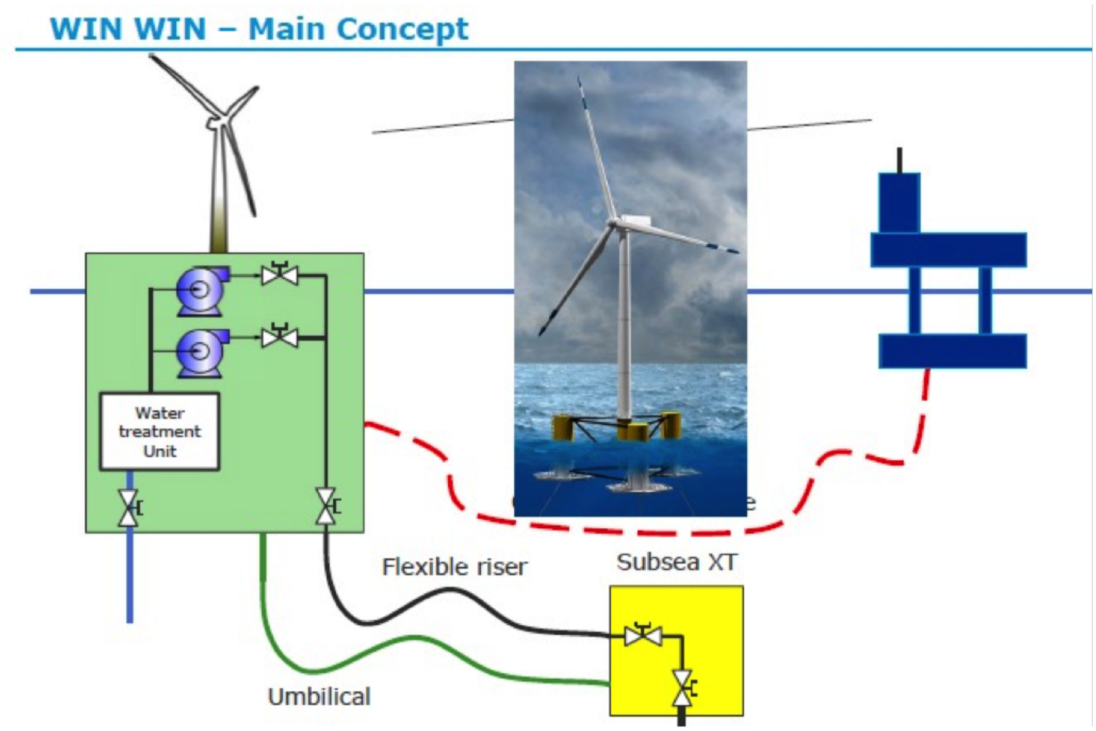

Figure 11: WIN WIN concept from DNV GL [6]

Wind power is already a well established technology, with many wind turbines in operation, both onshore and offshore, which contributes to the lower costs and risk when compared to other renewable energy sources, such as wave and tidal. On the other hand, wind turbines require periodic inspection, which can bring O&M challenges and higher costs for offshore wind turbines, especially in deep waters, where the remote location has dificult access for maintenance personnel [26, 34].

3.3 Wave

As a fraction of the solar energy is transformed into wind, and a fraction of the wind energy is turned into energy carried by the waves, the wave energy is called as tertiary solar energy [12]. Global resources of wave energy have a theoretical potential of more than 1 TW [35]. Micro ripples in the water, hit by the wind field, form waves, where both wave height and speed depend on the driving wind speed [12].

Several wave energy conversion (WEC) principles exist, using different solutions to absorb energy from waves. The European Marine Energy Centre (EMEC) has identified eight main types of WEC devices [36]:

- Attenuator
- Point Absorber
- Oscillating Wave Surge Converters (OWSC)
- Oscillating Water Column (OWC)
- Overtopping Device
- Submerged Pressure Differential
- Bulge Wave
- Rotating Mass

The WEC technologies need these basic components: 1) structure and prime mover that captures the energy of the wave; 2) foundation or mooring keeping the structure and prime mover in place; 3) power take-off (PTO) system by which mechanical energy is converted into electrical; and 4) control system for safeguard and optimisation of the operating performance [37].

Wave speed, wave length, water density and maintenance cost of the mechanical systems exposed to varying forces over a long period of time are the main factors influencing the economics of wave power [12]. Due to the low level of maturity of the several WEC devices nowadays, the estimated levelised cost for wave energy is between 330-630 EUR/MWh, but is expected to drop to 150-180 EUR/MWh by 2030 [37], when technology maturity and the economies of scale will bring the cost to the same level as solar and wind energy.

Many companies are currently working on the development of WEC devices, where more than 100 pilot and demonstration projects exist throughout the world [37]. EMEC's website has an extensive list covering these companies worldwide [36]. Ocean Power Technologies (OPT) has developed a moored floating wave converter called PowerBuoy that has been through field trials in Hawaii, Scotland, Spain and off New Jersey, with system rating of 40 kW, 150 kW or 500 W [7]. A concept using OPT's PowerBuoy as power source for a subsea system can be seen in Figure 12.

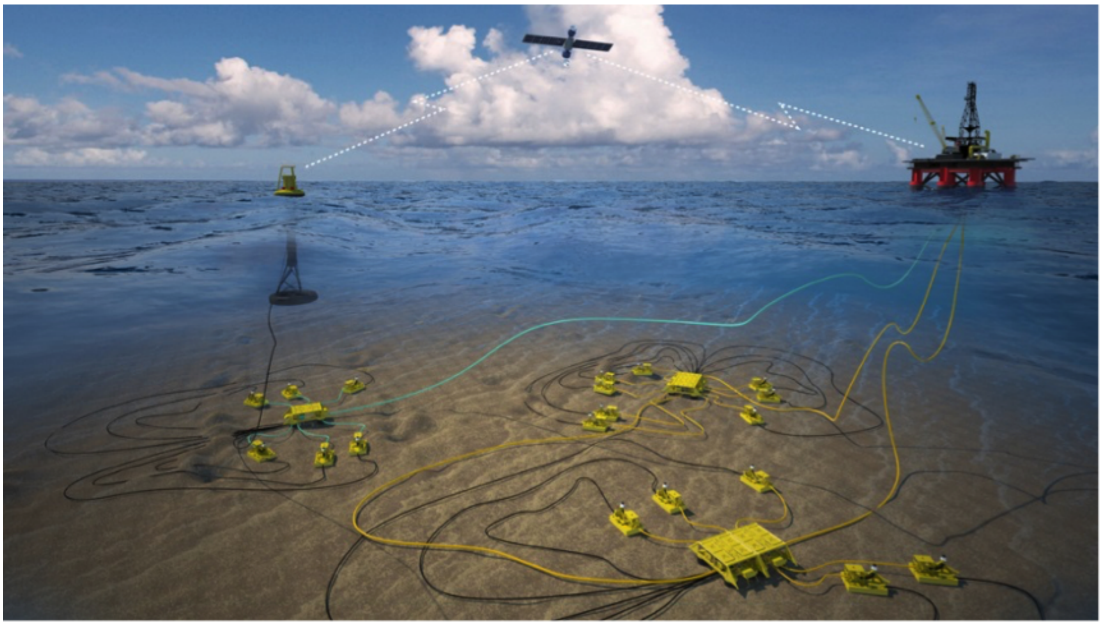

Figure 12: PowerBuoy concept from OPT [7]

WEC devices are submitted to a large variation of power and forces, where a feasible system needs to produce electricity at average wave climates while still being able to survive harsh weathers and storms [38]. Friction with the seabed decreases the wave energy density near the coastline. For this reason, wave energy density is higher in deeper waters.

3.4 Tidal

The oceans water level rises and falls in a predictable manner as tides, as the result of gravitational interaction between the Earth, the Moon and the Sun [12, 39]. Due to the known astronomical periodicities and constant effects of particular coastlines, prediction of tidal rhythms and amplitudes is mathematically exact, with main diurnal period τ of 24 hours and semi-diurnal period of 12 hours 25 minutes, with change in height between successive high and low tides R between 0,6 m and 10 m, and water movement that produces periodic tidal currents [40]. Worldwide potential for tidal energy is estimated at 1 TW [40].

Tidal energy has the advantage of being highly predictable with daily, bi-weekly, biannual and even annual cycles over a longer time span of a number of years, being able to generate energy both during day and night, and not much influenced by weather conditions [40].

Tidal energy technologies can be divided into 3 categories: tidal range technology, tidal current technologies and hybrid forms from the previous types. For offshore application, tidal current technologies are the ones of most relevance, converting the kinetic energy from tidal current or tidal stream into useable energy. There are several types of tidal current devices, such as horizontal-axis axial turbine, vertical axis cross flow turbine, reciprocating devices, rotating screw-like devices and tidal kites. Horizontal axis turbines are the most used ones so far, around 76%, having similar turbine designs to the ones used for wind turbines [40]. The stream speed needed for tidal current technology is of at least 1,5-2 m/s.

Since tidal current technologies are still in the demonstration phase, the levelised cost of electricity is higher than other types of renewable energy, in the range of 250-470 EUR/MWh, but it is expected that tidal current technologies achieve a high level of maturity within the next 5 years, with estimated levelised cost of electricity around 170-230 EUR/MWh in 2020 [40]. It is worth mentioning that tidal power technologies are capital-intensive, with no fuel cost needed [12], and O&M cost on the same level as for offshore wind power.

Several companies have tidal energy devices in different readiness levels, the technology survey performed by the SP Technical Research Institute of Sweden [41] has a comprehensive list of tidal devices and developers. And large turbine manufacturers as ABB, GE, Siemens and Voith Hydro have entered the tidal current sector [40]. Openhydro has a design for a open-centre turbine that is deployed directly on the seabed that has already been commercially deployed in Scotland and France, and has other projects under development in the UK, France and Canada [8]. Figure 13 shows Openhydro's open-centre turbine concept.

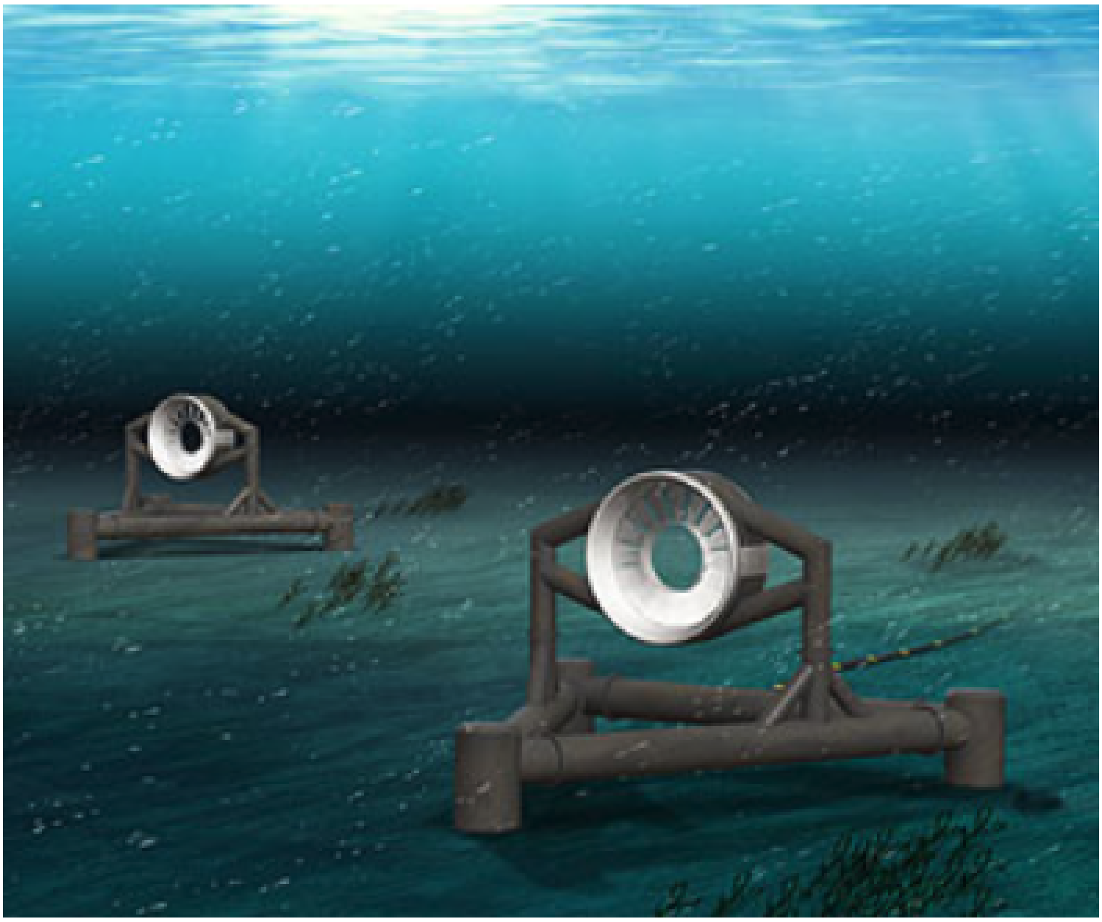

Figure 13: Open-Centre turbine concept from OpenHydro [8]

3.5 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) is the process of extraction and conversion of thermal energy into useful work for electricity generation by using the temperature difference of about 20°C between deep cold ocean water ($\sim$ 5°C) and warm tropical surface waters ($\sim$ 25°C) to operate heat engines [39]. This technology is mainly viable in equatorial areas where the temperature differential is about 20°C year round. It has a theoretical potential of 30 TW and deployments of up to 7 TW would have little effect on the oceanic temperature fields [42].

Figure 14 shows the working principle for OTEC, where a heat engine operates in a closed-cycle Rankine process, with a working fluid (e.g. ammonia) boiling in the evaporator and driving a turbine-generator for electricity supply; while on the output side of the turbine, the vapor condenses due to the pumped colder water [39].

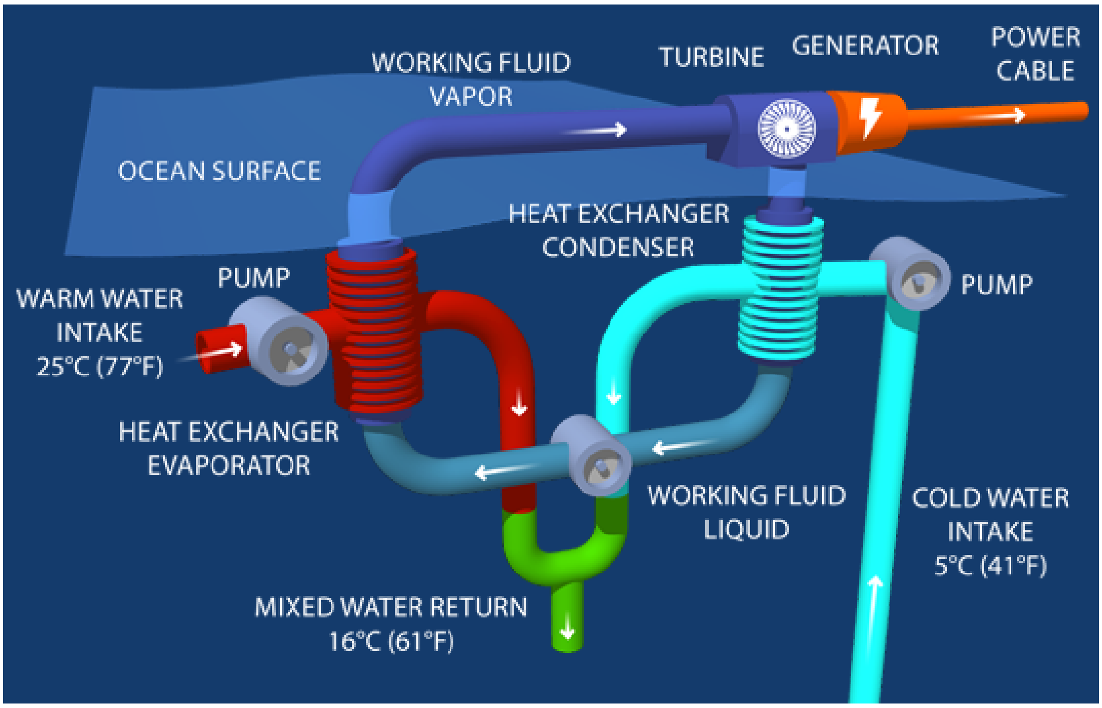

Figure 14: OTEC working principle [9]

An alternative open-cycle system can be used. The system has the same thermodynamic principles and limitations of the closed cycle OTEC, but using sea water as working fluid, which evaporates at reduced pressure before passing through the turbine and resulting in distilled water as condensate [39].

OTEC has the advantage of being able to provide electricity on a continuous basis, with a capacity factor around 90%-95% [42]. But the small temperature differential requires very large volumes of water at minimum pressure losses, with large seawater pumps and piping systems operating continuously in a hostile and corrosive environment [42].

The water temperature differential could be raised by, for example, using offshore solar ponds or solar thermal heating to increase the surface water temperature [42], but this concept has not been much explored yet.

The technology readiness level of OTEC is relatively low with just a few test facilities deployed, all with no long-term operation [43]. Besides, most OTEC projects have been deployed and seem economically viable in island countries and remote island states in tropical seas where generation can be combined with other functions (e.g. air-conditioning and fresh water production) [42].

The largest OTEC project still in operation is the 1 MW plant in Hawaii

(1993-1998), but some 10 MW projects are under development [42]. DCNS and Akuo Energy are developing a 10.7 MW OTEC plant in Martinique, called NEMO (New Energy for Martinique and Overseas), that is planned to start operation in 2016 [10].

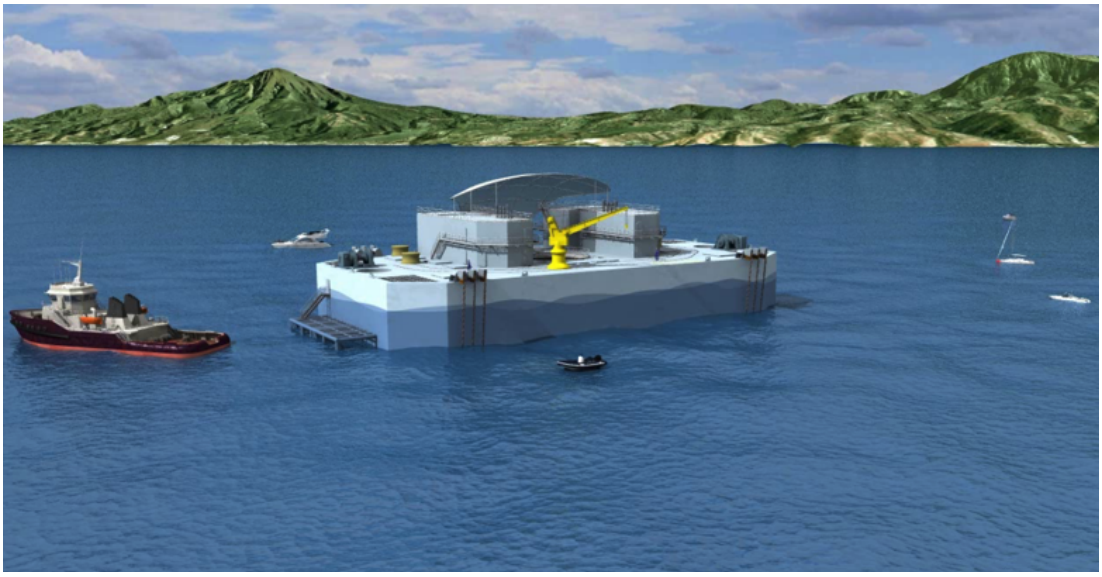

Figure 15: NEMO OTEC from DCNS [10]

Since the amount of OTEC projects is limited, most of the cost references come from feasibility studies, and the International Renewable Energy Agency (IRENA) [42] has summarised the levelised cost of electricity in USD/kWh from different sources and identified the main four cost drivers:

- Scale of the project;
- Choice between open and closed cycle designs;
- Production of by-products;
- Environmental conditions at the location where the cold water is extracted.

For a small scale project with size of 1 MW, the levelized cost of electricity is estimated around 600-940 EUR/MWh [44], but OTEC is more likely to be deployed as a large-scale power plant in the multi-MW range [45].

OTEC is currently an immature technology with expected high cost of implementation, but there are pilot projects under development that can help bringing the cost down. Due to its continuous power generation and high power output, OTEC can be an interesting technology for subsea processing projects where large compressors and pumps are required. Other potential solution is the combination of OTEC with CO_2 injection by using the evaporator output to absorb CO_2 and then pump it down into subsea reservoirs [39].

3.6 Nuclear

The french company DCNS has developed a subsea modular power plant with output capacity between 50 and 250 MWe, shown in Figure 16, comprising a small nuclear reactor, a steam turbine-alternator set, an electrical plant and associated electrical equipment, that can be deployed at a water depth of maximum 100 m and with a design life of 60 years [11]. But with production cycles of 40 months, need for major overhaul every 10 years and need for transportation to a support shipyard for refuelling and maintenance [11], the LCOE is expected to be very high compared to other technologies for supplying power to subsea equipment.

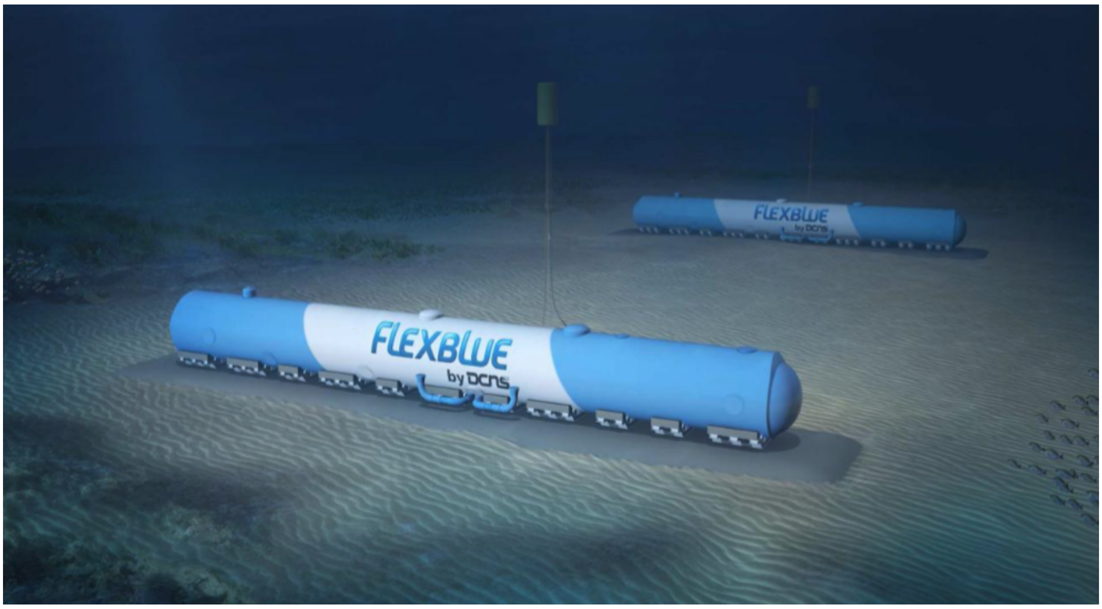

Figure 16: Flexblue concept from DCNS [11]

The risk associated with use of nuclear reactors subsea requires a deep accessment, and the actual political pressure against nuclear energy, especially after the Fukushima disaster in 2011, would pose an additional challenge for the implementation of a subsea nuclar power plant pilot project.

3.7 Turbo generator

A turbo generator, installed in the subsea production line, driven by oil or gas, and connected to a generator represent an option to generate low power. A turbo generator system, including AC/DC converters, rechargeable lead acid battery and lubrication accumulators was developed as part of the Deep Water Autonomous Multi-Well Production Systems (DAMPS) between 1990 and 1992, with power generation of 700 W [46], but the turbo generator concept for subsea use continues as a potential technology with little development.

3.8 Other technologies

Salinity gradient, the extraction of useful energy from the difference in salt concentration between the ocean and a nearby source of fresh water [39], **thermoelectric generation**, with use of thermoelectric generators (Seebeck effect) that can exploit the temperature difference between the production fluid at the well head and the seafloor water, and **deep ocean current** (e.g. the North Atlantic drift, the Gulf Stream and the Florida Straits current), are technologies that have had little industrial engagement and remain as technologies with low readiness level, where mainly laboratory experiments have been performed so far [43].

4 Energy storage

Some of the energy generation technologies described in Section 3, especially the renewable ones, are intermittent sources of power, making energy storage necessary for reliable constant supply to the subsea power consumers and power smoothing due to generation fluctuations. Table 1 summarizes the types of power source considered in this thesis and their type of supply (constant or intermittent).

Table 1: Power sources type

Power source	Type
Offshore wind	Intermittent
Tidal	Constant
Wave	Intermittent
Solar	Intermittent
OTEC	Constant
Turbo generator	Constant
Nuclear	Constant
Salinity gradient	Constant
Deep ocean current	Constant

Figure 17 shows an example of electricity production profile for a 1 MW solar PV power plant on a hourly basis over four days, where the intermittence characteristics can be observed with peaks of electricity production during the day and zero production during the night time.

Another example of the intermittency of renewable energy is given in Figure 18 for wind power, where wind speed variation within one day is shown with measurements each 5 minutes.

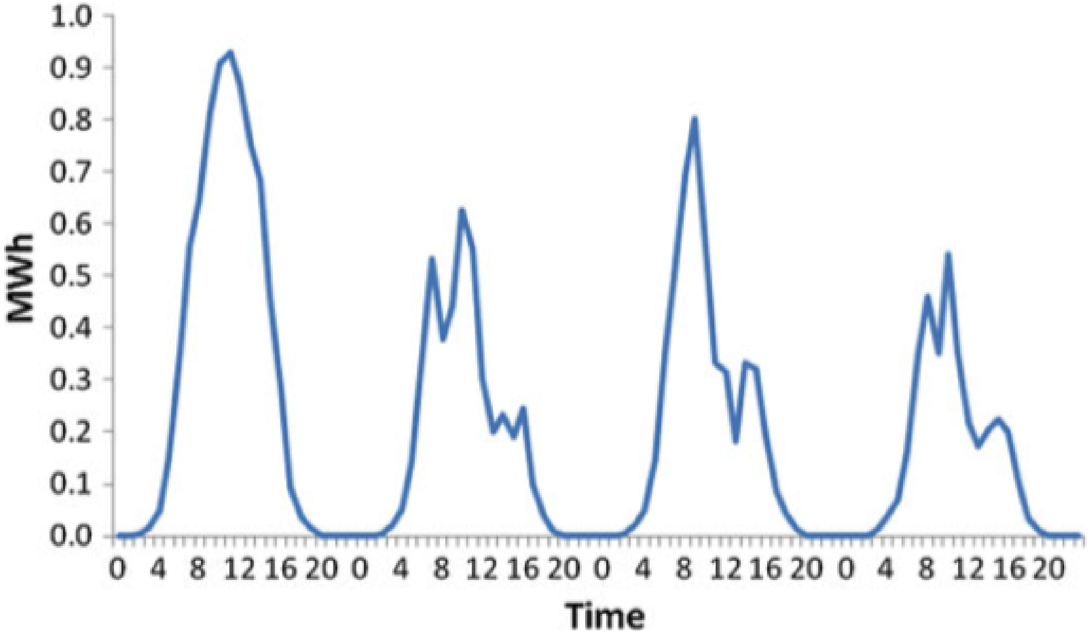

Figure 17: Electricity production profile on an hourly basis over four days of a 1 MW solar PV power plant [12]

Figure 18: Daily wind variation measured each 5 min at a weather station in England for October 21st, 2013 [12]

4.1 Storage technologies

There exists a wide range of storage technologies, that can be scientifically categorised as: mechanical, thermal, chemical, electro-chemical and electrial, as shown in Figure 19.

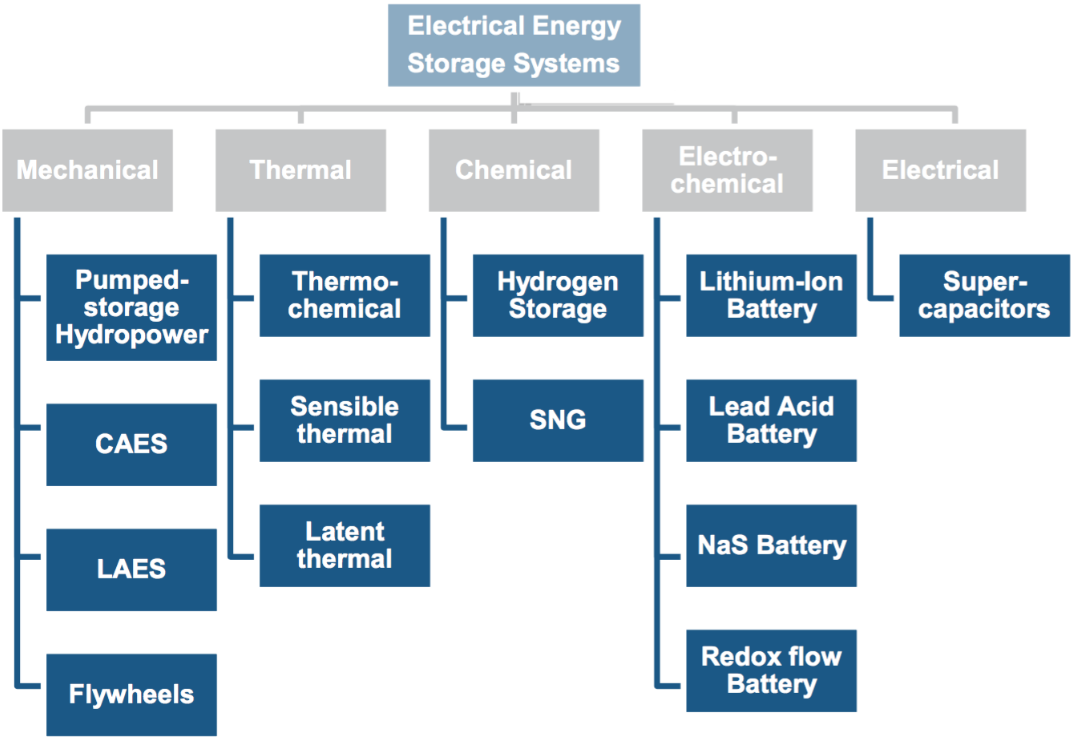

Figure 19: Scientific categorisation of storage [13]

Figure 20 shows a map of the different energy storage technologies currently available, their energy capacity and discharge time at rated power range, which are important factors when deciding the technology for energy storage in different applications. Other relevant factors in the decision making are cost and power density (volume and weight).

Since the main focus of this thesis in on the power generation technologies, the energy storage technologies are not deeply detailed. An overview of the technical characteristics of different types of energy storage technologies, including their main application, technology maturity, rated power, energy to power (E2P) ratio, efficiency, maximum depth of discharge, lifetime, response time, investiment and operation costs, can be found in [13].

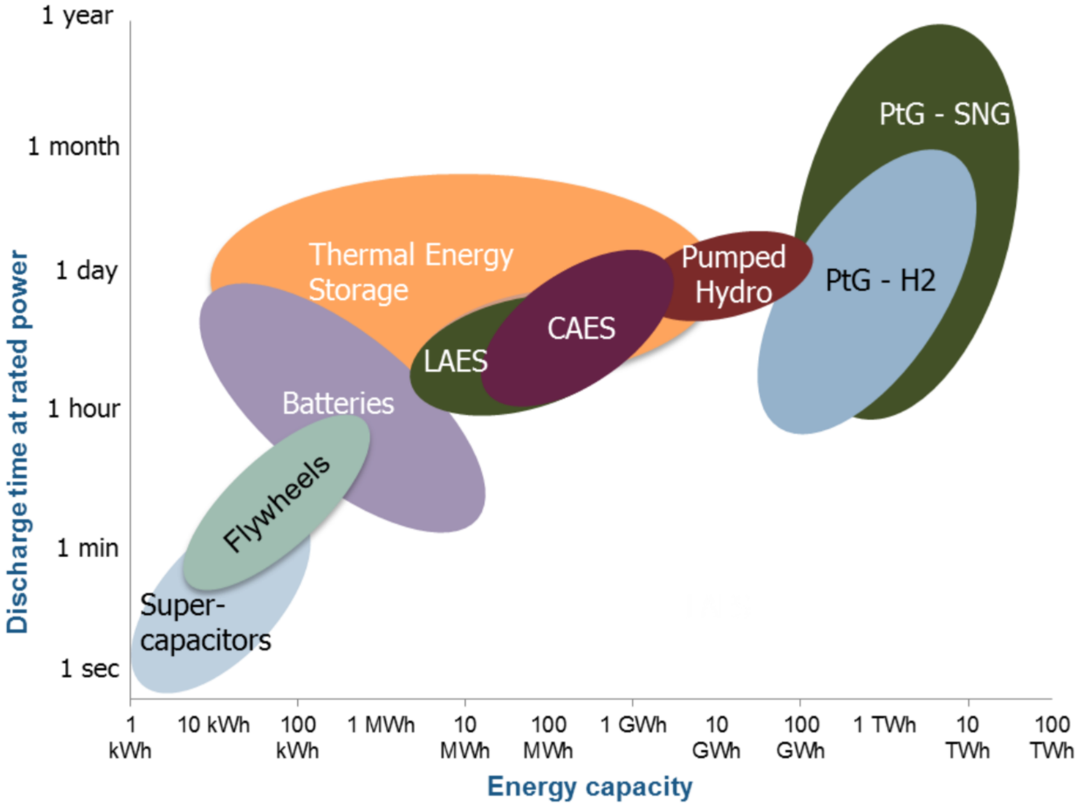

Figure 20: Storage technologies map according to performance characteristics [13]

4.1.1 Lithium-ion battery

Lithium-ion battery technology has been selected for the analysis performed in Section 5 due to its high energy density, overall performance and relative high maturity with many applications already in operation in subsea facilities, e.g., subsea electrical actuators for XTs and manifold valves, remote sensors and autonomous underwater vehicles (AUV).

Also, the cost of Lithium-ion batteries has fallen considerably in the last years due to the increased deployment of storage for variable renewable energy, developments in the consumer electronics sector and development of electric vehicles (EV) that have brought economies of scale in manufacture lithium-ion batteries, being expected to be much cheaper than other battery technologies (e.g. flow batteries, advanced lead-acid, sodium sulphur and sodium metal halide) by 2020 [14].

Figure 21 shows the experience curve for Lithium-ion batteries for both consumer electronics and electrical vehicles, where the price reduction with increase in the cumulative production capacity is a result of the economies of scale, manufacturing and engineering improvements [13].

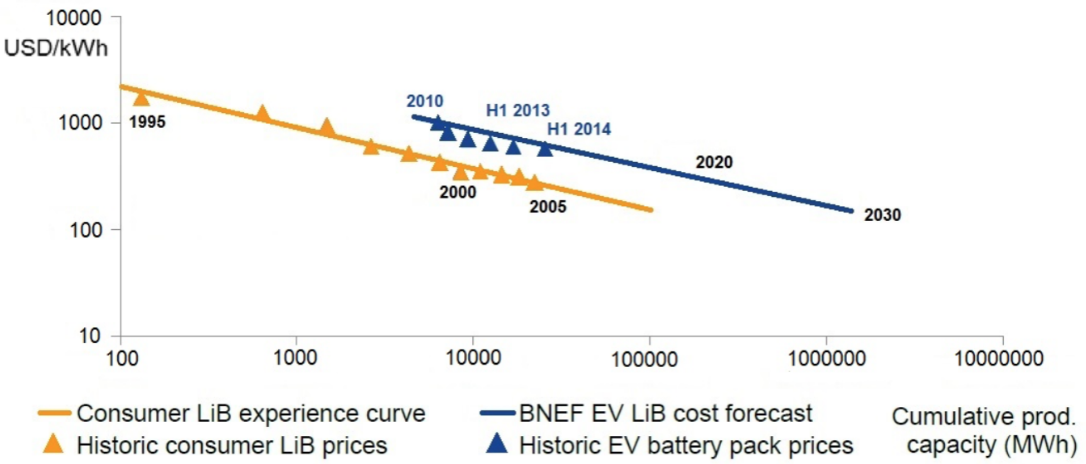

Figure 21: Experience curve for Lithium-ion battery [13]

There exist many manufacturers of lithium-ion batteires. The companies listed below produce Lithium-ion batteries suitable for offshore and subsea applications:

- Saft batteries;
- A123 Systems;
- Southwest Electronic - SWE;
- SubCtech.

As highlighted in [47], the high amount of lithium-ion products available in the market, with a large range of designs, makes it difficult to make a clear comparison between them. An overview of the factors that need to be taken into acount during the battery selection process is presented in Figure 22.

For the analysis performed in this thesis, one specific lithium-ion cell from Saft batteries was selected due to is high power density and track record in subsea applications. Figure 23 illustrates a battery pack from Saft developed for subsea application.

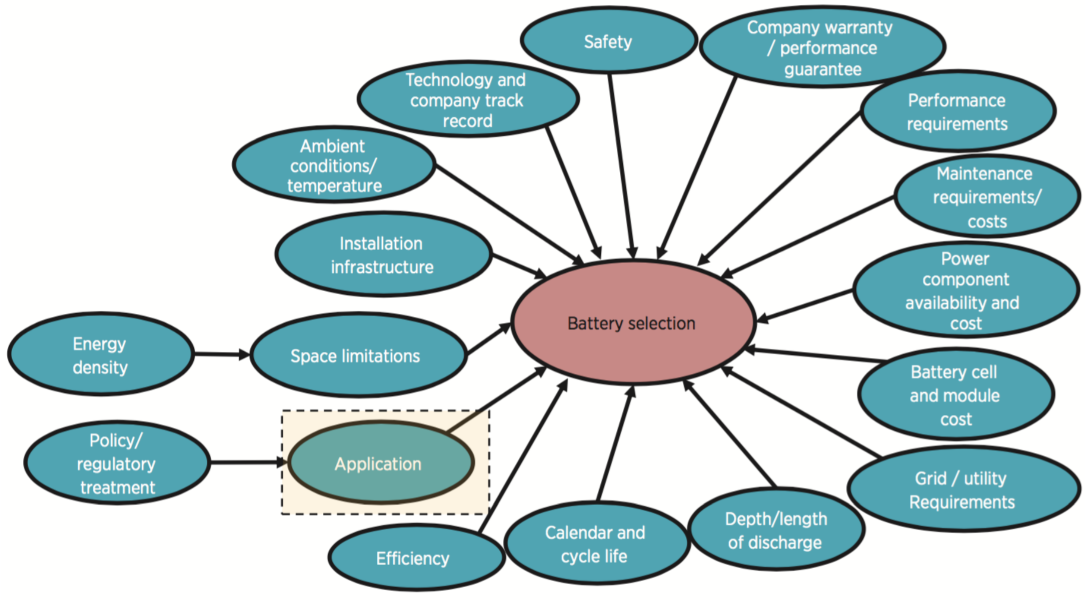

Figure 22: Important considerations for battery selection [14]

Figure 23: Lithium-ion battery from Saft for subsea application [3]

5 Case study

In this section, the technologies described in Section 3 are ranked, using a qualitative concept selection methodology, and a quantitative cost estimation. The latter using the LCOE methodology, which is performed for the selected technologies, considering four different subsea cases. Sensitivity analysis is also performed to verify the influence of specific inputs into the LCOE.

5.1 Description of selected cases

Four typical subsea cases were selected for the cost estimation:

- Subsea Isolation Valve (SSIV)
- Single subsea well (1 XT)
- 8 subsea wells (8 XT + 2 manifolds)
- Subsea boosting station

These cases have different power consumption requirements, varying from 50 W to 3 MW, as summarized in Table 2. And, in all cases, power shall be instantly available when the intermittent load (electrical actuators or pump) is activated. All cases were considered in a location offshore Norway with 300 m of water depth. A more detailed description of each case is given in the subsections below.

Table 2: Power consumption for the analysed cases

Case	SSIV	Single well	8 wells	Boosting
Continuous	50 W	400 W	4 kW	800 W
Intermittent	3 kW	3 kW	10 kW	3 MW

5.1.1 SSIV

A subsea isolation valve (SSIV) is used as a safety barrier between a subsea flow line and an offshore platform, with the main function of protecting the platform and its personnel from unintended hydrocarbons release from the subsea wells.

Installation of the SSIV can be done as an standalone module or integrated in a riser base or pipeline end manifold (PLEM), for example [15].

Figure 24: Subsea isolation valve [15]

The system requires continuous power of 50 W and maximum power of 3000 W during valve operation, giving an annual power consumption of 876 kWh. A simplied system layout is given in Figure 25.

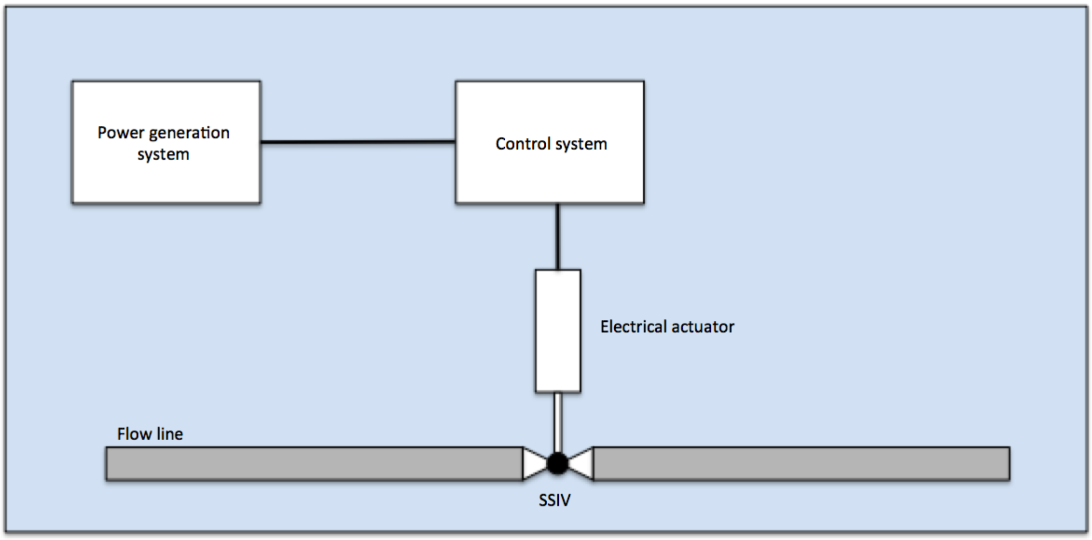

Figure 25: SSIV system layout

5.1.2 Single subsea well

A subsea XT has the main function of directing the produced fluid from the well to the flow line (production XT) or to canalize the injection of water or gas into the reservoir formation (injection XT) [2]. The configuration of a single subsea well, also known as satellite well, is often needed in developments with a small reservoir.

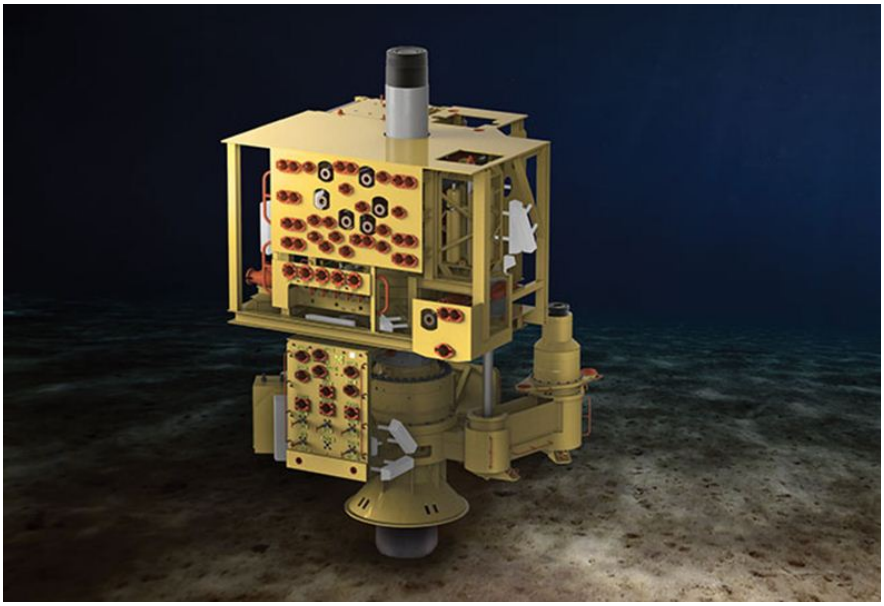

Figure 26: Subsea well with XT [16]

A set of electrical actuators are considered for operation of the XT. The system is considered to require continuous power of 400 W and maximum power of 3000 W during a valve operation, giving an annual power consumption of 3942 kWh. A simplified system layout is given in Figure 27.

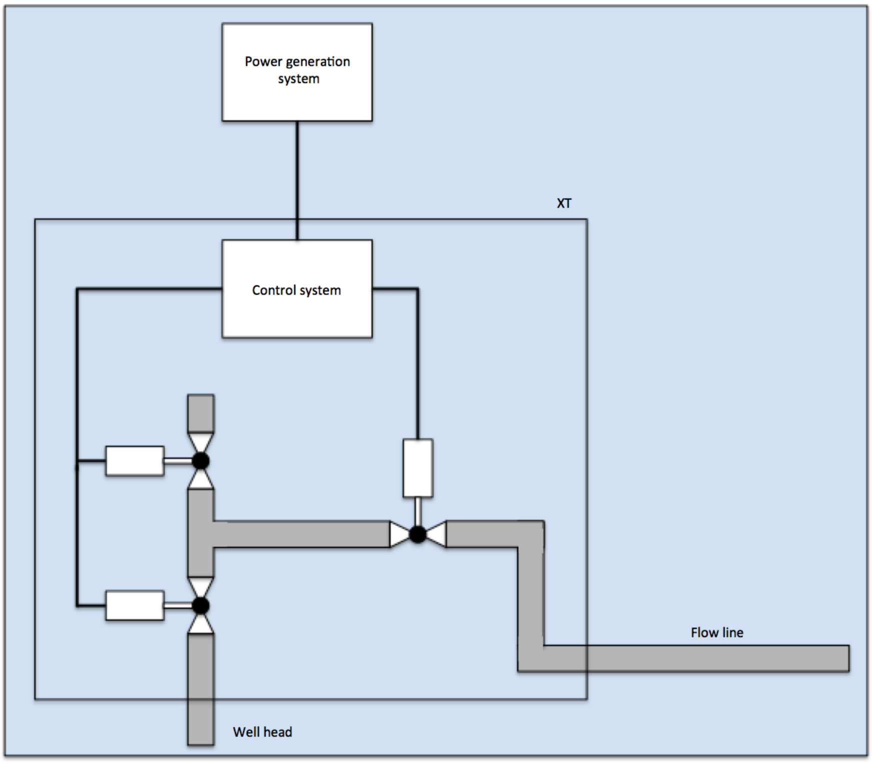

Figure 27: Single subsea well system layout

5.1.3 8 subsea wells

For fields with bigger reservoirs, subsea wells are grouped in a cluster or template configuration. In the Norwegian Continental Shelf (NCS), most subsea fields use well templates, where each template can support four or six wells. A subsea layout consisting of 2 templates for 4 wells each is quite commom configuration, as illustrated in Figure 28 for the Maria field offshore Norway.

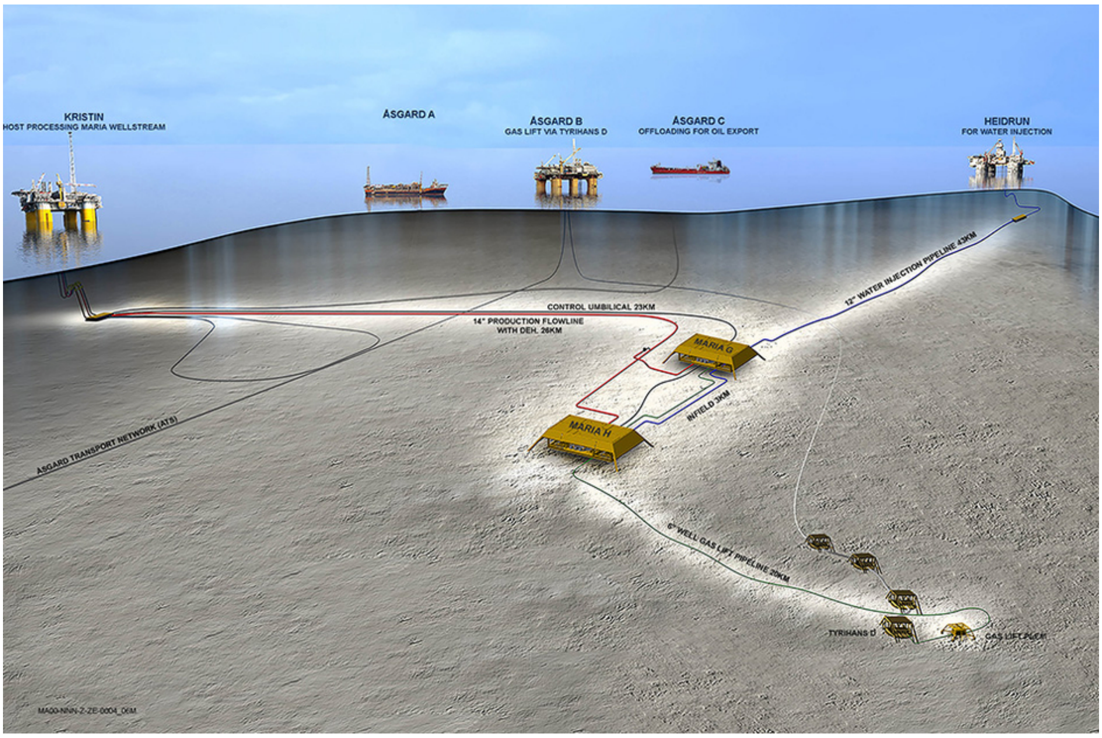

Figure 28: Typical subsea template layout[17]

Electrical actuators are considered for operation of the manifold and XT valves. The system requires continuous power of 4 kW and maximum power of 10 kW during valve operation, giving an annual power consumption of 36,5 MWh. A simplified system layout is given in Figure 29.

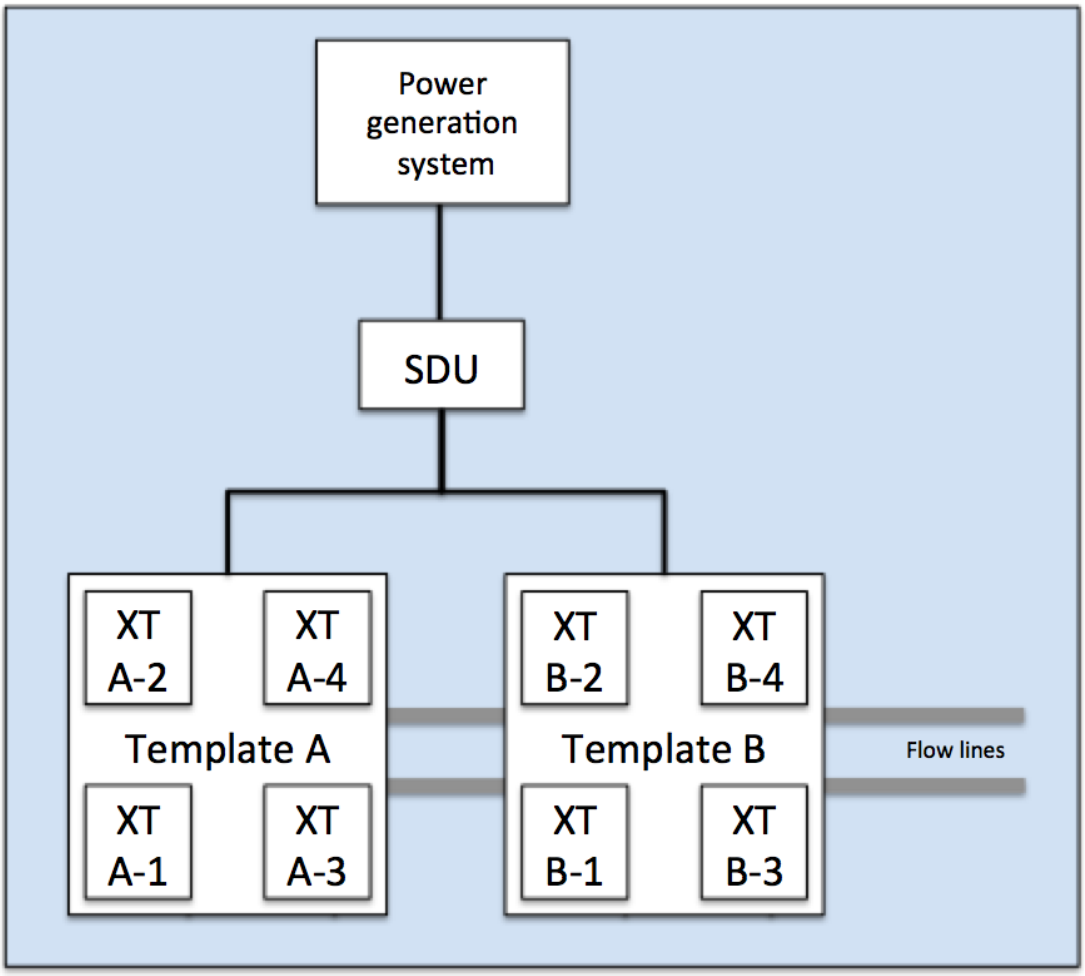

Figure 29: Subsea templates system layout

5.1.4 Subsea boosting station

It is commom that the reservoir pressure declines after few years of production from the subsea field, affecting the flow rate of oil or gas to the receiving facilities. Subsea boosting is used to tranfer energy to the fluid by reducing reservoir backpressure, which increases flow rates and reservoir recovery rates. Subsea pumps, typically, have a power rate range of 1 to 6 MW. A typical subsea boosting station is shown in Figure 30.

Figure 30: Subsea boosting station [18]

Electrical actuators are considered for operation of the valves in the boosting station and the pump is run by an electrical motor. The system requires continuous power of 800 W and maximum power of 3 MW during pump operation, giving an annual power consumption of 26,3 GWh, considering continuous pump operation. A simplified system layout is given in Figure 31.

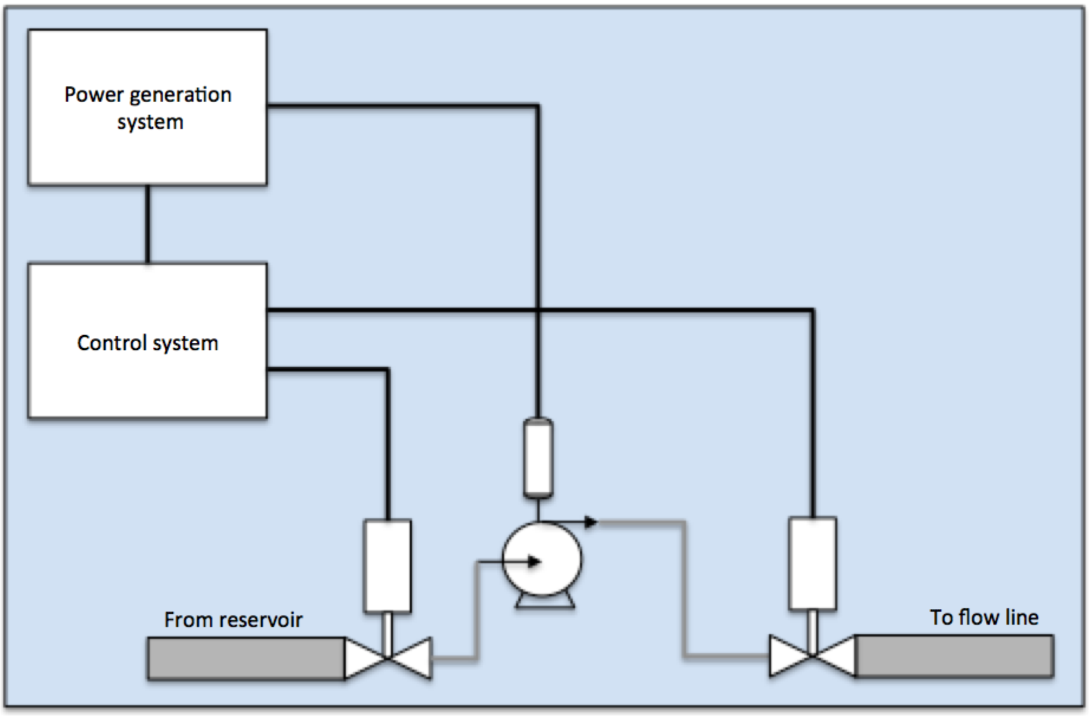

Figure 31: Subsea boosting system layout

5.2 Qualitative screening of concepts

A first stage qualitative screening of the technologies described in Section 3 has been performed with the goal of eliminating the power generation concepts that are least suitable or not ready for use in powering subsea facilities. The evaluation principle used for ranking of concepts was based on the methodology proposed in [48], where the following steps were implemented:

- Identification of evaluation criteria;
- Weighting the evaluation criteria;
- Assessment of values;
- Determining overall value.

The evaluation parameters used in this screening were defined based on their relevance for the type of technology (power generation), the environment (underwater) and cost. These parameters are listed below:

- Technology readiness level (TRL);
- Efficiency;
- Power density;
- Design life;
- Installation, Maintenance and Repair (IMR);
- Environmental impact;
- Need for energy storage;
- Cost.

Technology readiness level was defined based on the levels 0 to 7 from DNV RP-A203 [19]. These levels are summarized in Table 3.

Table 3: Technology readiness levels from DNV RP-A203 [19]

Technology Readiness Level	Description
TRL 0	Unproven idea/proposal Paper concept. No analysis or testing has been performed.
TRL 1	Concept demonstrated. Basic functionality demonstrated by analysis, reference to features shared with existing technology or through testing on individual subcomponents/subsystems. Shall show that the technology is likely to meet specified objectives with additional testing.
TRL 2	Concept validated. Concept design or novel features of design validated through model or small scale testing in laboratory environment. Shall show that the technology can meet specified acceptance criteria with additional testing.
TRL 3	New technology tested. Prototype built and functionality demonstrated through testing over a limited range of operating conditions. These tests can be done on a scaled version if scalable.
TRL 4	Technology qualified for first used. Full-scale prototype built and technology qualified through testing in intended environment, simulated or actual. The new hardware is now ready for first use.
TRL 5	Technology integration tested. Full-scale prototype built and integrated into intended operating system with full interface and functionality tests.
TRL 6	Technology installed. Full-scale prototype built and integrated into intended operating system with full interface and functionality test program in intended environment. The technology has shown acceptable performance and reliability over a period of time.
TRL 7	Proven technology integrated into intended operating system. The technology has successfully operated with acceptable performance and reliability within the predefined criteria.

The other decision drivers were defined between three levels (1 to 3) where 1 represents low level, 2 represents medium level and 3 represents high level. Efficiency, power density, design life and IMR have positive values since they have positive effects on the ranking of each technology. Environmental impact, need for storage and cost have negative values since they have negative effects on the ranking of each technology. And for simplicity of the analysis, all parameters were assigned with equal weight.

Allocation of the levels for each technology considered was done based on the research performed as part of this thesis. The results of the ranking of the power generation concepts are reflected in Table 4.

From Table 4, the four technologies that have the highest ranking are:

1. Offshore wind (Sum = 10)
2. Tidal (Sum = 9)
3. Wave (Sum = 7)
4. Solar (Sum = 6)

The technologies listed above are used in the quantitative analysis in Section 5.3 due to their highest ranking, as a consequence to their overall higher level of readiness for subsea used when compared to the other technologies considered in this analysis.

Table 4: Quantitative ranking of power generation concepts

Concept	TRL	Efficiency	Power density	Design life	IMR	Environmental impact	Need for storage	Cost	Sum
Offshore wind	7	2	2	3	2	−2	−3	−1	10
Tidal	5	2	2	2	2	−1	−1	−2	9
Wave	5	2	2	2	2	−1	−3	−2	7
Solar	4	1	1	3	3	−1	−3	−2	6
OTEC	3	3	2	2	1	−2	−1	−3	5
Turbo Generator	2	3	3	3	1	−3	−1	−3	5
Nuclear	3	2	2	2	1	−1	−1	−3	5
Salinity gradient	2	2	2	1	1	−1	−1	−3	3
Deep ocean current	2	2	2	1	1	−1	−1	−3	3

5.3 Concepts viability analysis

A second stage quantitative screening has been performed to identify the most feasible power generation concept for the cases described in Section 5.1. The methodology for economic appraisal suggested in [35] was modified to be used in this study for all power generation concepts selected in Section 5.2 and can be seen in Figure 32.

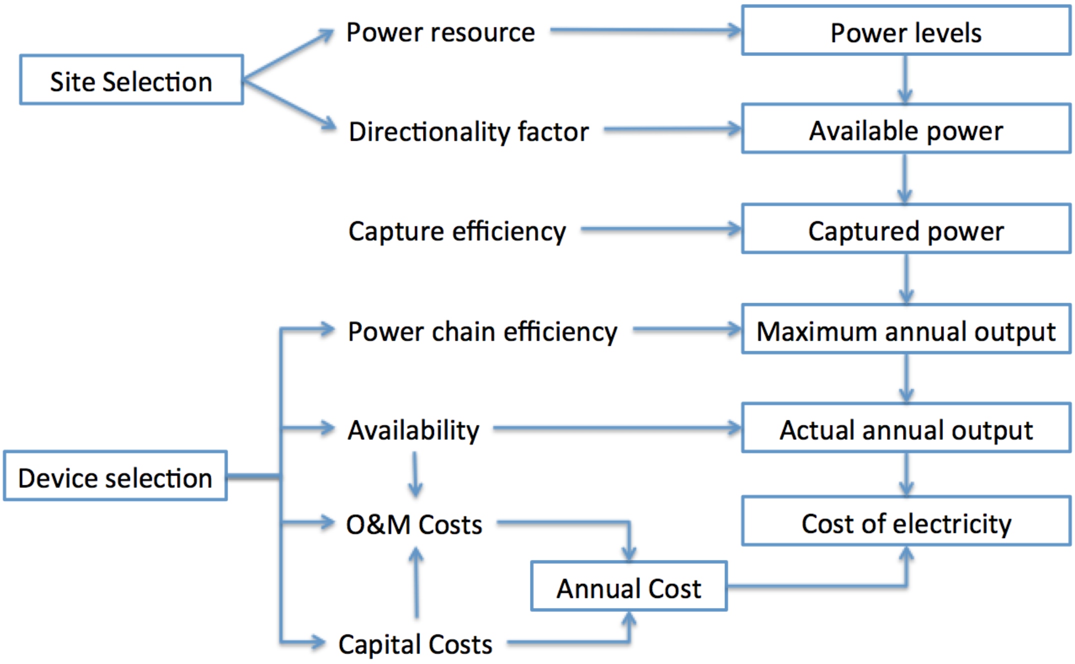

Figure 32: Methodology for economic analysis

The cost of electricity was defined using the Levelised Cost of Electricity (LCOE) methodology, which allows for comparisons between energy sources on a unit cost basis over the lifetime of different energy technologies [12].

The LCOE analysis takes into account capital costs, operation and maintenance costs and fuel costs. Since all four technologies evaluated in this thesis are renewable, fuel costs are not relevant and, therefore not considered.

The LCOE formula used is presented below.

$$C_{LCOE} = \left[\frac{R \cdot c_p}{H \cdot f}\right] + \left[l \cdot \left(\frac{c_o}{H \cdot f}\right)\right] \tag{1}$$

where:

$$R = \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \tag{2}$$

and

$$l = \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \cdot \frac{(1+e)}{(r-e)} \cdot \left[1 - \left(\frac{1+e}{1+r} \right)^T \right] \tag{3}$$

The componens of the formulas above are described in Table 5.

The plant cost (c_p) for each technology was calculated based on values available in the literature and estimations, considering the following equipment:

- Energy colector equipment;
- Batteries;
- Control system;
- Inverters/charges;
- Mechanical structure;
- Subsea umbilical;
- Equipment installation.

Table 5: LCOE components

Component	Description
c_o	O&M cost
c_p	Plant cost
e	Escalation rate (in %)
f	Capacity factor (in %)
H	Hours per year
l	Levelization factor
r	Discount rate (in %)
R	Capital recovery factor (in %)
T	Plant life time (in years)

The values used in the calculations, which are commom for all analised cases are shown in Table 6 below.

Table 6: LCOE components values

Component	Offshore wind	Tidal	Wave	Solar
e	1 %	1 %	1 %	1 %
f	38 %	25 %	25 %	10 %
H	8 769	8 769	8 769	8 769
r	10 %	10 %	10 %	10 %
T	25 years	25 years	25 years	25 years

O&M annual costs were estimated on 2% of the plant cost for solar power due to the absence of moving parts, and to 10% of the plant cost for the other technologies (offshore wind, tidal and wave).

The currency used within the analysis is the Euro. Prices have been converted from US Dollar ($) at an exchange rate of 0,89 US Dollars to the Euro, and from Norwegian Krone (NOK) to the Euro at an exchange rate of 0,11 NOK to the Euro.

Main input parameter for each technology was based on mean annual values as stated below:

- Offshore wind (wind speed of $7m/s$)

- Tidal (tide speed of $1,5 m/s$)
- Wave (power density of $50 kW/m^2$)
- Solar (reference yield of $1200 kWh/m^2 \cdot an$)

The amount of lithium-ion cells for energy storage, considered for the power generation concepts, was based on a five days supply of power to the subsea system in the case of offshore wind, solar and wave power. For tidal power, only two days supply to the subsea system was considered due to its characteristics of constant power generation. In the boosting case, only supply to the control equipment was considered for the energy storage dimensioning since the amount of power needed for the pump operation is considerably high (3 MW) and would require an amount of cells that would make the concept infeasible for subsea.

5.3.1 SSIV case

For the SSIV case described in Section 5.1.1, the resulting LCOE is shown in Figure 33.

Offshore wind and solar power rank as the most cost effective technologies, with similar LCOE values of 57,72 EUR/kWh and 58,22 EUR/kWh respectively. Tidal and wave power rank as more expensive technologies, with LCOE values of 131,71 EUR/kWh and 197,12 EUR/kWh respectively.

The lower LCOE for both offshore wind and solar power is a consequence of the high level of maturity for wind turbines when compared to the other technologies and the simplicity of the solar power system, with low need for O&M activities.

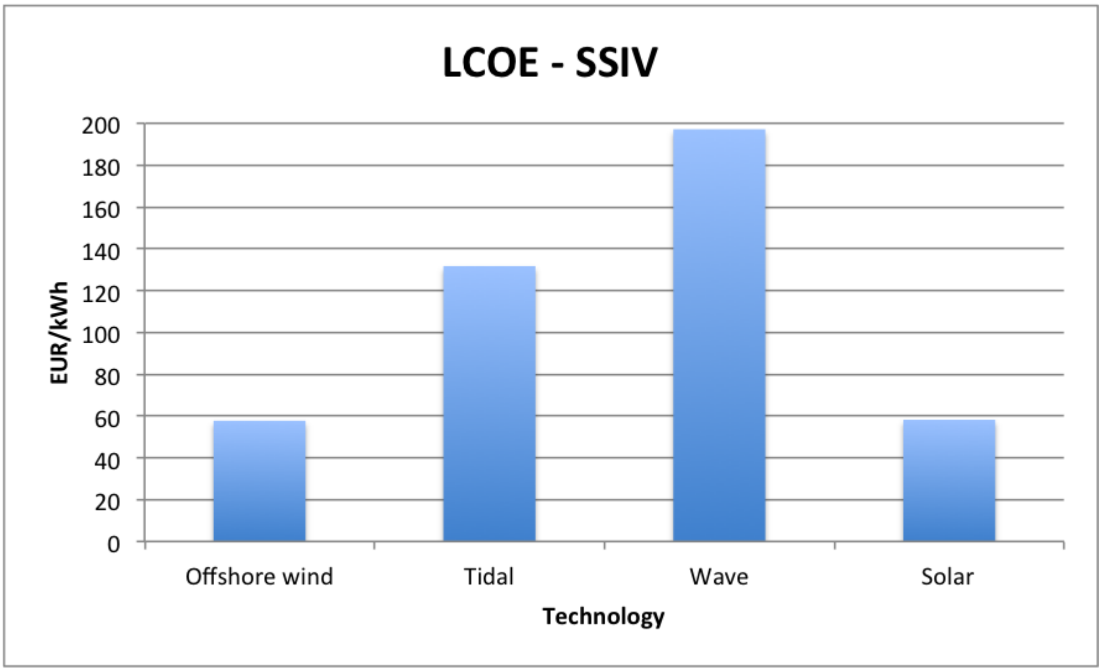

Figure 33: LCOE for SSIV case

Comparison is also made with a more traditional configuration where power is provided from shore through a subsea umbilical. And from Figure 34 can be seen that the cheapest analyzed alternative, offshore wind in this case, is more cost effective when the step-out distance is greater than 5,6 km.

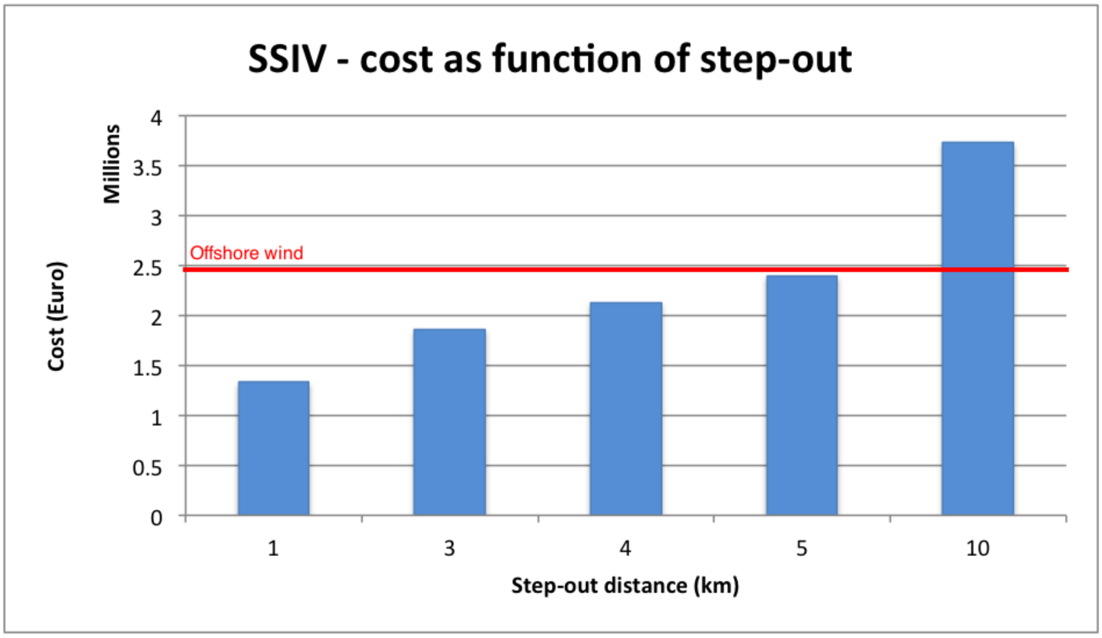

Figure 34: Cost as function of umbilical step-out distance for SSIV case

5.3.2 Single subsea well case

For the single subsea well case described in Section 5.1.2, the resulting LCOE is shown in Figure 35.

Solar power and offshore wind rank as the most cost effective technologies, with similar values of 13,27 EUR/kWh and 14,54 EUR/kWh respectively. Tidal and wave power rank as more expensive technologies, with values of 33,14 EUR/kWh and 49,56 EUR/kWh respectively.

The lower LCOE for both offshore wind and solar power is a consequence of the high level of maturity for wind turbines when compared to the other technologies and the simplicity of the solar power system, with low need for O&M activities.

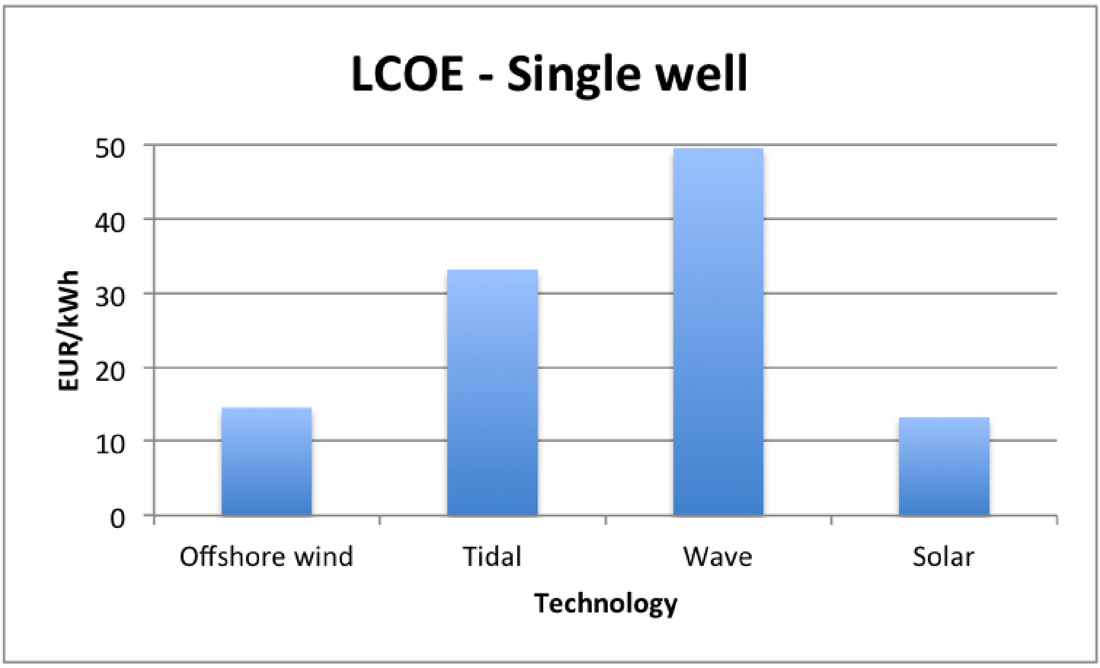

Figure 35: LCOE for single subsea well case

Comparison is also made with a more traditional configuration where power is provided from shore through a subsea umbilical. And from Figure 36 can be seen that the cheapest analyzed alternative, solar power in this case, is more cost effective when the step-out distance is greater than 8,8 km.

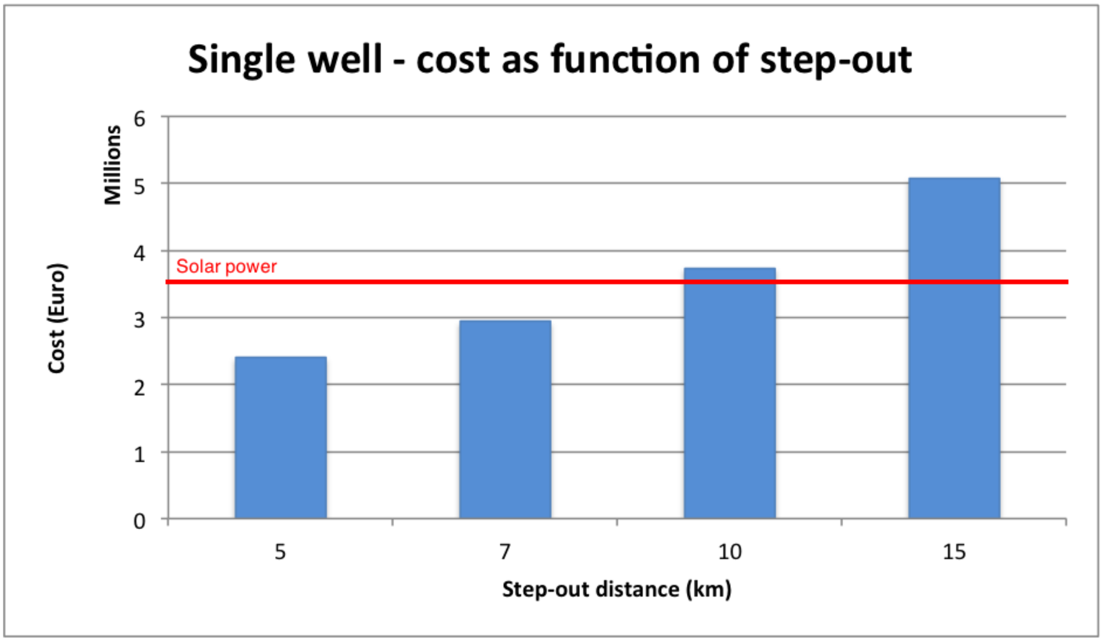

Figure 36: Cost as function of umbilical step-out distance for single well case

5.3.3 8 subsea well case

For the 8 subsea wells case described in Section 5.1.3, the resulting LCOE is shown in Figure 37.

Offshore wind and solar power rank as the most cost effective technologies, with similar LCOE values of 1,73 EUR/kWh and 2,85 EUR/kWh respectively. Tidal and wave power rank as more expensive technologies, with LCOE values of 3,95 EUR/kWh and 5,89 EUR/kWh respectively.

The lower LCOE for both offshore wind and solar power is a consequence of the high level of maturity for wind turbines when compared to the other technologies and the simplicity of the solar power system, with low need for O&M activities. Tidal power converters have relatively high maturity in the kW range, making it more cost effective than wave power.

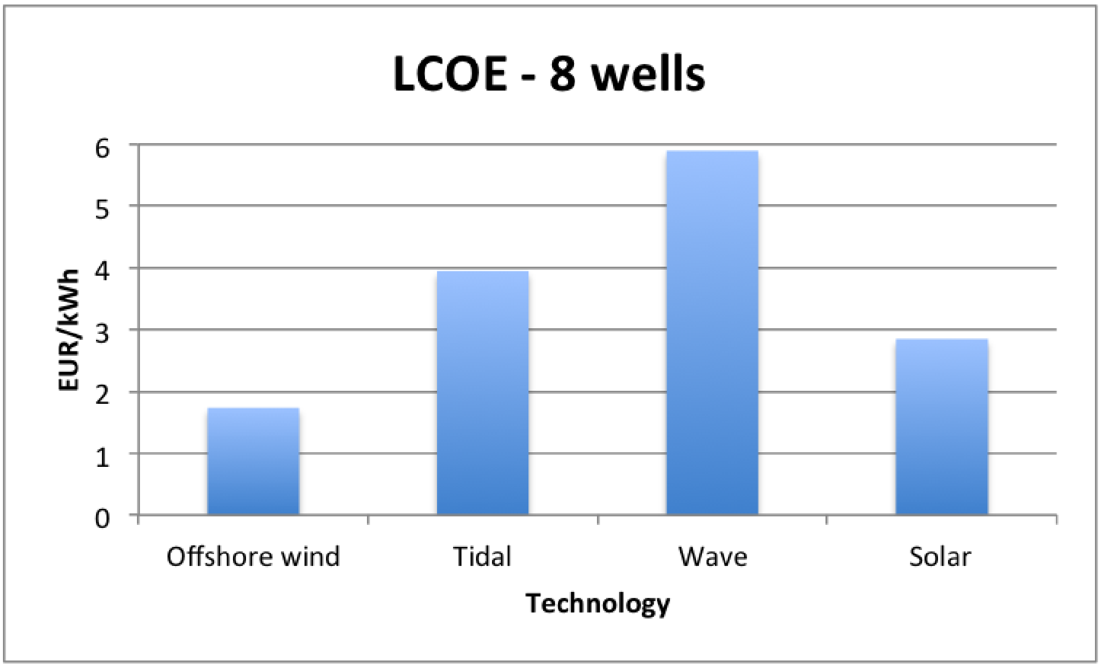

Figure 37: LCOE for 8 subsea wells case

Comparison is also made with a more traditional configuration where power is provided from shore through a subsea umbilical. And from Figure 38 can be seen that the cheapest analyzed alternative, offshore wind in this case, is more cost effective when the step-out distance is greater than 14,1 km.

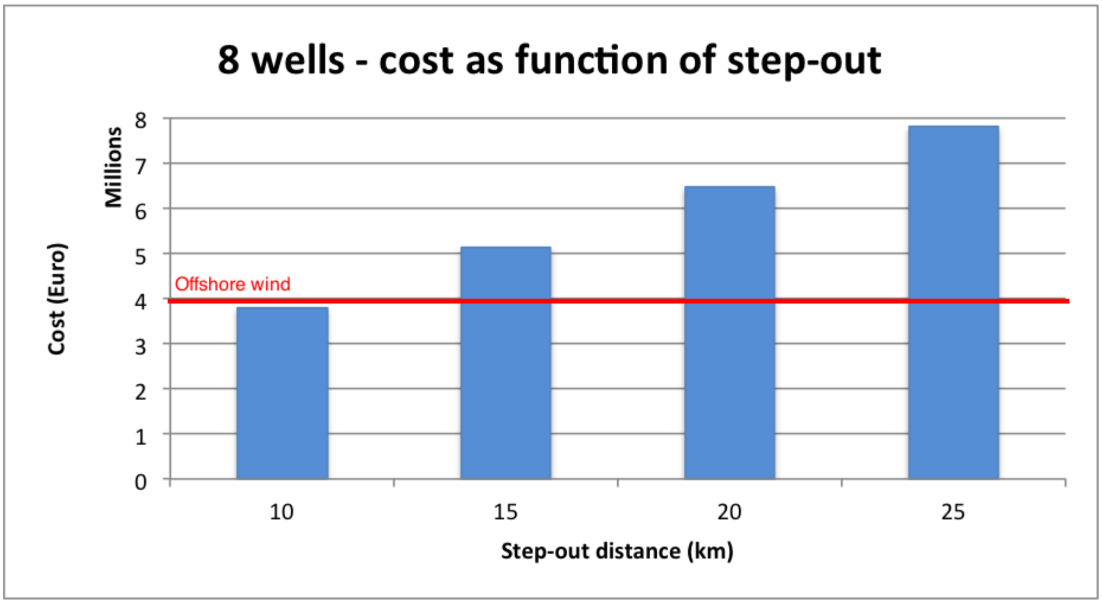

Figure 38: Cost as function of umbilical step-out distance for 8 wells case

5.3.4 Boosting case

For the boosting case described in Section 5.1.4, the resulting LCOE is shown in Figure 39.

Offshore wind and tidal power rank as the most cost effective technologies, with the values of 0,27 EUR/kWh and 0,54 EUR/kWh respectively. Solar and wave power rank as more expensive technologies, with values of 1,16 EUR/kWh and 1,30 EUR/kWh respectively.

The lower LCOE for both offshore wind and tidal power is a consequence of the high level of maturity for wind turbines when compared to the other technologies and the fact that tidal power requires much less energy storage than solar power, in this case.

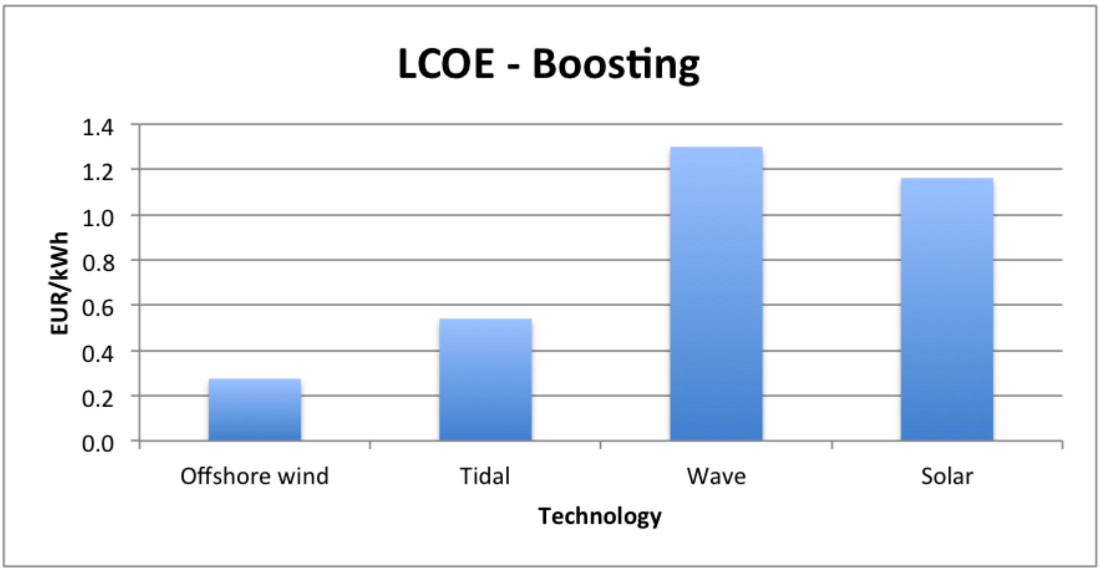

Figure 39: LCOE for boosting case

Comparison is also made with a more traditional configuration where power is provided from shore through a subsea umbilical. And from Figure 40 can be seen that the cheapest analyzed alternative, offshore wind in this case, is more cost effective when the step-out distance is greater than 10 km.

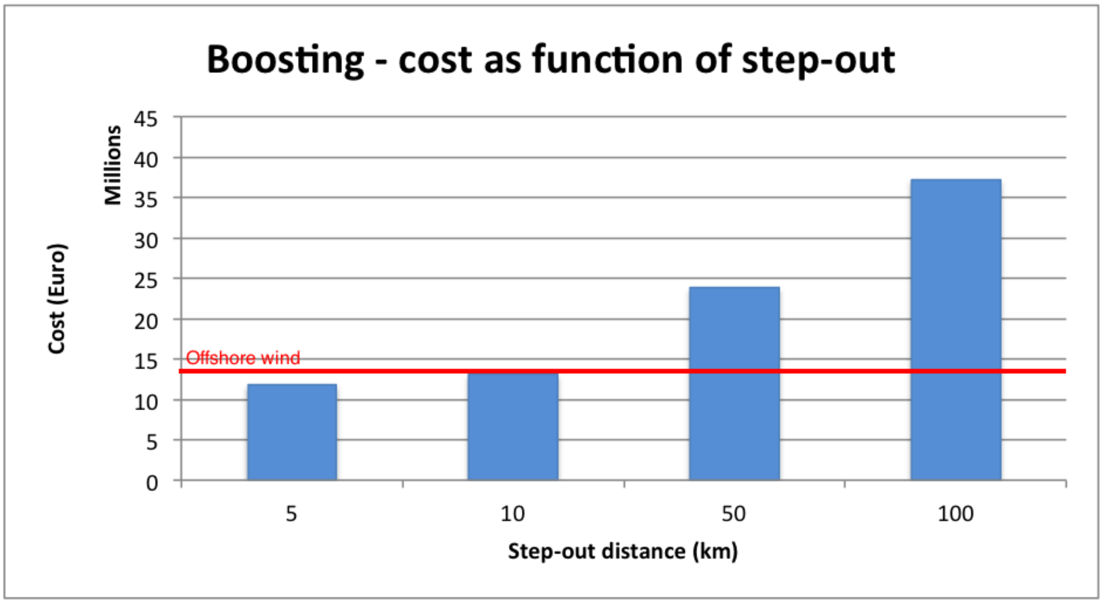

Figure 40: Cost as function of umbilical step-out distance for boosting case

5.3.5 Sensitivity analysis

Sensitivity analyses for one of the technologies were conducted to identify the impact of some of the input parameters in the LCOE. The analyses were performed by keeping all reference assumptions constand and varing only the parameter in question. Variation on capital expenditure, operating expenditure and average wind speed were analised. Offshore wind power was selected for the sensitivity analyses since it is among the most attractive technologies in all cases analysed in this thesis.

5.3.5.1 CAPEX variation

A variation of ±10% in the capital expenditure (CAPEX) for all four analysed cases was set and the resulting LCOE are shown in Table 7. And can be seen that the CAPEX variation has little influence in the LCOE, ranging from $\pm 0,005\%$ to $\pm 0,18\%$.

Table 7: CAPEX influence on LCOE

Case	SSIV	Single well	8 wells	Boosting
Base case	57,718	14,535	1,733	0,275
+10%	57,772 (+ 0,094%)	14,554 (+ 0,127%)	1,736 (+ 0,180%)	0,275 (+ 0,005%)
−10%	57,663 (- 0,094%)	14,517 (- 0,127%)	1,729 (- 0,180%)	0,275 (- 0,005%)

5.3.5.2 OPEX variation

A variation of ±10% in the operating expenditure (OPEX) for all four analysed cases was set and the resulting LCOE are shown in Table 8. And can be seen that the OPEX variation has high influence in the LCOE, ranging from $\pm 9,820\%$ to $\pm 9,995\%$.

Table 8: OPEX influence on LCOE

Case	SSIV	Single well	8 wells	Boosting
Base case	57,718	14,535	1,733	0,275
+10%	63,435 (+ 9,906%)	15,970 (+ 9,873%)	1,903 (+ 9,820%)	0,302 (+ 9,995%)
−10%	52,000 (- 9,906%)	13,100 (- 9,873%)	1,562 (- 9,820%)	0,247 (- 9,995%)

5.3.5.3 Wind speed variation

A variation of ±10% in the average wind speed for all four analysed cases was set and the resulting LCOE are shown in Table 9. And can be seen that the wind speed variation has high influence in the LCOE, ranging from + 23,6% to - 32,3%.

Table 9: Wind speed influence on LCOE

Case	SSIV	Single well	8 wells	Boosting
Base case	57,718	14,535	1,733	0,275
+10%	39,068 (- 32,311%)	9,842 (- 32,286%)	1,174 (- 32,246%)	0,186 (- 32,378)
−10%	71,330 (+ 23,585%)	17,969 (+ 23,631%)	2,143 (+ 23,704%)	0,339 (+ 23,464%)

6 Conclusions and recomendations for further work

The main objective of this thesis was to evaluate power generation technologies that can be used for powering subsea located oil & gas production equipment as an alternative to powering from the topside facilities of the platform (gas turbines) or from onshore facilities.

Firstly, a review of the current solutions for powering the subsea equipment was performed. This was followed by a survey and review of the alternative power generation technologies relevant for subsea application. Power storage technologies were also evaluated due to the need for storage by some of the technologies considered.

Then, a selection of the most relevant power and storage technologies was performed, with a cost evaluation for those selected technologies in different subsea equipment configurations, to identify the most suitable technology for each scenario.

As a result of the work performed during this thesis, it can be concluded that there is technology available, with high TRL, that can be satisfactory for powering subsea located oil & gas production equipment, as an alternative to powering from the topside facilities of the platform (gas turbines) or from onshore facilities.

Deployment of these technologies may solve some of the challenges faced when there is not enough space for new power generation equipment, in case of new tie-backs to existing production facilities, or in long step-out cases where the umbilical can become very expensive.

Deployment of these technologies, in a real subsea application, also needs to break through the first user barrier in the subsea industry, where the decision makers in the field development projects always avoid the use of new technologies due to the risks associated with them.

The analysis performed showed that having the power generation equipment close to the subsea consumers is more cost effective than the traditional configuration of having a subsea umbilical from the platform or from onshore in not that long step-outs (in the range of 10 km).

It can also be observed that the LCOE value is proportional to the readiness level of the technology, where the technologies with lower TRL have higher LCOE than the technologies with higher TRL. Offshore wind and solar energy were the most cost effective technologies due to that, but that picture can change in the near future with the expected reduction in the cost of tidal and wave.

From the sensitivity analysis performed, if can be concluded that the OPEX and the energy resource availability (e.g. wind speed) are the input parameters that have the highest influence in the LCOE. The CAPEX variation did not shown much influence in the LCOE since it is diluted in the plant total design life of 25 years.

And, as also observed in [45], the lack of an international and standardised approach in the development of LCOE estimates, with lack of consistance in the boundaries and assumptions, makes it difficult to compare the results from estimates performed by different sources.

This thesis has also sought to know, topics that could be further detailed. These topics could be further examined in future theses. Future studies on this topic might include a more detailed cost evaluation of one specific power generation technology for a real subsea scenario. By gathering detailed information about the power necessary, power resource availability in the geographic location and time for project execution, a more precise cost picture could be used as part of the decision making process during the field definiton phase.

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