OTC-30933-MS

Repurposing of Offshore Oil and Gas Cables for Renewable Generation: Feasibility and Conceptual Qualification

Ramy Magdy A. Mahmoud, UCL Energy Institute, Overseas Solutions Ltd.; Hazem Fayad, Subsea System Consultant; Paul E. Dodds, UCL Institute for Sustainable Resources

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, TX, USA, 16 - 19 August 2021.

Abstract

Wind farms are expected to be deployed in the North Sea in increasing numbers and at ever greater distances from land, over the coming decades. Many nearby oil and gas fields have reached or are near the end of their lifespans, and their operators are eager to explore innovative ways to reduce decommissioning costs. One possibility would be to repurpose some of their infrastructures for use by wind farms, which would both delay decommissioning and reduce the wind farm capital costs. This paper investigates the potential for repurposing existing submarine power cores in decommissioned oil and gas fields as transmission cables for offshore renewables.

Offshore power cables generally have longer lifetimes than are needed to deplete hydrocarbon reservoirs. Cable transmission capacity could be too low to provide the main connection to wind farms, but there is scope to increase capacity or use cables as auxiliary connections. A qualification methodology is proposed to assess whether existing cables might be usefully repurposed. Repurposing cables has an impact on renewable project capital expenditure (CAPEX) and levelised cost of energy (LCOE), it also positively affects decommissioning cost and the environment. The qualification methodology provides a cost-effective initial appraisal prior to field testing.

Keywords: Energy Transition, Repurposing, Submarine Cable, Decommissioning, Offshore Facilities

INTRODUCTION

The North Sea contains numerous oil and gas extraction facilities that will be decommissioned over the next few decades (RSA, 2015). At the same time, offshore renewable generation has expanded rapidly in recent years and this trend is forecast to continue in the future (IEA, 2017; Jepma and Van Schot, 2017). One method to reduce decommissioning and renewable generation costs might be to repurpose existing oil and gas infrastructure for use by renewable generation. The Round 3 Wind Farm expansion in the North Sea will increasingly lead to renewable developments in the vicinity of oil and gas facilities (Cockburn et al., 2010; Red Penguin, 2012).

The timescale for decommissioning an offshore asset is mainly dictated by the design life of the hydrocarbon reservoir rather than designs of power transmission systems. OGUK (2013) estimated that around 2,500 pipelines, umbilicals (i.e. a bundle that contains single or several power cores with other components such as tubes or fibre optics) and cables have been installed across the North Sea region since 1966, with a length exceeding 45,000 kilometres. UK Government guidance for decommissioning recommends removing cables with small diameters that are not trenched, and leaving trenched cables and umbilicals in situ to avoid excessive environmental disturbances. At present, some operators recover small quantity of the cables to re-use copper, but most are left in place.

Repurposing of subsea cables has received relatively little attention as most offshore wind has been constructed during this century and the peak of decommissioning activities is not anticipated to be reached until the 2030s, as shown in Figure 1 (Topham and McMillan, 2017). Reusing offshore energy infrastructure takes place by replacing existing wind turbines with more powerful models at the end of their lifetimes. Villena-Ruiz et al. (2018) studied the economic borderlines for repowering wind farms and demonstrated that it is profitable. Hou et al. (2018) introduced optimum strategy of repowering the farms. Both of these studies were confident that subsea cable repurposing and life extension are feasible.

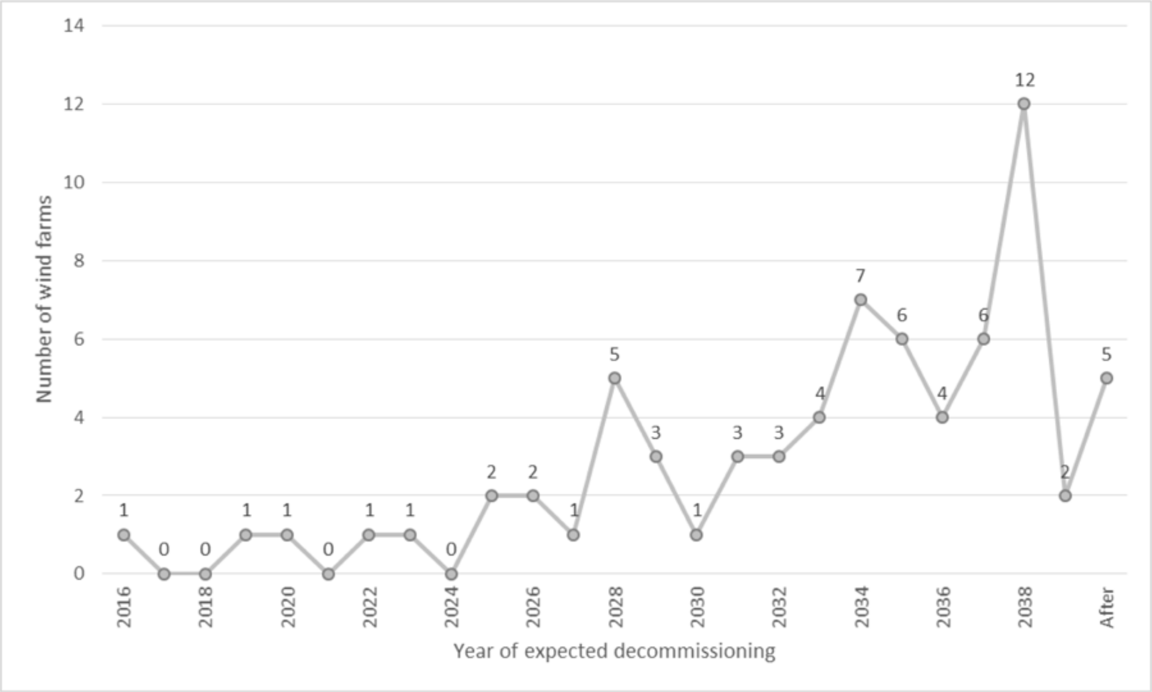

Figure 1—Number of wind farms to be decommissioned in the future (Topham and McMilan, 2017)

This article investigates the feasibility of repurposing oil and gas power cables/umbilicals and proposes criteria to assess whether they could be used by offshore renewables in the future. This is important because electrical transmission to land accounts for more than 10% of the total cost of offshore renewables capital expenditure (BVG Associates 2010). Another benefit could be to power offshore industries still in production using renewable electricity. This study is limited to offshore power generation and transmission, and does not investigate transmission cables on land.

Connecting hydrocarbon facilities with offshore renewables

The concept of connecting renewables and hydrocarbons offshore has received little attention. Solar panels are often installed on offshore platforms to generate power for navigation aids. While historically, diesel generators have supplied offshore rigs with electricity, in principal offshore rigs could supply all of their needs through renewable energy, through creation of a microgrid connecting them to offshore wind farms, however, such initiatives have not occurred (MacDonald, 2014; Korpås, 2012). Using oil and gas platforms to generate electricity offshore is not feasible due to technical constraints (e.g. size of offshore facilities).

Recent attempts to maximise connection between hydrocarbons and renewables facilities are taking place. Equinor and partners are exploring possibilities of supplying the Gullfaks and Snorre fields using power from floating offshore wind, which would be the first time an offshore wind farm were directly connected to oil and gas facilities (SUT, 2018) and is projected to reduce greenhouse gas emissions by 200 ktCO$_2$/a. Jepma and Van Schot (2017) argued that oil and gas platforms in the North Sea could be profitably converted into production and storage units that convert electricity from offshore wind farms into hydrogen, which could be methanated to produce synthetic natural gas. A positive business case if the gas were sold to a dedicated niche market for green gas (e.g. the transportation sector).

Reusing hydrocarbon structures near end of its life has been examined continuously in recent studies. Leporini et al. (2019) studied reconversion of offshore oil and gas platforms in renewable energy production, while Caulk and Tomac (2017) studied reuse of abandoned oil and gas wells for geothermal energy. All this recent work emphasises the current opportunity surrounding oil and gas infrastructure, and potentials for connecting them with renewables.

Types of cables used by hydrocarbon and renewable industries

Manufacturers of submarine cables usually supply both the hydrocarbon and renewable energy sectors. The cables use similar technologies but differ in terms of their electrical capacity and purpose (e.g. ABB, 2012). Generally, offshore cables are armoured (i.e. with inner cores protected by series of steel armour wires arranged in helical arrangement). Their weight and diameter vary, depending on cable characteristics (i.e. AC or DC cable, single or three phase, and if it is high, medium or low voltage).

Offshore wind farms usually rely on high voltage DC cables for power export and AC cables as array cables between turbines. Both AC and DC export cables can transmit electricity from offshore renewable fields. However, long-distance AC cables are rarely used as they reduce the active power rating (Lian et al., 2013).

Oil and gas facilities do not generally have high electricity loads and in many cases, low or medium voltage AC cores are sufficient even for HV application. This means that one of the principal impediments to repurposing cables is likely to be insufficient capacity of existing power cores. However, subsea cables used for complex, deep-water facilities and subsea pumping have higher capacity, and the capacity can be increased on some cables.

Benefits and challenges of reusing cables

BVG Associates (2010) estimate the capital cost of a 500 MW typical offshore wind farm to be £1.5bn, which includes £60m to purchase and £80m to install the export power cable, depending on location, distance from land and water depth. Although offshore wind costs have reduced substantially in recent years (Wind Europe, 2019), power cables are mature technologies with few options for cost reductions. The revised 1 GW offshore cost estimate by BVG Associates (2019) demonstrated that the proportion of the total cost that is accounted for by cables has almost unchanged since 2010.

There would be further advantages if an existing power core was used to export power from offshore energy islands floating around decommissioned platforms, as cable cost would represent a higher percentage of the total renewable field CAPEX. Offshore solar power would reduce onshore land use for solar. Energy and solar islands have potential for expansion during the next few decades and have been investigated by several sources such as Bard (2014). They are large, lightweight semi-submersible floating platforms that could combine more than a single source of energy such as wind and wave (Hanssen, 2015). Procurement and manufacturing of an offshore power cable could take up to 18 months. In contrast, repurposing an existing cable requires only qualification, testing and connection.

Fowler et al. (2018) have identified a number of environmental benefits from leaving existing offshore infrastructure in the sea, such as avoidance of seabed disturbance and loss of developed community (i.e. flora and fauna).

There are three principal impediments to reusing power cables for renewable generation:

1. Renewable fields might require larger capacity cables than are available from nearby hydrocarbon fields (Section 1.2).
2. Reusing of power cables requires field testing and inspection, which are costly and time-consuming, particularly if many cables are being assessed.
3. Hydrocarbons and renewables are separate business sectors, involving different parties, so the potential for reusing hydrocarbon assets has not been considered.

Increasing capacity by switching AC cables to DC

Several studies examined power losses for DC cables against AC cables for distant offshore renewable fields. Lazaridis (2005) presents a full economic comparison for several offshore wind farms, with different capacities, and demonstrated that DC cables are more efficient in long distance power transmission. Negara et al. (2006) also confirmed that DC cables have lower power losses than AC cables. A comparison between power loss of AC and DC cables for various distances, 100 to 300km based on data evaluated by Negra et al. (2006) is reproduced in Figure 2.

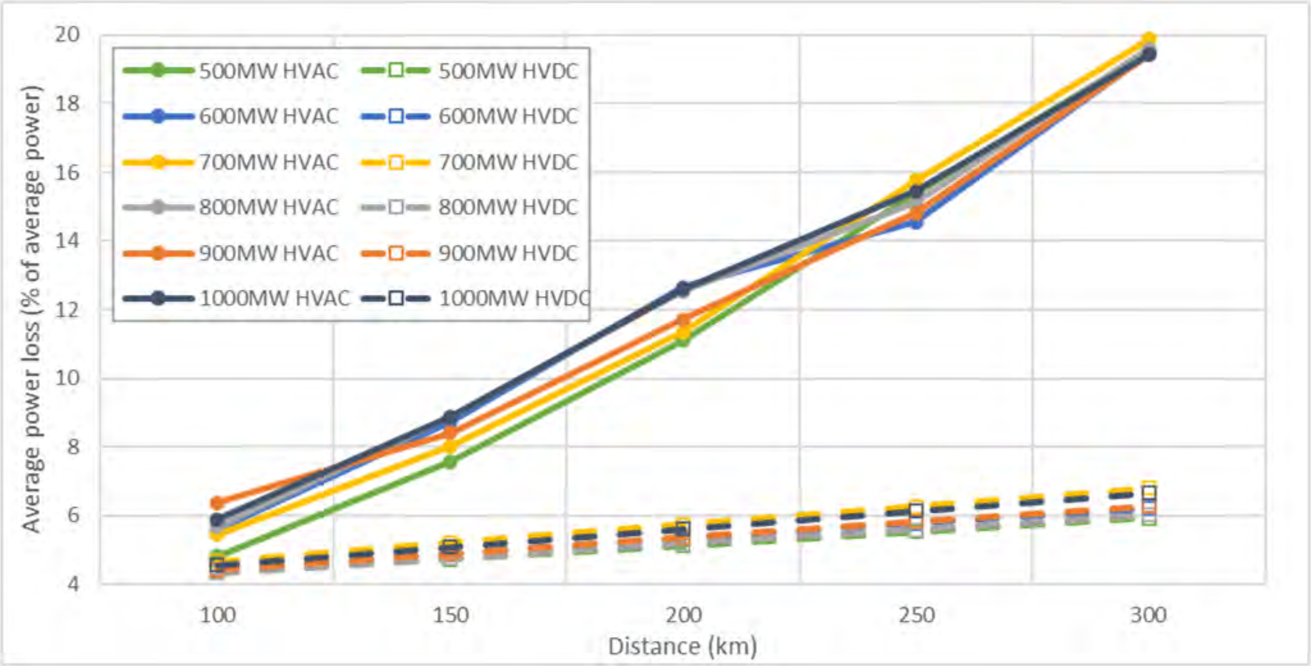

Figure 2—Efficiency of DC power cables against AC cables for 500 to 1000 MW wind farms

Converting power cables from AC to DC could theoretically almost triple the capacity, as cable resistance would be substantially lower. However, there are some parameters to consider (e.g. skin and proximity effects), and for some cables there might not be a tangible enhancement in performance (Burstein et al., 2017).

Subsea equipment can be installed to convert power from AC to DC, which limits losses in power transmission and increases cable capacity. Modules can be also installed on Topside Platforms to convert the function of those cables. Installation of new equipment on existing offshore facilities is a common practice for brownfield development. AC could be rectified to DC and transmitted to the cable / umbilical, then inverted back to AC if required.

Hyttinen et al. (2004) discuss using VSC HVDC to supply direct current power to offshore installations. This VSC technology requires smaller filters and no local generation or synchronous condensers. They were initially developed for land-based applications and went into operation in 1997 onshore (Chokhawala, 2008). Light weight systems have since been developed for offshore installations.

Cable design requirements

Essential design parameters for transmission power cables are (DNVGL-ST-0359, 2016):

- required capacity;
- design lifespan;
- cost (fabrication and connection/installation); and,
- length (route).

DNVGL-ST-0359 (2016) also lists additional parameters to be considered for power cable design, such as mechanical requirements and environmental loads, but these are already considered for existing cables during initial design and proven in the field.

To correlate assessment requirements with DNV GL design parameters, an existing cable is therefore deemed to be a viable alternative if is characterised by:

- sufficient transmission capacity;
- acceptable lifespan;
- cost efficient compared to a new cable; and,
- located sufficiently close to the new wind farm.

Outline of this article

Old cables would not be expected to match the performance of a dedicated new cable and detailed testing and investigation of an existing cable would come at unreasonable cost during early project stages, in particular if several cables were deemed potential alternatives. As an alternative, this paper proposes a fast and cost-effective process to evaluate if an existing cable is a viable alternative to a new cable prior to field testing. Survival analysis is used to develop a set of qualification metrics and build survival curves that compare existing cables to the performance of dedicated new cables. Each qualification metric examines one of the design characteristics in Section 1.5. Aggregating the scores for each metric produces a quantitative assessment of the potential value of a repurposed cable.

METHODOLOGY

The method needs to be adequate for early qualification, applicable for all cable design parameters discussed in Section 1.5, and should not require field operations or unnecessary associated costs. Survival analysis method was selected as an appropriate option because it was historically applied in several fields, which makes it usable for various parameters with different units (physical capacity, age, cost efficiency, and length). This method also provides tangible assessment against well-defined baseline, which is the performance of a dedicated new cable.

Survival Analysis Method

Goel et al. (2011) stated that survival analysis is used to determine the duration until particular event(s) occur; it is implemented for many applications such as determination of death in biological organisms or failure of mechanical systems. The Kaplan-Meier estimate is a commonly used methods of measuring the fraction of subjects living for certain amount of time after treatment. It can be used to decide optimal time for an equipment or facility rehabilitation or replacement. If the facility is proven healthy, with good score on the survival curve, then it has a sufficient life expectancy to remain in operation. The Kaplan-Meier estimate calculated using following formula:

$$S_t = \frac{\text{Number of subjects living at the start} - \text{Number of subjects died}}{\text{Number of subjects living at the start}}$$

This survival curve equation can be redefined to decide if an existing cable can be economically repurposed:

$$S_t = \frac{\text{Targeted performance} - \text{Degradation due to operation or loss in characteristics}}{\text{New cable performance}}$$

To produce a more realistic relationship between the characteristics of a new cable and an existing cable, adjustments can be made to the survival curve to represent rapid degradation of cable properties in specific conditions, uncertainty of cable performance, or to reflect that the existing curve will not be viable beyond a specific time point. Such relationships and adjustments are best fitted using statistical distribution formulae, where suitable data are available. Each qualification metric curve is discussed separately in the next section.

Qualification Metrics

In line with essential typical cable design parameters discussed in Section 1.5, the proposed qualification methodology includes four metrics, each examining a certain aspect of existing power core or cable as follows:

- Capacity: transmission capacity compared with a new cable.
- Reliability: remaining lifespan comparable to projected renewable generation lifetime.
- Profitability: cost saving efficiency and cost of field modifications/connections.
- Proximity: vicinity of the cable to the proposed renewable generation location.

Generating a survival curve for each qualification metric as per Section 2.1 requires finding the essential variable for each cable design parameter. This variable will perform at different levels when compared to new cable, and is normalised to a scale of 0% to 100%. Calculated performance of existing cable is reproduced as a factor (i.e. qualification metric factor) using survival curve equation explained in Section 2.1.

Capacity. Cable capacity, or ampacity (i.e. ampere capacity), is primarily related to the cable resistance. There are several methods to calculate cable ampacity, with the Neher-McGrath Equation (Newton, 2000) being one of the most common:

$$I = \sqrt{\frac{T_c - (T_a + \Delta TD)}{R_{dc}(1 + Y_c)R_{ca'}}}$$

where I is the ampacity; T_c is the conductor temperature; T_a is the ambient temperature; ΔTD is the conductor temperature rise due to dielectric loss; R_{dc} is the conductor DC resistance; Y_c is the loss increment due to conductor skin and proximity effects; and, $R_{ca'}$ is the thermal resistance between conductor and ambient.

The essential variable between existing and new power cores for capacity comparison is the conductor resistance. Hence, the capacity qualification metric is derived using Neher-McGrath Equation by comparing the capacity of an existing cable to new cable requirement. The capacity factor varies between 0 to 10, refer to Figure 3.

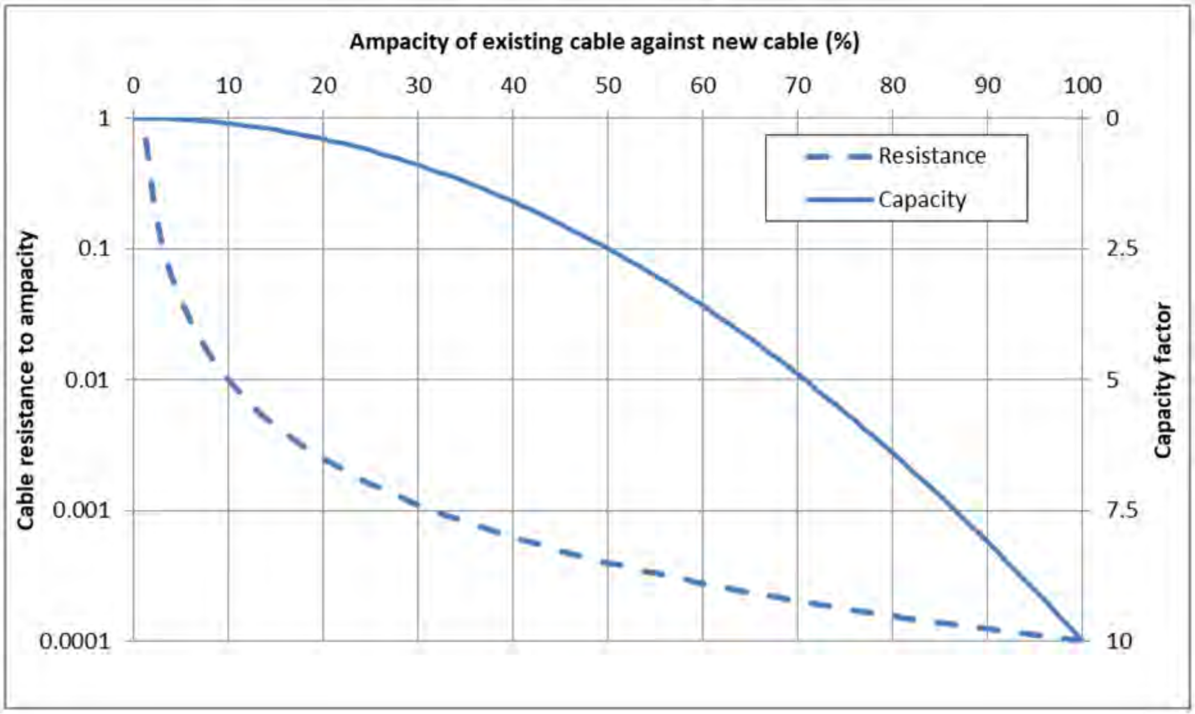

Figure 3—Metric measuring existing cable capacity against a new cable

Figure 13 shows that cable capacity is very sensitive to resistance. For example existing cable with approximately 73% resistance – when compared to new cable – has a factor of 5, while 33% of resistance has a score less than 1. Cables with lower factor might only be repurposed if substantial enhancement to their capacity is feasible (i.e. switching AC to DC or by utilising spare cores in the umbilical) or they could be used for partial development of the field (i.e. relying on more than a single cable for power transmission). Cable ampacity and rating are normally provided by manufacturers, and some de-rating is applied during design phase to ampacity, by as much as 15% of the nominal rating (Zhang, 2017), which indicates that existing cables have higher capacity than the design rating.

Reliability. Power cables in the North Sea are usually buried, which protects and increases the reliability of existing power cores by providing mechanical protection. EMEC Orkney (2015) found that 70% of cable failure mechanism could be attributed to external or environmental factors, based on 15 years' historical data. Submarine cables are typically designed with a design life of 25 years, but a well-protected subsea power cable can achieve life of 30-40 years (Zhang, 2017) or even 60 years for onshore cables (National Grid, 2015).

Thomson and Harrison (2015) state that the typical design life of an offshore wind farm is 20 years, based on the electromechanical components' life of the wind turbine. In practice, actual lifespan is affected by strategic, economic and operational factors. Subsea cables are already able to operate longer than their planned life, not least because seawater naturally cools the cable and the cables are less likely than onshore cables to suffer third-party damage.

Cables and umbilicals have an integrity management plan, so records from existing surveys and umbilical performance could be gathered to assess the reliability of existing cables prior to selection or use.

One approach to comparing the residual age of the cable to the required repurposing lifetime would be a linear relationship as exhibited by Figure 4. If the cable will perform for less than 50% of the field life (10 years), it is not practically a preferred alternative, but if it can operate for 75-90% or even more then it is a very good alternative to a new cable, this is owing to less operating experience (i.e. vulnerability) and hence lower probability of failure. Therefore, a more appropriate relationship might use a probabilistic distribution based on a typical lifetime of 20 years and with 10 degrees of freedom, which represents project's mid-life. This improves acceptance levels for cables satisfy more than 50% of designed life and vice versa.

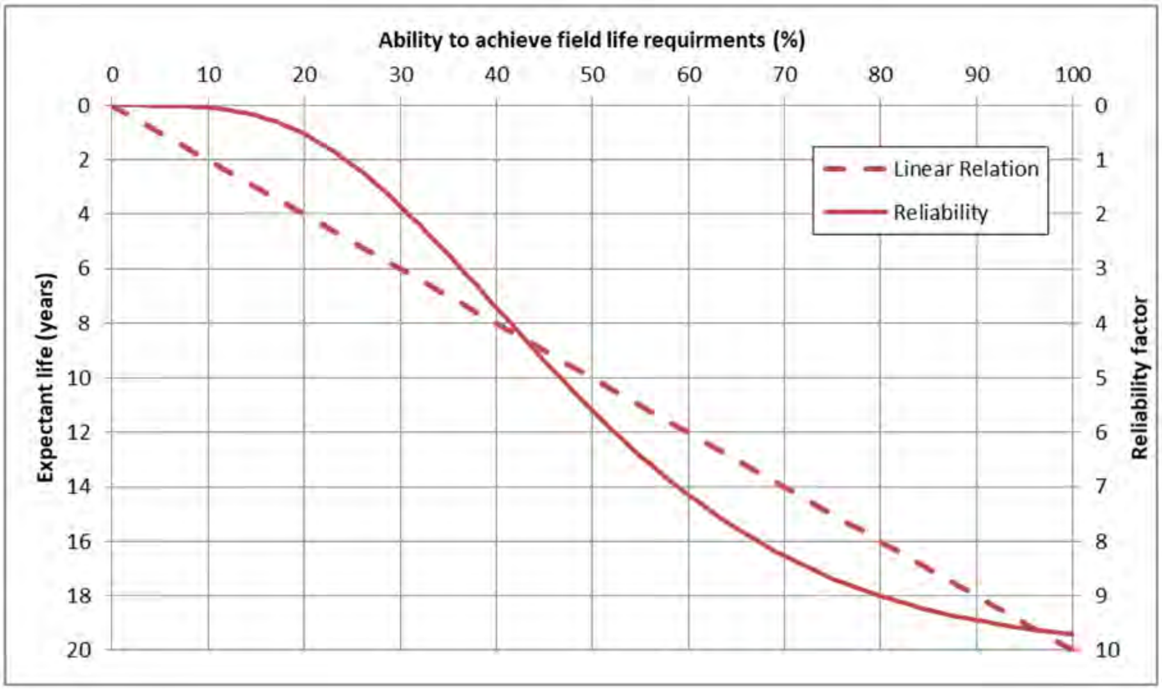

Figure 4—Existing cable reliability

However, the probability that an existing cable could achieve a new design life would ideally be assessed based on actual field statistics to obtain more realistic relationship than assumed in Figure 4.

Profitability. Repurposing cables should reduce CAPEX and the levelised cost of energy (LCOE) from renewable generation, due to avoiding the procurement and installation of a new cable, but offset by any costs of modifying the existing cable for its new application. Transmission costs represent approximately 10% to 15% of LCOE (ORE, 2016).

Savings from cable procurement and installation could be more than 10% of the total renewable cost (BVG Associates, 2010), but this would be reduced by facility repurposing costs, connections and possibly additional equipment to convert power from AC to DC to enhance the cable efficiency.

Field modification could use subsea mechanical connectors or umbilical termination head (UTH). Otherwise, more complex installations and structural modifications with new equipment would be required. The cost of field modification depends on many factors such as characteristics of existing facilities and new field requirements. Without detailed quotations and study, the cost of field modifications is most easily specified as a percentage of total renewable generation CAPEX. A field operator could accept excessive brownfield development because of availability of equipment, avoidance of higher decommissioning cost or purpose/market of the power generated.

LCOE can be calculated by several methods but the most common is IEA Method, which is as follows (IEA, 2016):

$$LCOE = \frac{\Sigma_t^T \frac{C_t+O_t+F_t+D_t}{(1+r)^t}}{\Sigma_t^T \frac{E_t}{(1+r)^t}}$$

Where C is the capital cost, O is operation and maintenance cost, F is fuel cost, D is the decommissioning cost, E is the electricity produced, r is the discount rate, and t is the year in which cost occurs during a lifetime of T.

Using this formula, simplified calculations of LCOE were produced based on BVG Associates (2010) estimation for offshore wind farm CAPEX with a constant discount rate of 10%. The comparison between expected reduction of LCOE for existing cable and parallel profitability is provided by Figure 5. LCOE is a linear relationship that considers cable overall cost out of project CAPEX as shown in Figure 5. Final profitability factor is calculated using LCOE linear relationship and considering the impact of field modification. The new transmission cable cost is taken as 10% of project CAPEX, while the cost of field modification is at variable percentages of the total project CAPEX starting as 1% and increasing gradually to 10%, proportional to LCOE reduction.

For a better explanation of Figure 5, without any need of additional new cable, an existing cable will achieve 9.6 profitability factor due to LCOE reduction. If the total field modification cost is 1% of project CAPEX, the score would slightly go down to 8.7. For a cable that can achieve 75% of new performance, profitability would become 7.2, and by considering 3% field modifications it would be 5.1.

Previous LCOE is considered indicative as there are several methods to calculate, various parameters affect it and nevertheless it changes from year to year. This method is considered fit for initial assessment as it is conservative. If the cable is qualified during the first stage, detailed assessment would include accurate estimation of the impact on LCOE.

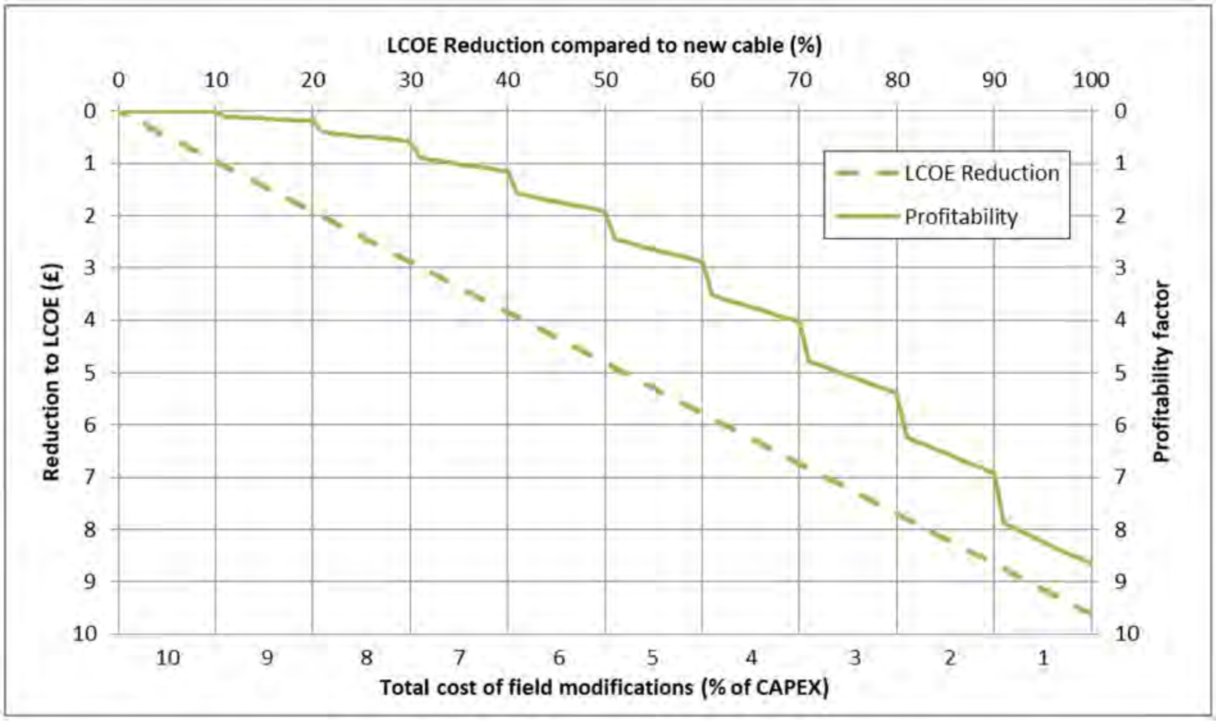

Figure 5—Profitability of the use of existing cable

Proximity. National Grid (2011) anticipates accelerated growth of offshore facilities for renewables during the next 20 years. There are various locations of potential wind farms which are in vicinity of complex of oil and gas facilities. This is confirmed by comparing Round 3 of UK offshore wind farms developments highlighted by Cockburn et al. (2010) with oil and gas footprint mapped by Red Penguin (2012) as shown in Figure 6.

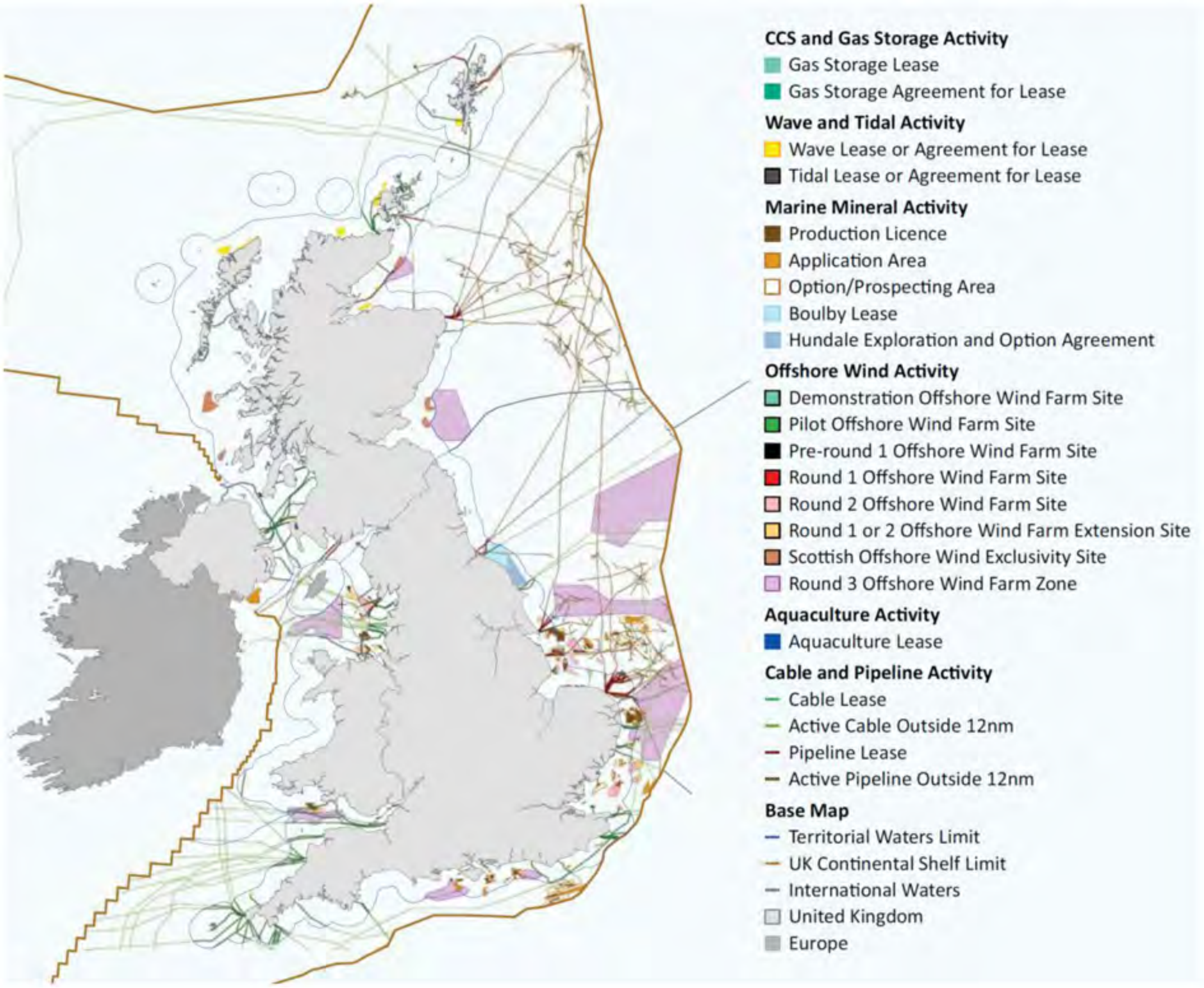

Figure 6—UK offshore oil and gas fields against offshore renewable development (Red Penguin, 2012)

In cable selection, the existing cable should be in vicinity of proposed new cable route as practically possible. The shorter the length of additional cable required, the higher possibility it could be part of array cables installation campaign, which will add minimal duration to the overall installation window and avoid utilising a dedicated installation vessel with additional mobilisation / demobilisation rates.

During the early stages of renewable field developments, there is some flexibility in the field location. Relocating the field to become closer to oil and gas facilities would enhance proximity and accordingly CAPEX and LCOE. Another potential benefit could be the availability of historical geophysical, geotechnical and metrological surveys from oil and gas developments.

Using a linear relationship between additional distance required for an existing cable and total new transmission cable length is not sensible. This is due to the balance between installation cost and cable capacity against procurement of new a cable, which will favour short distance additional cable. This article proposes giving the proximity survival curve a higher score for short additional cables, set at up to 25% of total length of new cable, but this should be investigated further considering installation constraints and flexibility of wind farms. The proximity factor can be calculated from Figure 7.

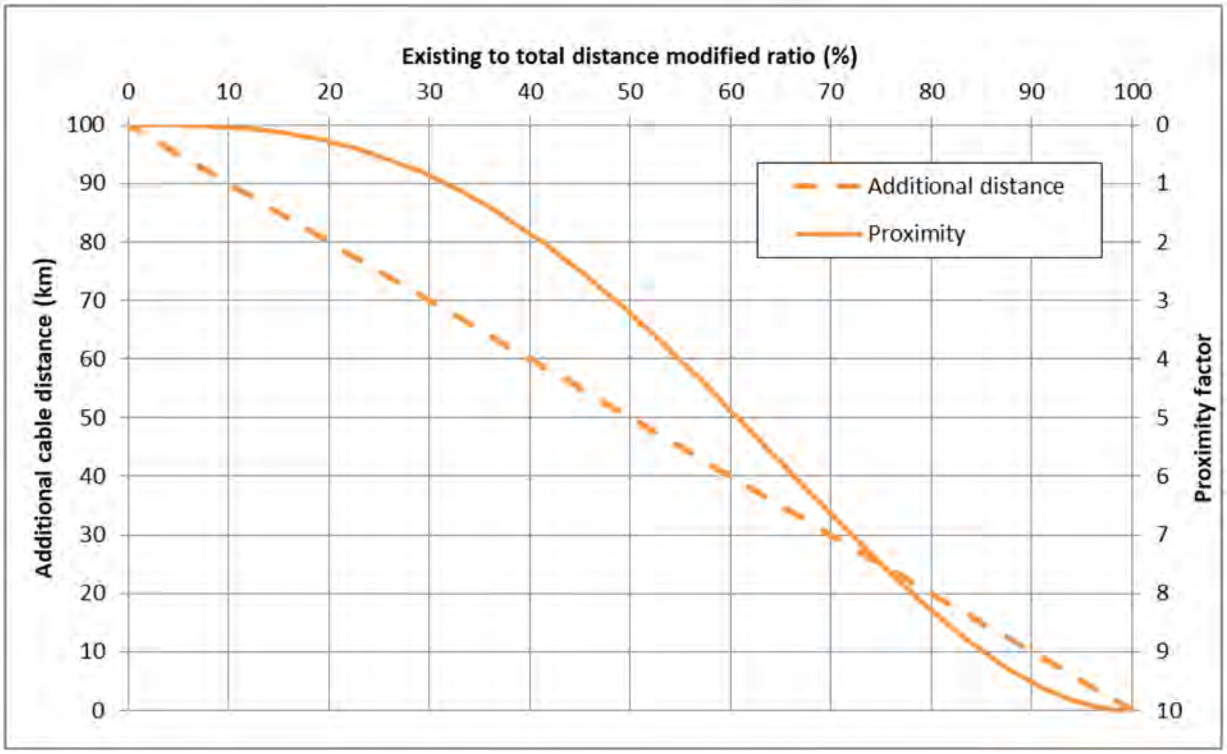

Figure 7—Proximity of existing cable

Although proximity is mainly a function of cost, the preference is to maintain it as a separate qualification metric and not an implicit parameter of profitability. This is due to possibility of locating the proposed offshore renewable field near existing facilities. Flexibility in proposed field location would be an advantage if an existing cable has high capacity, reliability and profitability scores, yet it requires an additional long distance cable. In that case relocating the field towards existing facilities would shorten additional distance and enhance proximity factor. A decision to relocate the renewable field would require a recalculation of the profitability factor.

Combining the qualification metrics

Figure 8 combines all qualification metrics together. A feasible alternative to new cable would have a high score in all four qualification metrics. Cables with medium score in one or more metric would require extension of the assessment, where additional project driven parameters might add some weight to this alternative, e.g. benefits of early power generation, phasing the field development or expansion of adjacent renewable field. Low scores in qualification metric would disqualify existing power core as it would not be a valid substitute for a new cable.

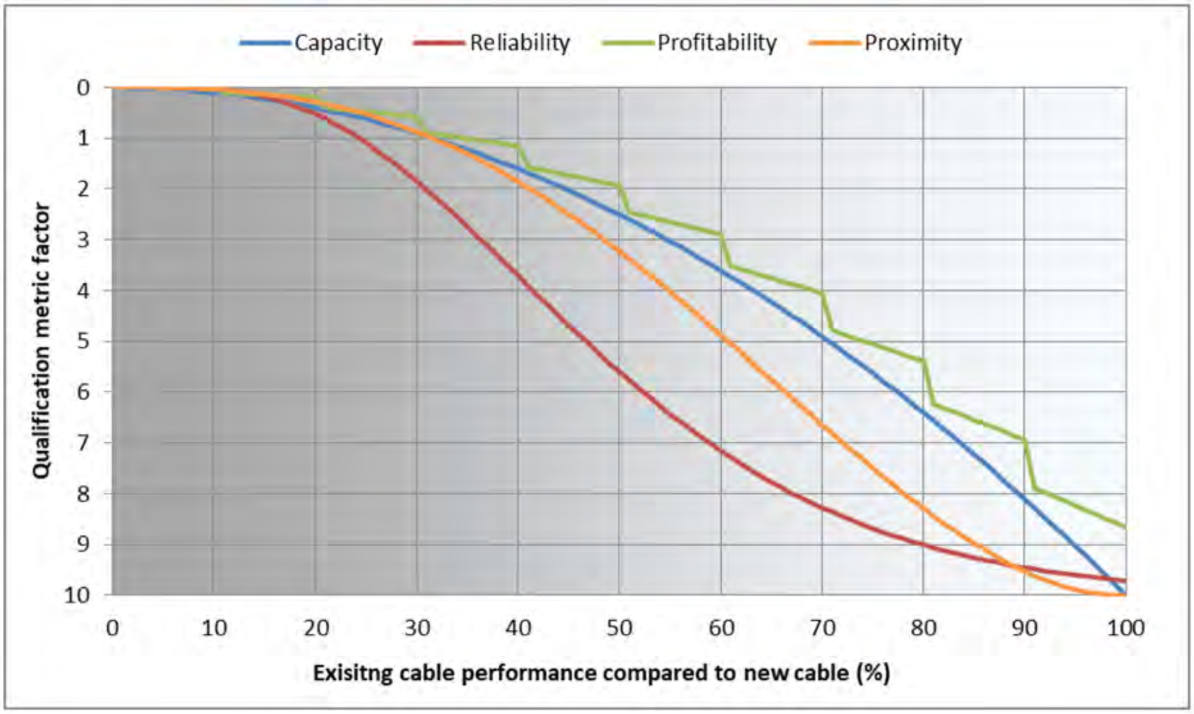

Figure 8—Qualification metrics for existing cable

Figure 8 provides a preliminary and quick assessment to decide if repurposing an existing cable is feasible or not. It is a theoretical method to conduct a screening for as many cables as required before next phase prior to final decision to put the cable back into service. Qualification metrics could be applied to decommissioned cables in the North Sea to rectify them in order to map viable cables then considered in offshore renewables development. This would provide an additional factor to have more efficient energy and better consumer rates.

Second qualification phase prior to putting the cable back to service

Qualified cables would require a risk assessment, inspection and testing prior to re-use decision. Risk assessment could dictate more regular inspection and monitoring during operation, and it must be reflected in the integrity management plan. Initial survey and inspection might lead to some intervention for existing cable to enhance cable reliability. This should be considered for additional maintenance cost which is not investigated in this article. Industry practice (DNVGL-RP-0360, 2016) recommends three different prior testing operations for power cores as follows:

1. Visual Inspection: to investigate any damage to armour and outer layers, also to find out any displacements or exposure of buried sections.
2. Time Domain Reflectometer (TDR).
3. Electrical Test: should include a high voltage test, power cores can be tested through connection points.

For umbilicals, industry specifications (API Specifications 17E, 2017) illustrate in detail different methods for testing which extend to other components as well, for example armour and insulation resistance, which is the most important factor during testing.

CASE STUDY EXAMPLE OF THE QUALIFICATION METRICS

Evaluating the usefulness of the proposed qualification methodology is challenging because cables have not been repurposed for renewable generation in the past. Repurposing offshore cables for new function requires detailed assessment and field measurement, and accompanied with offshore operations cost. This decision is risky if there is a low likelihood that a cable can be repurposed, particularly if the assessment involves several cables.

In the absence of historical data, this section illustrates the qualification assessment for a typical potential repurposed cable as an example. This case study is schematically exhibited by Figure 9. The proposed offshore wind farm requires a new power cable distant 100 km from an onshore terminal (Option A), which is relevant to distances of round 3 of offshore renewables developments. In the same field there is an adjacent oil and gas facility with 80 km existing power core and will require procurement and installation of 20 km additional cable (Option B) to link the old cable to renewable field.

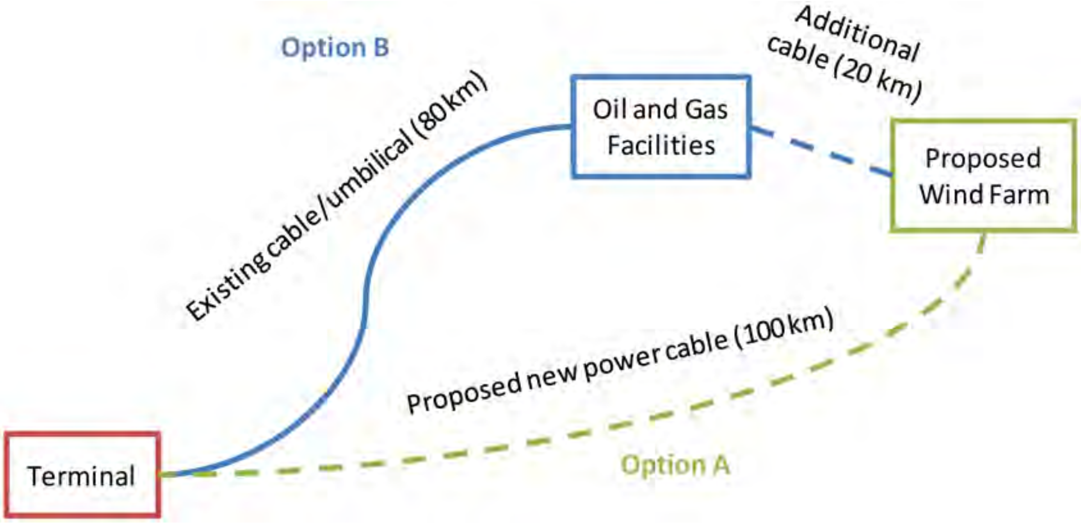

Figure 9—A schematic of the case study

16 and 32 mm^2 typical oil and gas power cores are assumed, which are smaller than a 50 mm^2 renewable power core. The maximum expected cable life is 40 years. The cable was considered that it had operated continuously for 20 years then was out of service for 6 years. Therefore, the remaining cable life anticipated is 14 years (i.e. 70% of the expectant renewable field life). Assumptions of this case study are summarised in Table 1.

Table 1—Case study of existing umbilical compared to new cable

Parameter	Units	New power cable (Option A)	Existing cable (Option B)
Cross section	mm^2	50	16 and 32
Expectant life	years	>20	14 (70% of project life)
Length	km	100	80
Cost of modification	%	n/a	2

Figure 10 illustrates the timeline for cable operational and expectant life besides developments of facilities in the field.

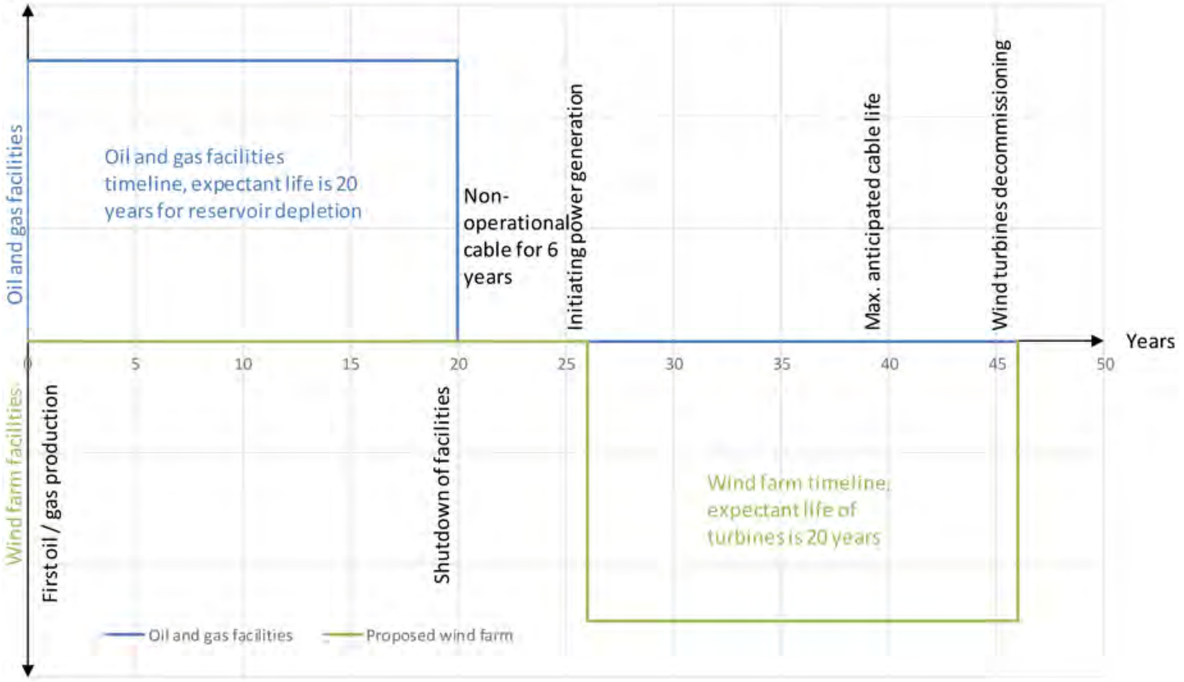

Figure 10—Timeline of field developments in the case study

Applied metrics

The calculated qualification metrics for (Option B), relying on an existing cable, are listed in Table 2:

Table 2—Assessment of existing cable (option B) using qualification metrics criteria

Qualification metric	Existing cable score	Notes
Capacity	1.0 (16 mm^2) 4.1 (32 mm^2)	ampacity is 32% of a new cable and 64% for 32 mm^2
Reliability	8.3	this equals to 70% of field life
Profitability	6.2	LCOE reduced by 7%
Proximity	8.3	Existing distance is 80%

As shown in Table 2, all qualification metrics are acceptable and have good scores except the capacity which is considered low for 16 mm^2 and medium for 32 mm^2 power cores. As mentioned before, further consideration to alter the power core into DC cable will enhance the ampacity but this comes at further increase to project CAPEX, which is considered as 2% during this study. Very small power cores such as 16 mm^2 in this case study will not totally substitute the new cable even with potential increase in the capacity, but they could become auxiliary connections or transmit power during early phase of the project. Figure 11 plots the value for each qualification metric for this case study.

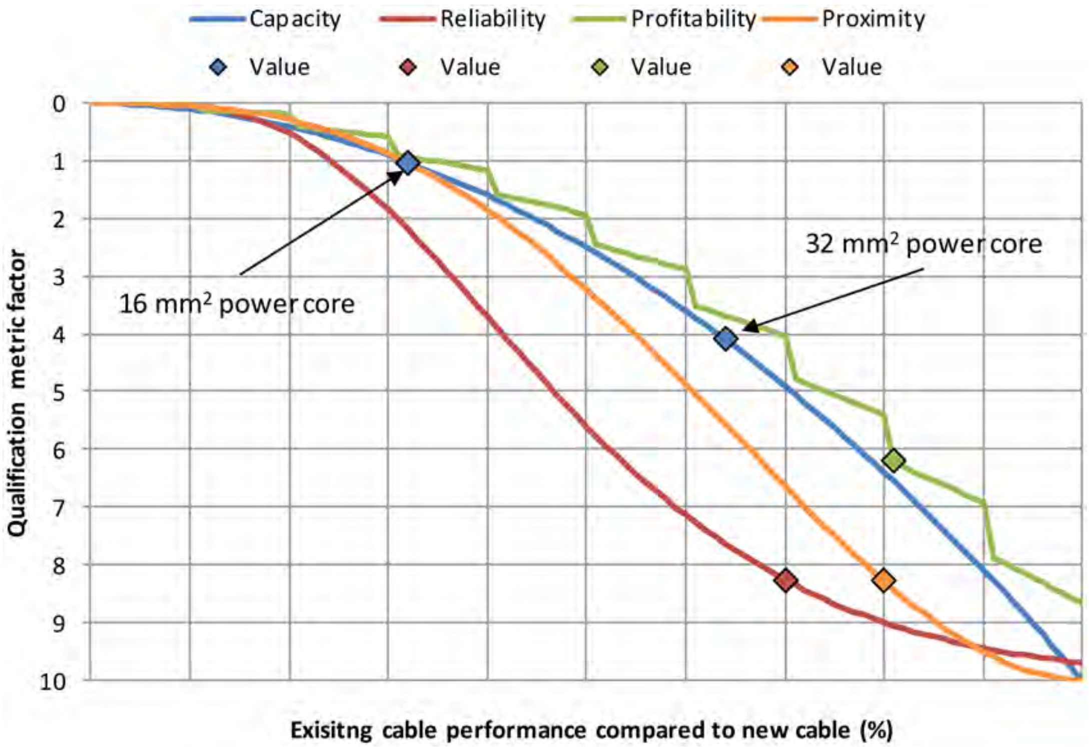

Figure 11—Measuring qualification metrics for a case study

Impact of additional cable length and cost of field modifications

Capacity and reliability metrics reflect well defined cable characteristics (i.e. conductor properties and cable age). The remaining qualification metrics (profitability and proximity) rely mainly on distance between fields, but they are also a function of miscellaneous parameters such as: installation cost; fabrication cost; field modification cost; and, LCOE.

Extended relationships between additional cable distance required, and proximity / profitability are exhibited in Figure 12. Distance between proposed wind farm and existing oil and gas facility is considered between 5 km to 25 km, which represent 5% to 25% of the total new power cable length respectively. Profitability was produced with field additional modification cost equivalent to 2% and 4% of project CAPEX. Examination of these relations will help to understand how excessive cable length and complex modifications adversely affect the profitability metric.

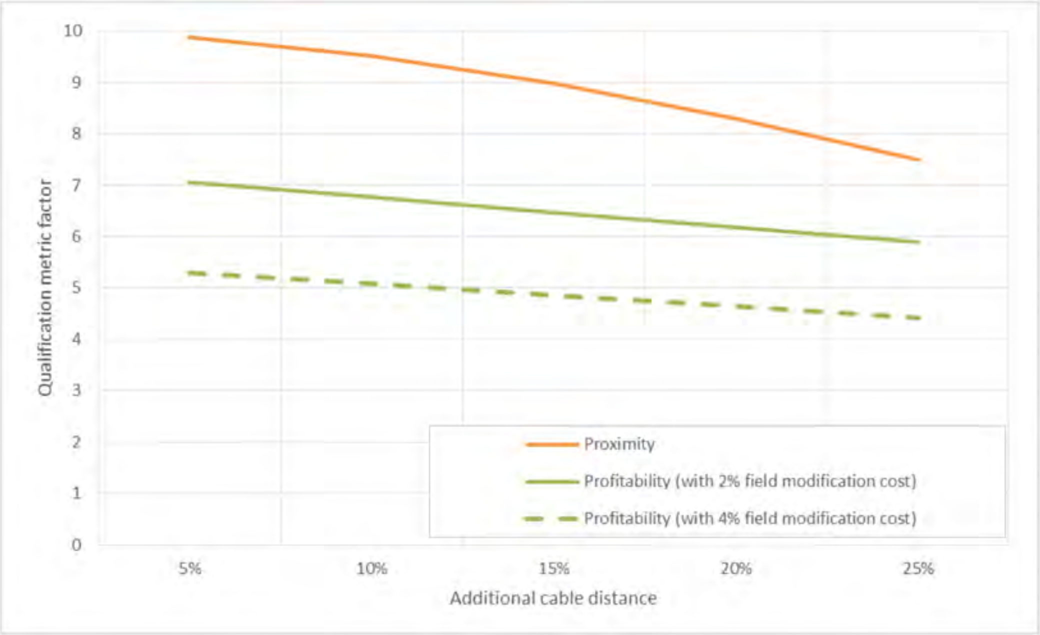

Figure 12—Acceptance of existing cable with variable distances to field development

Cable age evaluation and needs of future cable

Discounting of procurement and installation of new cable will have a positive impact on CAPEX and LCOE as explained before, yet the future need of new cable installation cannot be ultimately ruled out. This could possibly occur if the old cable became uneconomic for continuous operation due to repetitive failures. Thus, discounted new cable cost was estimated during the wind farm design life and for a range of different discount rates (3%, 7% and 10%). Figure 13 exhibits cable future costs based on discounting basics provided of EWEA (2009).

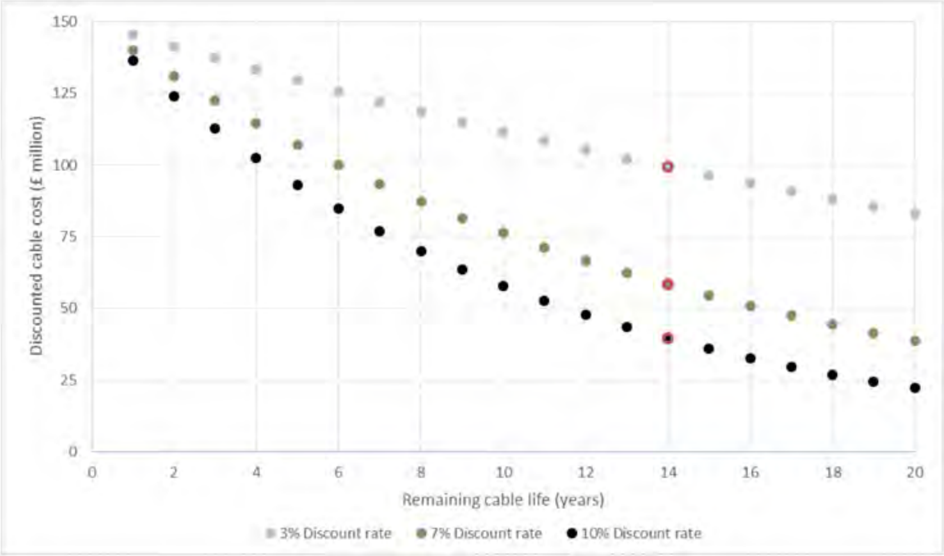

Figure 13—Discounted cable costs for different rates during wind farm design life

The existing cable remaining life was assumed 14 years during the case study. As per Figure 13 and highlighted in red, if a new cable was installed, the discounted cost would be between £40 million and £100 million instead of £150 million at the beginning of the project. Hence, a reduction of between 3.4% and

7.4% of the original project CAPEX is achievable. Discounting of investments is an additional parameter that supports reuse of existing facilities but, as per Figure 13, it is very sensitive to discount rates.

DISCUSSION

Reutilising offshore cables in the North Sea is viable because of their natural ability to survive beyond oil and gas reservoirs' design life, vicinity of offshore renewables expansions, and potentials to increase their capacity. Detailed assessment and field testing are required prior to put a cable back into operation but it is an additional financial burden and time-consuming decision. Hence, an early qualification method is required to support this decision or to rule out existing cable alternative. The qualification method proposed assesses alternatives to existing cables and compares them to a new cable, which provides some evidence to investigate the cable further.

Methodology improvements in the future

At present, there are no tangible experiments for cables that has been reused, in particular if they operate above transmission capacity. Accordingly, there are no reliable records regarding increasing of maintenance cost and probability of failure. The proposed method does not explicitly account for discounting of investments. These are some of the suggestions to readjust survival curves generated in this methodology:

- Capacity qualification metric to account for higher cable temperature and impact on efficiency if it operates above capacity or without de-rating.
- Records and testing of existing cables with long operational life will adjust survival curve for reliability and could account for increasing probabilities of corrosion or failure.
- Further evaluation to other parameters that have an impact on LCOE and profitability such as discounting of investments.
- Investigate additional factors that could affect proximity (e.g. metrological data, detailed installation cost and borderlines between array / export cables installation).

Other complementary uses of offshore infrastructure

There are growing potentials for a complete integration between offshore hydrocarbons and renewables in the future in particular in the North Sea, this is due to energy market rebalance of fossil fuel share in addition to recent attention of reutilising oil and gas infrastructure. In light of current ongoing research, there are more opportunities for energy transition and expanding connections beyond just power cables, which include hydrogen production on platforms using excess wind power generation, carbon capture and storage (CCS) and reuse of fibre optic cables.

CONCLUSIONS

Repurposing decommissioned power cores / conductors in offshore oil and gas facilities into clean energy power cables is feasible, but this was not practically assessed at this stage. There are numerous benefits to oil and gas operators in North Sea as many of their zero cost assets have already reached the end of their design life and are located in vicinity of proposed offshore renewables developments.

Many technologies and methods are being investigated to reduce the LCOE of renewable generation (BVG Associates, 2017). Reutilising cables would have marginal and direct effect on CAPEX and LCOE in addition to considerable positive effects on decommissioning cost and environmental impact.

The main impediment in this concept is that many cables for oil and gas are described as lower capacity medium voltage cables, however, higher capacity cables are used for complex facilities, and in addition, there are methods and design margins that can enhance existing power cores efficiencies (i.e. original cable de-rating or use of spare cores in umbilical). Otherwise, oil and gas cables can become auxiliary connections or transmit power during early phase of the project.

The concept and qualification metrics proposed by this article can be applied for screening and finding potential cables in the North Sea and map feasible cables for offshore renewable development. This method is considered an initial phase of assessment. Feasible cables need inspection, testing, risk and detailed assessment prior to put them back into service, but being qualified is a motive to have a budget for detailed investigation.

Qualification metrics were examined using a case study comprised of typical cables and field parameters. Results indicated positive effects for medium size cables on LCOE as it would be reduced by 7%, and acceptable levels of performance, though there might be a need of cable capacity enhancement. Project CAPEX also could be reduced by 6% even with 2% field modification cost. Very small core cables will not totally replace a new cable.

Based on this article's conclusions, further research and work should be conducted to investigate any regulatory requirements or constraints for use of facilities on long lifespan, to continue previous work by del Río et al. (2011). Old transmission cables need more research to determine probabilities of failure or additional maintenance cost if they operate with higher capacity. This article could also be another cornerstone for North Sea power grid research and infrastructure decommissioning and developments.

ACKNOWLEDGEMENTS

We thank the reviewers at OTC conference for their careful reading of our manuscript and their insightful comments.

NOMENCLATURE

AC	Alternate Current
CAPEX	Capital Expenditure
DC	Direct Current
HV	High Voltage
LCOE	Levelised Cost of Energy
TDR	Time Domain Reflectometer
UTH	Umbilical Termination Head
VSC	Voltage Source Convertor

REFERENCES

1. ABB, Submarine Power Cables: Cables for offshore platforms, ABB AB – High Voltage Cables (2012). https://new.abb.com/.
2. ABB, Submarine Power Cables: Cables for offshore wind farms, ABB AB – High Voltage Cables (2012). https://new.abb.com/.
3. API, Specification 17E: Specification for Subsea Umbilicals, American Petroleum Institute (2017). https://www.api.org/Standards/.
4. J. Bard, Multi-use Platform Concepts for the Oceans of Tomorrow, in: ICOE - International Conference Ocean Energy, Nova Scotia, Canada (2014). https://www.icoe-conference.com/publication/multi-use-platform-concepts-for-the-oceans-of-tomorrow/.
5. A. Burstein, V. Ćuk, E. De Jong, Determining potential capacity gains when repurposing MVAC cables for DC power transportation, *CIRED - Open Access Proceedings Journal* **2017** (2017) 1691–1694. https://doi.org/10.1049/oap-cired.2017.0142.
6. BVG Associates, A Guide to an Offshore Wind Farm, Published on behalf of The Crown Estate, (2010). https://bvgassociates.com/cases/guide-offshore-wind-farm/.

7. BVG Associates, A Guide to an Offshore Wind Farm Updated and extended, Published on behalf of The Crown Estate, Offshore Renewable Energy Catapult. (2019). https://www.thecrownestate.co.uk/media/2861/guide-to-offshore-wind-farm-2019.pdf.
8. BVG Associates, Future renewable energy costs: offshore wind, InnoEnergy (2017). https://bvgassociates.com/wp-content/uploads/2017/11/InnoEnergy-Offshore-Wind-anticipated-innovations-impact-2017_A4.pdf.
9. R.A. Caulk, I. Tomac, Reuse of abandoned oil and gas wells for geothermal energy production, *Renewable Energy*. **112** (2017) 388–397. https://doi.org/10.1016/j.renene.2017.05.042.
10. R. Chokhawala, Powering platforms: Connecting oil and gas platform to mainland power grids, *ABB Review* (2008). https://library.e.abb.com/public/aab4c01eb564adf3c1257427002e53a5/52-561M811_ENG72dpi.pdf.
11. C.L. Cockburn, S. Stevens, E. Dudson, Accessing the far shore wind farm, RINA, in: The Royal Institution of Naval Architects, RINA - Marine Renewable and Offshore Wind Energy Conference (2010) 153–158. https://www.bmt.org/publications/paper-56/.
12. P. Del Río, A. Calvo Silvosa, G. Iglesias Gómez, Policies and design elements for the repowering of wind farms: A qualitative analysis of different options, *Energy Policy*. **39** (2011) 1897–1908. https://doi.org/10.1016/j.enpol.2010.12.035.
13. DNVGL, DNVGL-RP-0360: Subsea power cables in shallow water renewable energy applications, Det Norske Veritas GL (2016). https://www.dnvgl.com/rules-standards/index.html.
14. DNVGL, DNVGL-ST-0359: Subsea power cables for wind power plants, Det Norske Veritas GL (2016). https://www.dnvgl.com/rules-standards/index.html.
15. EMEC Orkney, PFOW Enabling Actions Project : Sub-sea Cable Lifecycle Study, Published on behalf of The Crown Estate (2015). http://www.emec.org.uk/?wpfb_dl=232.
16. EWEA, The economics of wind energy, The European Wind Energy Association (2009). http://www.ewea.org/fileadmin/files/library/publications/reports/Economics_of_Wind_Energy.pdf.
17. A.M. Fowler, A.M. Jørgensen, J.C. Svendsen, P.I. Macreadie, D.O.B. Jones, A.R. Boon, D.J. Booth, R. Brabant, E. Callahan, J.T. Claisse, T.G. Dahlgren, S. Degraer, Q.R. Dokken, A.B. Gill, D.G. Johns, R.J. Leewis, H.J. Lindeboom, O. Linden, R. May, A.J. Murk, G. Ottersen, D.M. Schroeder, S.M. Shastri, J. Teilmann, V. Todd, G. Van Hoey, J. Vanaverbeke, J.W.P. Coolen, Environmental benefits of leaving offshore infrastructure in the ocean, *Frontiers in Ecology and the Environment* **16** (2018) 571–578. https://doi.org/10.1002/fee.1827.
18. M.K. Goel, P. Khanna, J. Kishore, Understanding survival analysis: Kaplan-Meier estimate, *International Journal of Ayurveda Research* **1**(4) (2010) 274–278. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3059453/.
19. J.E. Hanssen, L. Margheritini, K. O'Sullivan, P. Mayorga, I. Martinez, A. Arriaga, I. Agos, J. Steynor, D. Ingram, R. Hezari, J.H. Todalshaug, Design and performance validation of a hybrid offshore renewable energy platform, in: 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies - EVER (2015): pp. 1–8. https://doi.org/10.1109/EVER.2015.7113017.
20. P. Hou, P. Enevoldsen, W. Hu, C. Chen, Z. Chen, Offshore wind farm repowering optimization, *Appl. Energy*. **208** (2017) 834–844. https://doi.org/10.1016/j.apenergy.2017.09.064.
21. T.N. M Hyttinen, JO Lamell, New application of voltage source converter (VSC) HVDC to be installed on the gas platform Troll A, in: *CIGRÉ - International Council on Large Electrical Systems* (2004). https://www.semanticscholar.org/paper/New-application-of-voltage-source-converter-(-VSC-)-Hyttinen-Lamell/a20d72b6c5bc22c69ad6e5ee11db8d44ca635557.
22. IEA, World Energy Investment Report 2016, IEA: IEA - International Energy Agency (2016). https://webstore.iea.org/world-energy-investment-2016.

23. C.J. Jepma, M. Van Schot, On the economics of offshore energy conversion: smart combinations_Converting offshore wind energy into green hydrogen on existing oil and gas platforms in the North Sea, EDI - Energy Delta Institute (2017). https://www.semanticscholar.org/paper/On-the-economics-of-offshore-energy-conversion%3A-Jepma-Schot/39e660db8aca8f7dbf5c10cac9f63767d5fbdddd.
24. M. Korpås, L. Warland, W. He, J.O.G. Tande, A case-study on offshore wind power supply to oil and gas rigs, *Energy Procedia*. **24** (2012) 18–26. https://doi.org/10.1016/j.egypro.2012.06.082.
25. L.P. Lazaridis, Economic comparison of HVAC and HVDC solutions for large offshore wind farms under special consideration of reliability, Royal Institute of Technology, (2005). http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.66.4595&rep=rep1&type=pdf.
26. M. Leporini, B. Marchetti, F. Corvaro, F. Polonara, Reconversion of offshore oil and gas platforms into renewable energy sites production: Assessment of different scenarios, Renew. *Energy*. **135** (2019) 1121–1132. https://doi.org/10.1016/j.renene.2018.12.073.
27. Y. Lian, S.J. Finney, DC collection networks for offshore generation, in: RPG 2013 - Second IET Renewable Power Generation Conference (2013) 2011. https://doi.org/10.1049/cp.2013.1789.
28. J. MacDonald, Providing Scope for Reducing the Carbon Footprint of an Offshore Oil Rig, University of Strathclyde (2014). http://www.esru.strath.ac.uk/Documents/MSc_2014/MacDonald.pdf.
29. National Grid, Offshore Transmission Network Feasibility Study, Published on behalf of The Crown Estate (2011). http://www.nationalgrid.com/NR/rdonlyres/A594DC29-54E7-4A46-A6C5-51EDFC31AB6C/49218/Part13AppendixL.pdf.
30. National Grid, Undergrounding high voltage electricity transmission lines: The technical issues, National Grid (2015). https://www.nationalgridet.com/sites/et/files/documents/39111-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf.
31. N.B. Negra, J. Todorovic, T. Ackermann, Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms, *Electric Power Systems Research* **76** (2006) 916–927. https://doi.org/10.1016/j.epsr.2005.11.004.
32. G.C. Newton, Understanding the Neher-McGrath Calculation and the Ampacity of Conductors, Electriciancalculators.com. (2013). http://www.electrician2.com/ampacity/understanding_nm.pdf.
33. OGUK, Decommissioning of Pipelines in the North Sea Region 2013, OGUK - Oil and Gas UK (2013). https://oilandgasuk.co.uk/wp-content/uploads/2015/04/pipelines-pdf.pdf.
34. ORE Catapult, Offshore Transmission Benchmarking and Cost monitoring, ORE - Offshore Renewable Energy Catapult (2016). https://ore.catapult.org.uk/app/uploads/2018/02/Offshore-Transmission-Benchmarking-and-Cost-Monitoring.pdf.
35. Red Penguin, Submarine cables and offshore renewable energy installations Proximity Study, Published on behalf of The Crown Estate (2012). http://www.redpenguinltd.com/.
36. RSA, North Sea Oil and Gas Rig Decommissioning & Re-use Opportunity Report: The RSA Great Recovery and Zero Waste Scotland Programme, RSA - The Royal Society for the Encouragement of Arts, Manufactures and Commerce (2015). https://www.thersa.org/globalassets/pdfs/reports/rsa-great-recovery---north-sea-oil-and-gas-report.pdf.
37. SUT, Powering oilfields – Wind farm being considered at Snorre and Gulfaks, UT3 Mag. **12** (2018) 60–61. http://www.ut-2.com/pdf/Issue4.pdf.
38. R.C. Thomson, G.P. Harrison, Life cycle costs and carbon emissions of wind power, ClimateXChange (2015). http://www.climatexchange.org.uk/files/4014/3324/3180/Executive_Summary_-_Life_Cycle_Costs_and_Carbon_Emissions_of_Wind_Power.pdf.
39. E. Topham, D. McMillan, Sustainable decommissioning of an offshore wind farm, *Renewable Energy* **102** (2017) 470–480. https://doi.org/10.1016/j.renene.2016.10.066.

40. R. Villena-Ruiz, F.J. Ramirez, A. Honrubia-Escribano, E. Gómez-Lázaro, A techno-economic analysis of a real wind farm repowering experience: The Malpica case, *Energy Conversion and Management* **172** (2018) 182–199. https://doi.org/10.1016/j.enconman.2018.07.024.
41. Wind Europe, Wind energy in Europe in 2018 Trends and Statistics, *Wind Eng*. **16** (2019) 35–47. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf.
42. C. Zhang, Specifications of submarine power cables, The E&T Energy and Power Hub. (2017). https://www.theiet.org/.