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Optimising Network Design Options for Marine Energy Converter Farms

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Abstract— **This paper introduces a techno-economic analysis framework to assess different transmission options for marine energy converter (MEC) farms. On the technical front, the feasibility of the transmission option considering supply quality constraints and the optimal sizing of reactive power compensation to allow maximum real power transfer capability in the subsea transmission cable have been considered. The economic viability of different transmission options are measured based on component costs and the costs associated with losses. A case study has been presented in the paper, which demonstrates the application of this techno-economic analysis framework on a range of MEC farm sizes and distances from the shore.**

Keywords— **Marine energy converter arrays, transmission system, optimisation, cost-benefit analysis, network integration.**

I. INTRODUCTION

As marine energy converter (MEC) deployment moves from single device installations to arrays and farms of devices, a concept engineering study of the electrical infrastructure is required to inform the connection of these commercial scale farms to the electricity network. Although the marine energy sector can learn from experience in the offshore wind sector, e.g. [1]-[3], there are a number of engineering challenges which are unique to the marine energy sector. The fact that there are potentially more subsea components in areas with stronger wave and tidal current conditions creates new design challenges for the operation and installation of electrical networks and components.

The harsher operating conditions in the marine renewable energy (MRE) environment may require the use of specialised components, which are generally more expensive than commercially available products. This can result in a higher levilised cost of energy (LCOE) – which defines the power cost per unit to break even over the project lifetime – than competing offshore generation technologies. In order to gain a market share, the LCOE of MEC arrays has to be comparable. Without subsidy, there are two general ways to achieve this: by reducing component cost or by maximising the use of existing assets. Reducing component cost will require an increase in production volume and will only happen when the industry reaches maturity. However, by detailed cost-benefit analysis, electrical networks can be designed to ensure maximum possible return for the available resources and network capacity.

In this paper, a techno-economic analysis framework for allowing maximum real power transfer across the transmission network is described. This is illustrated by assessing the impact of two of the most important array parameters, the installed capacity and the export cable length, on the cost and performance of the transmission system. The boundaries of these parameters are defined with respect to the current needs of the industry, and are representative of pre-commercial and full commercial deployment. They are set to installed capacity of less than or equal 100 MW and an export cable length of less than or equal to 50 km, respectively [4].

In this operating region, ac transmission is still the most economical solution (dc transmission may become a better solution for distances greater than 50 km and for farm sizes greater than 500 MW [5]-[7]). With ac transmission, the capacitance of the cables causes a charging current to flow through it. This limits the real power transfer back to shore if the transmission system is not properly designed. The fact that the cost of the export cable is high, and that it can constrain the output of the array, makes it particularly interesting for cost-benefit analysis.

The transfer capability of the ac transmission can be improved using reactive power compensation and a detailed study of the sizing of onshore and offshore reactive power compensation to utilise the transmission capacity of the export cable is presented. A case study investigates the impact of this on MEC array cost and efficiency, highlighting the importance of the design of the transmission network to the array performance. The results presented here is part of ongoing research and will serve to highlight the sensitivity of the overall system to alternative designs, and will help to determine the prevailing parameters for optimal design of offshore networks [4].

The paper is structured as follows. Section II introduces the main systems present within an offshore MEC farm, with further details of the components given in Section III. The techno-economic analysis framework is defined in Section IV. Both the technical and economic aspects are described in more detail in Section V and VI respectively. A case study is presented in Section VII. The conclusions and areas of further work are discussed in Section VIII.

II. DESIGN OF MARINE ENERGY CONVERTER FARMS

The electrical system of a MEC farm follows a hierarchical structure from production to grid connection. A generic offshore network architecture is shown in Fig. 1 which clearly identifies the subsystems within.

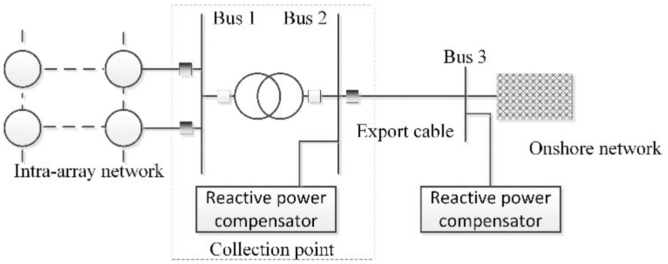


Fig. 1 Simplified generic offshore electrical network for MEC arrays

The design of the MEC farm layout depends on a multitude of factors, ranging from the site characteristics to the level of performance required from the system to the available capital cost. Some of the most important decisions which must be taken during the design can be defined as follows:

- The transmission system between the collection point and the onshore network;
- The number and type of offshore collection points;
- The intra-array network layout.

The network design will typically start with the selection of the export cable. Once this has been defined, the need for a collection point is then assessed, which will be performed in conjunction with decisions on the layout of and control within the intra-array network. This section presents an overview of the options that are currently available to the network designer.

A. *Transmission System*

As previously discussed, the distances (less than 50km) and transferred power (less than 500 MW) currently required by the MRE sector can be served using ac transmission systems. Alternative dc solutions are being considered as a way to improve the commercial viability, e.g. [5],[7], but are still in the pre-commercial/R&D phase. The main disadvantage of ac transmission systems is the requirement of reactive power compensation when the transmission distance becomes long and the size of the farm increases. The impact of this is discussed in detail in later sections where it is shown that compensation may be required both onshore and offshore. The offshore compensation will be housed within the collection point discussed in the following section.

B. *Collection Point*

Due to the high cost of the export cable, commercial scale arrays will collect the power generated by the individual MECs at offshore collection points in order to reduce the number of transmission cables required. Collection points can be classified into two general categories:

- Passive hub: which collects and exports power at the intra-array voltage. This may or may not include switchgear;
- Offshore substation: which includes step-up transformer and associated switchgear.

It is possible to have subsea and surface piercing variants of both; however, a surface piercing passive hub is unlikely to be found in practice and is omitted from further discussion.

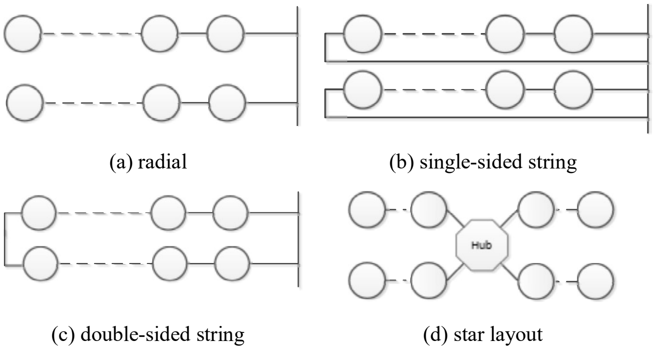
1) Subsea Passive Hub: Subsea hubs have been utilised in the oil & gas (O&G) industry as process control points. Therefore, this can be considered a mature technology which may be adapted for use in MEC farms. The WaveHub test site off the South West coast of England is an example of an offshore subsea hub without transformers [8]. Although it can be expected that vast majority of commercial arrays will contain only one offshore collection point, multiple subsea hubs may be utilised in future applications. Floating hubs are also possible but are still in the early stages of development.

2) *Offshore Surface Piercing Substation:* As MEC farms become larger and their distance to the shore increases, transmitting power at medium voltage may become uneconomical due to the associated high power losses. For large farms far away from the shore, the power would need to be transmitted at higher voltages. This would require step-up transformers (and its associated switchgear and any reactive power compensation) on offshore substations. This option is most likely to be used in the short to medium term in MEC farms. The experience available from the offshore wind industry is another advantage of this option.

3) *Offshore Subsea Substation:* Subsea transformers and switchgear have been used in subsea O&G production units. However, it is unlikely to be used within MEC farms in the near future as subsea components will be costlier than air-installed variants.

C. *Intra-array Network Layout*

An array of MECs consists of multiple converters linked by subsea cables, delivering electricity to the onshore network. There are a number of intra-array network layout options available for MEC farms, with some examples in Fig. 2.



(a) radial (b) single-sided string

(c) double-sided string (d) star layout

Fig. 2 Offshore network configurations

All the layout options are variants of the radial layout, with different levels of redundancy. The number of devices per radial is a technical constraint which is decided based on the rated capacity of the device, the spacing between two neighbouring devices and the rating of the intra-array cable [9].

The layout is chosen as a trade-off between power losses in the network, its robustness and the cost of the farm. However, the resource characteristics and the sea bed conditions of the site are also crucial factors to be considered before the intra-array electrical network is designed.

III. Electrical equipment within MEC farms

This section provides an overview of the main electrical equipment used within MEC farms. A more comprehensive review of components is available at [10].

A. Submarine cables

Submarine power cables are used to collect the power generated by the farm through the intra-array electricity network and also to export the generated power from the collection point to the shore. In addition to transferring power, submarine cables serve the crucial role of transmitting communication signals between the array equipment and the shore.

1) Static cables: are restricted in movement by installation techniques, either by burial or cable protection measures. They form the main arteries of the offshore network and also transmit the generated power back to shore.

2) *Umbilical cables:* are dynamic cables that transfer the power generated by floating MECs to the subsea network. They must be carefully designed to withstand severe wave and tidal loading conditions.

B. Subsea connectors

Subsea connectors are used to connect umbilicals with the subsea electricity network, subsea cables with a subsea hub or the offshore substation and umbilicals with floating MECs. They should allow easy connection/disconnection of the electrical equipment within farms, thereby reducing operational downtime and maintenance costs.

1) Wet-mate connector: connection / disconnection can be performed either in dry atmosphere or under water. Wet mate connectors with a voltage and current rating of 30 kV and 500 A respectively (approximately 26 MVA) have been used in the O&G industry and are commercially available [11]. Wet-mate connectors are more expensive than dry-mate connectors and are less developed for the same voltage and power ratings. The advantage is that they can be connected under water; however, expensive and specific ROVs (Remotely Operated Vehicle) or specialist divers are needed.

2) Dry-mate connector: connection / disconnection is performed in dry atmosphere. Dry mate connectors of more of less the same rating as wet-mate connectors are commercially available. The main disadvantage of dry-mate connectors is that they must be connected in dry conditions; this entails procedures for refloating operations and additional dry-deck areas on-board the vessel.

C. Transformers

Within MEC farms, transformers may be present within each MEC device and may also be required in offshore substations. For use offshore, the cooling arrangements within transformers are different. For indoor use dry, air-cooled type transformers are preferred [12]. For outdoor use, liquid-cooled transformers need to be hermetically sealed and the cooling medium should not be toxic [12].

D. Switchgear

Switchgear is used both within the intra-array network and in the offshore substation to protect electrical equipment and to isolate electrical subsystems either for maintenance or when faults occur. The MEC farm switchgear arrangement is expected to be similar to that used in offshore wind farms. This arrangement is shown in Fig. 3, with a simplified overview of the collection point configuration shown in Fig. 1.

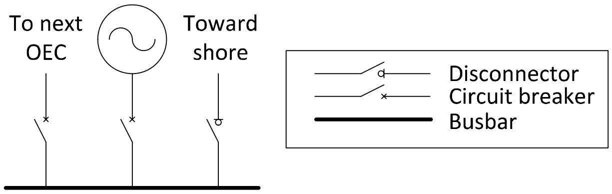


Fig. 3 Offshore wind switchgear arrangement, based on [13]

E. Power quality equipment

The term power quality equipment covers all filter types required to ensure grid compliance and also reactive power compensation to ensure optimal utilisation of transmission/export capabilities. This is can be divided into: harmonic filters, reactors, capacitor banks and flexible AC transmission systems (FACTS). As this research is concerned only with steady-state power flows, only the selection of reactive compensation is considered in detail in this paper.

IV. Techno-economic analysis Framework

Techno-economic analysis is a widely implemented approach for comparing systems when more than one solution is possible. The performance of each solution is effectively normalised against the cost until an optimum value is reached.

There are two cost components that should be included when evaluating the transmission system. The first one is the actual cost of supply and installation of the transmission system. This cost is a function of the network capacity and redundancy and increases proportionally with network capacity and/or redundancy. The second is the cost associated with generated energy lost in the form of transmission power losses. These losses generally reduce with an increase in network capacity. The objective of the techno-economic analysis is, thus, to identify the transmission system configuration corresponding to the lowest total cost point in the curve in Fig. 4.

The techno-economic framework is developed around a MATLAB power flow solver to analyse the network performance: ensuring technical feasibility and accurate assessment of network losses. The process for a given export voltage rating can be described as follows:

1. Define array/farm characteristics: rated power, intra-array operating voltage;

2. Calculate the power output of the MEC farm for each identified sea states;
3. Define array/farm characteristics: rated power, intra-array operating voltage;
4. Calculate the power output of the MEC farm for each identified sea states;
5. Assess technical feasibility: steady-state voltage variations and reactive power compensation. Proceed if the solution satisfies grid code requirements;
6. Run the power flow for each identified MEC operating condition;
7. Multiply the transmission loss for each sea state with the frequency of occurrences of that sea state to calculate the energy loss in Watt-hours.
8. Add the transmission loss over the entire range of sea states to obtain the total energy loss.

Further details on the technical feasibility and the cost modelling are included in subsequent sections.

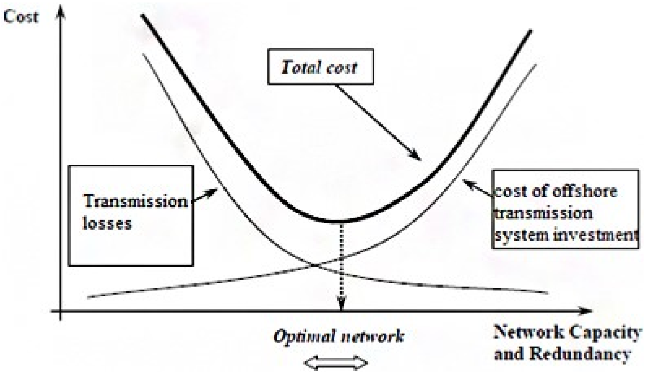


Fig. 4 Concept of the techno-economic analysis [1]

V. TECHNICAL FEASIBILITY

Commercial size arrays must achieve Grid Code compliance. For the steady-state power flow analysis considered in this research, the MATLAB power flow solver is used to assess the steady-state voltage variations and reactive power support. All discussions here refer to the UK Grid Code requirements [14].

A. *Voltage regulations*

In the offshore network, the voltage variation from nominal is determined by the number and size of devices connected to a string and the impedance of the cables. The offshore voltage regulation requirements are assumed to be identical to the onshore requirements. For the medium voltage levels considered in this analysis, the voltage regulation requirements stipulate a maximum steady-state operating range of 0.9 to 1.1pu [15].

B. *Reactive power compensation*

In offshore MEC farms with ac transmission systems, the capacitance of the cable causes a charging current to flow through it. The thermal characteristics of a cable limits the continuous current that it can safely carry. Therefore, if the charging current is high, a constraint on the real power that the cable can transmit is placed. The distance over which real power can be efficiently transmitted by an ac cable is limited due to this characteristic.

There are two sources of charging current in MEC farms: the intra-array network cables and the transmission link to shore. Adequate reactive power compensation, both onshore and offshore, is required to fully utilise the real power carrying capacity of subsea cables. This is particularly important considering the high procurement and installation costs of subsea cables. This section presents a methodology to determine the optimal size of reactive power compensation.

1) *Reactive power compensation required for the intra-array network:* Fig. 1 shows a network schematic of typical MEC farms. Bus 1 is the offshore grid entry point (GEP). The power factor at bus 1 is assumed to be fixed at 1 (unity power factor – UPF) to meet the UK Grid Code requirements [14]. This means that any reactive power generated or stored in the intra-array network needs to be absorbed/generated by a compensator on bus 1. Whether reactive power is generated or absorbed by the intra-array network depends on a variety of factors - how much power is being generated/carried into/by the network, the length of cabling within the array, the size of the individual devices etc.

The reactive power generated by the intra-array network was found to be maximum when the generators were not generating any real power. Such a scenario would be seen for very low energy sea states outside the operating regime of the MEC when the MEC does not generate any power. The generators in the MEC would be idling during this period. The reactive power loss in the intra-array network was found to be maximum when the generators were generating at rated capacity. Therefore, the reactive power compensation at bus 1, capable of both generating and absorbing reactive power, can be sized to be the greater of the reactive power generated/absorbed at these two conditions. Compensating the reactive power generated by the intra-array network does not increase the active power carrying capability of the intra-array network, but ensures UPF operation at bus 1.

Reactive power compensation required for the transmission link: The onshore and offshore reactive power compensation required for the transmission link is calculated assuming that the power the MEC array feeds the network at the offshore GEP is at UPF, using appropriately sized compensation at bus 1 (defined in the previous section). Additionally, the onshore compensation required is calculated to maintain the voltage at the onshore GEP (bus 3) at 1 pu. Although, the voltage at the onshore GEP is defined through an agreement between the network operator and the generator operator [14], 1 pu is a reasonable assumption. The offshore compensation aims to maximise the real power capacity of the cable (by reducing charging current) and to ensure that the offshore substation voltage lies within statutory limits. The onshore compensation does not affect the charging current that the cable carries and, thus, can be treated separately.

The amount of offshore reactive power compensation is determined using an iterative method shown in Fig. 5. This is based on the procedure used with offshore wind farms in [1]. The reactive power compensation at the offshore substation is selected to allow the maximum possible real power transfer for the smallest offshore compensation. As a severe voltage rise at bus 2 may be observed for some of the lower rated cables, the reactive power compensation is also sized to ensure that the bus 2 voltage remains within ±10% (UK limits) of the nominal value [15]. To meet the supply quality requirements, there may be a need to constrain generation due to capacity limits imposed by the reactive power transmitted through the transmission cable, as indicated in Fig. 5.

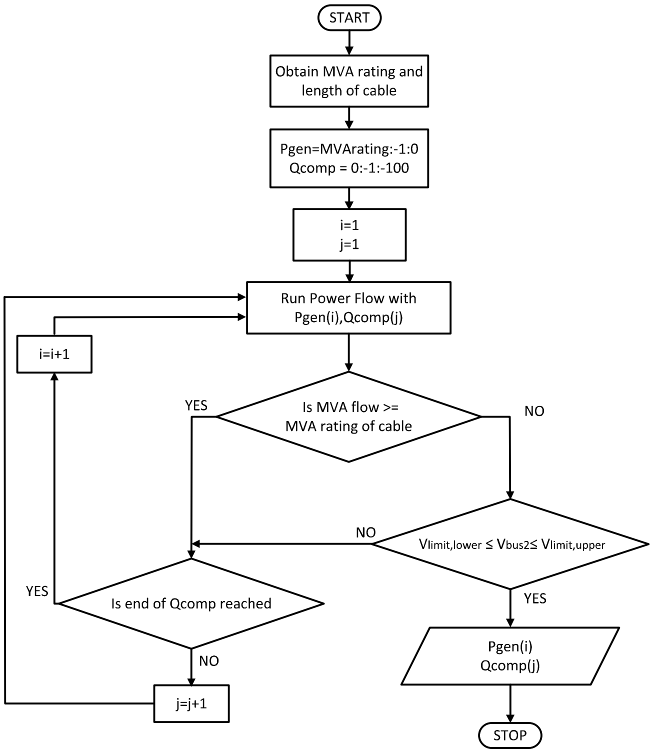


Fig. 5 Flowchart for determining the optimal value of the offshore reactive power compensation.

The onshore compensator aims to maintain a voltage of 1 pu at bus 3. To size the onshore compensator appropriately, the reactive power exchanged at bus 3 under the maximum and minimum power generation scenarios is analysed. Depending on the size of the MEC farm and the length of the transmission link the reactive power compensator may need to either absorb or generate reactive power. The onshore compensator is sized to be the bigger of the reactive power exchanged at bus 3 when comparing the maximum and minimum generation scenarios.

VI. COST FACTORS

As previously discussed, the cost factors to be considered are the capital cost of the transmission system and the cost of losses. The cost of the subsea connectors and the MECs have not been included in the framework as their unit price and the number of units remain the same across the range of transmission options considered.

A. *Transmission System Investment Cost*

The cost of the offshore transmission system includes the cost of the submarine cable and the offshore platform (including the electrical equipment like transformers, switchgear, and reactive power compensations on it) and their installation. As there are no commercial MEC farms in operation today, the cost models of the power transmission equipment from the offshore wind industry have been used here. This is justified as the power transmission equipment within both these industries is identical. The cost models for transformers, subsea cables, offshore platforms and switchgear have been obtained from [1], [3] and [4]. As part of ongoing research in [4], an MRE component database with indicative cost functions will be made publically available at a later date.

B. *Transmission System Losses Cost*

Once the total energy loss in the transmission system is identified, the cost associated with it can be calculated. An estimate of the price of the generated energy is required for this. In the UK, for example, under the Contracts for Difference regime, the strike price per MWh of wave or tidal generation can be used [16]. This price multiplied by the total energy loss gives the cost associated with the energy loss.

VII. TECHNO-ECONOMIC ANALYSIS FRAMEWORK: CASE STUDY

In this section, the techno-economic analysis framework is applied to a wave energy case study. This quantifies both cost components (either directly as a cost or as a measure of the cost involved) for a range of different farm sizes and distances from the shore and demonstrates the impact of these parameters on system efficiency, system cost and sizing of reactive power compensation.

The technical assessment of the transmission system options is focused on the evaluation of transmission power losses. Transmission losses for a range of farm sizes (0.75 MW – 99.75 MW) and distances from the shore (10-50 km) were calculated. Appropriately sized cables, substation transformers and onshore and offshore reactive power compensators were selected for each case. The electrical characteristics of subsea cables were obtained from [17]-[19]. The impedances and the X/R ratios of the transformers were obtained from [20] and [21]. The electrical parameters of the cables and transformers used are listed in Appendix A.

Some assumptions about the transmission system design have been made in this study. These assumptions are:

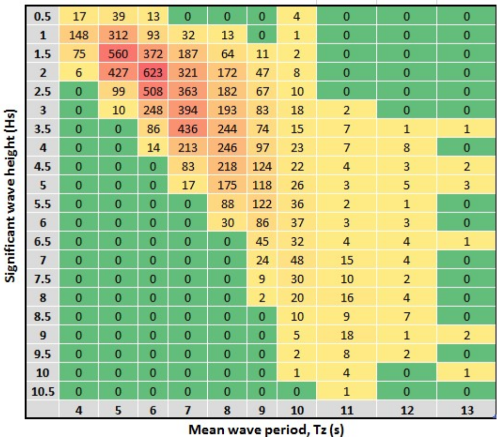
- AC transmission with a single three-core XLPE subsea cable has been used
- The MECs generate at 0.69 kV
- The intra-array network operates at 6.6 kV
- All solutions have an offshore platform
- One transformer per substation/platform
- Transmission at 11, 33 or 132 kV
- Each MEC has an on-board 0.69:6.6 kV transformer

A. Resource data and power output

For the analysis, wave data from the Belmullet wave energy test site, located off the west coast of Ireland was used [22]. Fig. 6 shows the scatter plot of the sea states at the site over a year. Note that the mean wave periods and significant wave heights over 60-minute durations are shown in the scatter plot.

The MEC farm used in the study is a wave energy converter farm of the Pelamis P1 device, each rated at 0.75. Fig. 7 shows the power matrix of the device. The losses in the intra-array network and the on-board transformers have not been included in the analysis discussed here.

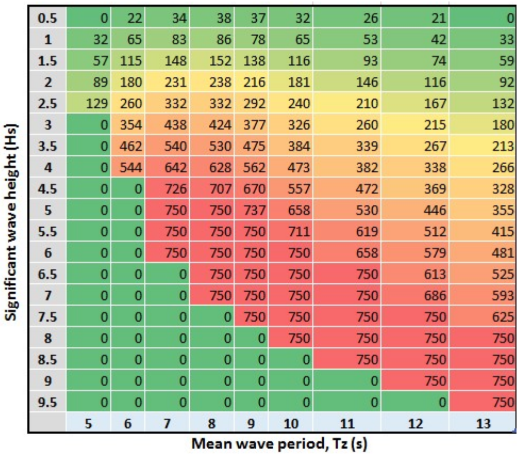
The resulting power output histogram for the site and technology combination is presented in Fig. 8. High power output is observed for site, representing favourable resource conditions and high performance of the selected device.



Significant wave height (Hs)	4	5	6	7	8	9	10	11	12	13
0.5	17	39	13	0	0	0	4	0	0	0
1	148	312	93	32	13	0	1	0	0	0
1.5	75	560	372	187	64	11	2	0	0	0
2	6	427	623	321	172	47	8	0	0	0
2.5	0	99	508	363	182	67	10	0	0	0
3	0	10	248	394	193	83	18	2	0	0
3.5	0	0	86	436	244	74	15	7	1	1
4	0	0	14	213	246	97	23	7	8	0
4.5	0	0	0	83	218	124	22	4	3	2
5	0	0	0	17	175	118	26	3	5	3
5.5	0	0	0	0	88	122	36	2	1	0
6	0	0	0	0	30	86	37	3	3	0
6.5	0	0	0	0	0	45	32	4	4	1
7	0	0	0	0	0	24	48	15	4	0
7.5	0	0	0	0	0	9	30	10	2	0
8	0	0	0	0	0	2	20	16	4	0
8.5	0	0	0	0	0	0	10	9	7	0
9	0	0	0	0	0	0	5	18	1	2
9.5	0	0	0	0	0	0	2	8	2	0
10	0	0	0	0	0	0	1	4	0	1
10.5	0	0	0	0	0	0	0	1	0	0

Mean wave period, Tz (s)

Fig. 6 Scatter plot of the Belmullet wave energy test site



Significant wave height (Hs)	5	6	7	8	9	10	11	12	13
0.5	0	22	34	38	37	32	26	21	0
1	32	65	83	86	78	65	53	42	33
1.5	57	115	148	152	138	116	93	74	59
2	89	180	231	238	216	181	146	116	92
2.5	129	260	332	332	292	240	210	167	132
3	0	354	438	424	377	326	260	215	180
3.5	0	462	540	530	475	384	339	267	213
4	0	544	642	628	562	473	382	338	266
4.5	0	0	726	707	670	557	472	369	328
5	0	0	750	750	737	658	530	446	355
5.5	0	0	750	750	750	711	619	512	415
6	0	0	750	750	750	750	658	579	481
6.5	0	0	0	750	750	750	750	613	525
7	0	0	0	750	750	750	750	686	593
7.5	0	0	0	0	750	750	750	750	625
8	0	0	0	0	0	750	750	750	750
8.5	0	0	0	0	0	0	750	750	750
9	0	0	0	0	0	0	0	750	750
9.5	0	0	0	0	0	0	0	0	750

Mean wave period, Tz (s)

Fig. 7 Power matrix of the Pelamis P1 device

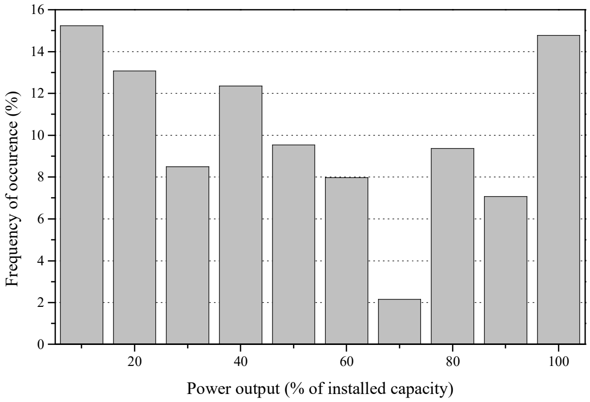


Fig. 8 Case study power output histogram

B. Technical feasibility

As previously discussed, reactive power compensation allows maximum real power transfer through the cable and also ensures supply voltage quality in the offshore network. It influences the power flow in the transmission link and has an impact on the power loss in the system. Fig. 9 shows the size of onshore and offshore reactive power compensation required for the three voltage levels and the range of farm sizes and distances to the shore considered.

For the 11 kV system, since the cable MVA ratings were more than the farm size, there was found to be no requirement for any offshore compensation to free up the cable capacity. The offshore compensation requirement shown in Fig. 9 (b) is purely to ensure that the voltage at bus 2 stayed within limits. This issue is significant for lower rated cables, which have higher resistances. The voltage rise issue meant that for some farm sizes and distances to the shore the real power generated by the farm had to be constrained to ensure continued connection to the onshore network.

For both the 11 kV and the 33 kV transmission options, the charging current and hence the onshore reactive power compensation requirement increases with an increase in distance to the shore and with an increase in the farm size. The presence of any offshore reactive power compensation affects the amount of reactive power compensation required onshore, which explains any behaviour away from these two general trends. For the 33 kV option, a few cases where there is a requirement for offshore compensation are seen. This is again attributed to the relatively higher resistance of the lower MVA rated cables, which causes voltage violations at bus 2.

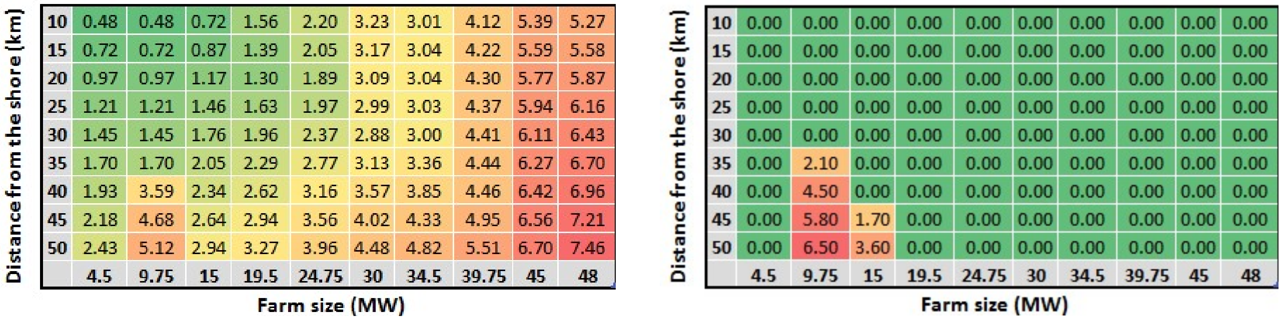
For the 132 kV transmission case, no requirement for any offshore compensation was found. This is partly due to the fact that a 96.02 MVA cable is used for all farm sizes up till 90 MW. This allows the cable to carry the reactive power the cable generates, without having to constraint the real power output of the farm. This is an unlikely scenario and has been included for completeness. Additionally, owing to the lower resistance (when compared to the 11 kV and 33 kV options) and the higher operating voltage (causing smaller currents for the same power) no voltage violations at bus 2 were seen for any sea state and farm size. The two general trends reported in the 33 kV system are observed for the 132 kV system too.

10	0.09	0.09	1.14	0.25	0.52	0.80	1.10	1.43	1.91
15	0.13	0.13	1.99	1.85	0.54	0.87	1.25	1.67	2.26
20	0.18	0.71	2.26	2.53	2.11	0.93	1.39	1.90	2.60
25	0.22	1.31	2.45	2.94	2.86	2.17	1.83	2.11	2.93
30	0.27	1.60	2.43	3.14	3.30	2.89	2.64	2.31	3.26
35	0.32	1.79	2.53	3.25	3.54	3.27	3.20	2.51	3.60
40	0.37	1.88	2.52	3.23	3.80	3.55	3.58	2.70	3.94
45	0.43	1.98	2.51	3.36	3.96	3.89	3.96	3.01	4.31
50	0.49	1.95	3.56	3.36	3.97	4.08	4.25	3.34	4.71
	0.75	1.5	3	4.5	6	7.5	9	10.5	12

(a) onshore reactive power compensation for the 11 kV system

10	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	1.90	1.60	0.00	0.00	0.00	0.00	0.00
20	0.00	0.80	2.20	2.30	1.50	0.00	0.00	0.00	0.00
25	0.00	1.40	2.40	2.70	2.20	1.10	0.30	0.00	0.00
30	0.00	1.70	2.40	2.90	2.60	1.70	0.90	0.00	0.00
35	0.30	1.90	2.50	3.00	2.80	2.00	1.30	0.00	0.00
40	0.60	2.00	2.50	3.00	3.00	2.20	1.50	0.00	0.00
45	0.80	2.10	2.50	3.10	3.10	2.40	1.70	0.10	0.00
50	0.90	2.10	3.00	3.10	3.10	2.50	1.80	0.30	0.00
	0.75	1.5	3	4.5	6	7.5	9	10.5	12

(b) offshore reactive power compensation for the 11 kV system



10	0.48	0.48	0.72	1.56	2.20	3.23	3.01	4.12	5.39	5.27
15	0.72	0.72	0.87	1.39	2.05	3.17	3.04	4.22	5.59	5.58
20	0.97	0.97	1.17	1.30	1.89	3.09	3.04	4.30	5.77	5.87
25	1.21	1.21	1.46	1.63	1.97	2.99	3.03	4.37	5.94	6.16
30	1.45	1.45	1.76	1.96	2.37	2.88	3.00	4.41	6.11	6.43
35	1.70	1.70	2.05	2.29	2.77	3.13	3.36	4.44	6.27	6.70
40	1.93	3.59	2.34	2.62	3.16	3.57	3.85	4.46	6.42	6.96
45	2.18	4.68	2.64	2.94	3.56	4.02	4.33	4.95	6.56	7.21
50	2.43	5.12	2.94	3.27	3.96	4.48	4.82	5.51	6.70	7.46
	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48

(c) onshore reactive power compensation for the 33 kV system

10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	5.80	1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	6.50	3.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48

(d) offshore reactive power compensation for the 33 kV system

10	7.12	7.12	7.12	7.12	7.12	7.12	7.12	7.12	7.12	8.13
15	10.68	10.68	10.68	10.68	10.68	10.68	10.68	10.68	10.68	11.50
20	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	15.34
25	17.81	17.81	17.81	17.81	17.81	17.81	17.81	17.81	17.81	19.18
30	21.38	21.38	21.38	21.38	21.38	21.38	21.38	21.38	21.38	23.02
35	24.95	24.95	24.95	24.95	24.95	24.95	24.95	24.95	24.95	26.87
40	28.53	28.54	28.54	28.54	28.54	28.54	28.54	28.54	28.54	30.73
45	32.12	32.12	32.12	32.13	32.13	32.13	32.13	32.13	32.13	34.60
50	35.72	35.72	35.72	35.72	35.73	35.73	35.73	35.73	35.73	38.47
	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75

(e) onshore reactive power compensation for the 132 kV system

10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75

(f) offshore reactive power compensation for the 132 kV system

Fig. 9 Sizing of reactive power compensation for the considered system.

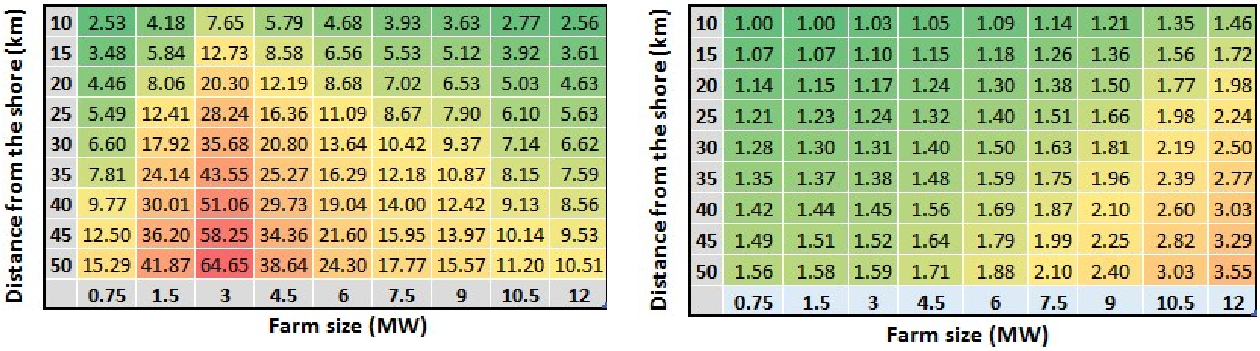
C. *Techno-economic assessment*

2) *Technical considerations:* Fig. 10 shows the percentage energy lost over a year for the range of farm sizes and distances from the shore when a 11 kV, 33 kV and a 132 kV transmission link is used. The percentage is with respect to the total energy yield of the farm over the year in Watt-hours, obtained by multiplying the power matrix and the scatter plot and adding the energy generated over all the sea states.

For the three transmission voltages and the same farm size, the percentage energy lost increased with an increase in distance to the shoreline. This is as expected since the resistance of the cable increases proportionally to the cable length. An increase in the cable length also increases the reactive power generated by it, which in turn increases the cable current. This also contributes to the increase in the energy losses seen when the distance to the shore increases.

For the same distance to the shore, the percentage energy lost increases initially and then decreases as the size of the farm increases. For example, for the 11 kV transmission system, considering the 50 km distance to shore case, the percentage energy lost peaks for the 3 MW farm and then drops. This can be attributed to the fact that energy lost is a function of the farm size and the resistance of the cable being used. The resistance of cables drops significantly as the cable rating increases, as shown in Fig 11. The same cable (rated at 3.18 MVA) has been used for the first three farm sizes (0.75-3 MW) in the 11 kV case and hence the energy loss peaked for the highest farm size from amongst the three. A similar feature is seen for the 33 kV transmission system, wherein the same cable is used for the first two farm sizes (4.5-9.75 MW).

The 132 kV transmission case is slightly different form the 11 kV and 33 kV cases. This is because the smallest 132 kV cable has an MVA rating of 96.02 MVA. This meant that this same cable was used for all the farm sizes up till 90 MW.



Distance from the shore (km)

10	2.53	4.18	7.65	5.79	4.68	3.93	3.63	2.77	2.56
15	3.48	5.84	12.73	8.58	6.56	5.53	5.12	3.92	3.61
20	4.46	8.06	20.30	12.19	8.68	7.02	6.53	5.03	4.63
25	5.49	12.41	28.24	16.36	11.09	8.67	7.90	6.10	5.63
30	6.60	17.92	35.68	20.80	13.64	10.42	9.37	7.14	6.62
35	7.81	24.14	43.55	25.27	16.29	12.18	10.87	8.15	7.59
40	9.77	30.01	51.06	29.73	19.04	14.00	12.42	9.13	8.56
45	12.50	36.20	58.25	34.36	21.60	15.95	13.97	10.14	9.53
50	15.29	41.87	64.65	38.64	24.30	17.77	15.57	11.20	10.51
	0.75	1.5	3	4.5	6	7.5	9	10.5	12

Farm size (MW)

(a) percentage energy lost for 11 kV transmission system

Distance from the shore (km)

10	1.00	1.00	1.03	1.05	1.09	1.14	1.21	1.35	1.46
15	1.07	1.07	1.10	1.15	1.18	1.26	1.36	1.56	1.72
20	1.14	1.15	1.17	1.24	1.30	1.38	1.50	1.77	1.98
25	1.21	1.23	1.24	1.32	1.40	1.51	1.66	1.98	2.24
30	1.28	1.30	1.31	1.40	1.50	1.63	1.81	2.19	2.50
35	1.35	1.37	1.38	1.48	1.59	1.75	1.96	2.39	2.77
40	1.42	1.44	1.45	1.56	1.69	1.87	2.10	2.60	3.03
45	1.49	1.51	1.52	1.64	1.79	1.99	2.25	2.82	3.29
50	1.56	1.58	1.59	1.71	1.88	2.10	2.40	3.03	3.55
	0.75	1.5	3	4.5	6	7.5	9	10.5	12

Farm size (MW)

(b) relative cost for 11 kV transmission system

Distance from the shore (km)

10	1.27	2.43	1.85	1.66	1.33	1.31	1.11	1.05	0.82	0.80
15	1.77	3.40	2.62	2.31	1.85	1.81	1.57	1.46	1.10	1.11
20	2.28	4.34	3.36	2.94	2.35	2.30	2.01	1.86	1.38	1.41
25	2.81	5.25	4.09	3.56	2.84	2.78	2.45	2.26	1.66	1.71
30	3.37	6.13	4.79	4.16	3.32	3.25	2.88	2.65	1.94	2.00
35	3.98	7.11	5.48	4.75	3.80	3.71	3.30	3.03	2.22	2.29
40	4.64	8.47	6.16	5.33	4.26	4.16	3.71	3.42	2.49	2.59
45	5.36	9.98	6.87	5.90	4.73	4.61	4.13	3.79	2.77	2.88
50	6.16	11.49	7.68	6.46	5.18	5.05	4.53	4.17	3.04	3.17
	4.5	9.75	15	19.5	24.8	30	34.5	39.8	45	48

Farm size (MW)

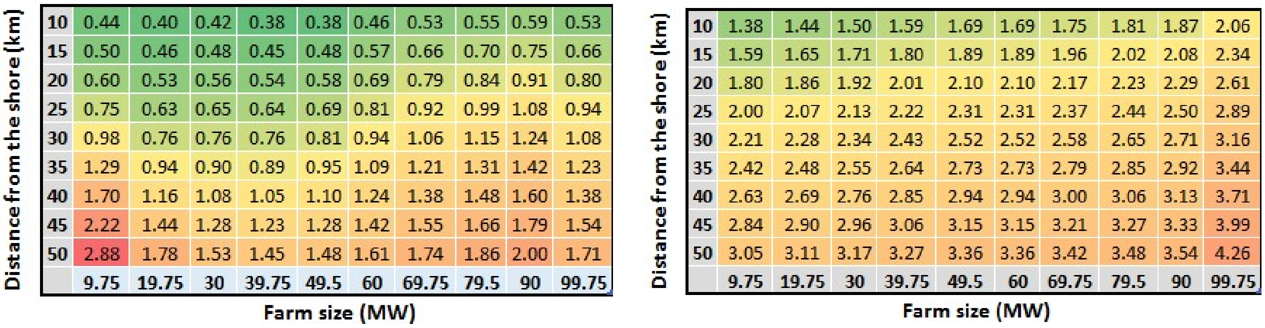
(c) percentage energy lost for 33 kV transmission system

Distance from the shore (km)

10	1.06	1.08	1.20	1.25	1.37	1.47	1.68	1.79	2.10	2.19
15	1.14	1.16	1.30	1.38	1.55	1.67	1.95	2.11	2.58	2.67
20	1.22	1.24	1.41	1.51	1.72	1.88	2.21	2.43	3.05	3.14
25	1.30	1.32	1.51	1.64	1.89	2.08	2.48	2.75	3.52	3.62
30	1.38	1.40	1.61	1.77	2.07	2.29	2.74	3.08	4.00	4.09
35	1.46	1.50	1.72	1.90	2.24	2.49	3.01	3.40	4.47	4.56
40	1.54	1.59	1.82	2.03	2.42	2.70	3.28	3.72	4.94	5.04
45	1.61	1.68	1.94	2.16	2.59	2.90	3.54	4.04	5.42	5.51
50	1.69	1.76	2.06	2.29	2.77	3.11	3.81	4.36	5.89	5.98
	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48

Farm size (MW)

(d) relative cost for 33 kV transmission system



Distance from the shore (km)

10	0.44	0.40	0.42	0.38	0.38	0.46	0.53	0.55	0.59	0.53
15	0.50	0.46	0.48	0.45	0.48	0.57	0.66	0.70	0.75	0.66
20	0.60	0.53	0.56	0.54	0.58	0.69	0.79	0.84	0.91	0.80
25	0.75	0.63	0.65	0.64	0.69	0.81	0.92	0.99	1.08	0.94
30	0.98	0.76	0.76	0.76	0.81	0.94	1.06	1.15	1.24	1.08
35	1.29	0.94	0.90	0.89	0.95	1.09	1.21	1.31	1.42	1.23
40	1.70	1.16	1.08	1.05	1.10	1.24	1.38	1.48	1.60	1.38
45	2.22	1.44	1.28	1.23	1.28	1.42	1.55	1.66	1.79	1.54
50	2.88	1.78	1.53	1.45	1.48	1.61	1.74	1.86	2.00	1.71
	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75

Farm size (MW)

(e) percentage energy lost for 132 kV transmission system

Distance from the shore (km)

10	1.38	1.44	1.50	1.59	1.69	1.69	1.75	1.81	1.87	2.06
15	1.59	1.65	1.71	1.80	1.89	1.89	1.96	2.02	2.08	2.34
20	1.80	1.86	1.92	2.01	2.10	2.10	2.17	2.23	2.29	2.61
25	2.00	2.07	2.13	2.22	2.31	2.31	2.37	2.44	2.50	2.89
30	2.21	2.28	2.34	2.43	2.52	2.52	2.58	2.65	2.71	3.16
35	2.42	2.48	2.55	2.64	2.73	2.73	2.79	2.85	2.92	3.44
40	2.63	2.69	2.76	2.85	2.94	2.94	3.00	3.06	3.13	3.71
45	2.84	2.90	2.96	3.06	3.15	3.15	3.21	3.27	3.33	3.99
50	3.05	3.11	3.17	3.27	3.36	3.36	3.42	3.48	3.54	4.26
	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75

Farm size (MW)

(f) relative cost for 132 kV transmission system

Fig. 10 Techno-economic comparison of the considered systems.

Considering the 132 kV system, for the same distance to shore, the percentage energy lost reduces initially and then increases with an increase in the farm size (up till the 90 MW farm). The power losses in the transmission cable is a function of both the real power and reactive power carried by it. For lightly loaded cables (up till 39.75 MW), the significantly higher reactive power the cable carries contributes more towards the losses. As the farm size increases from 9.75 MW to 39.75 MW, the cable loading increases, which reduces the reactive power generated by the cable and hence reduces the power transmission losses. For farm sizes greater than 39.75 MW up till 90 MW, the real power the cable carries contributes more towards the power losses. Hence, with an increase in the farm size, the transmission loss increases. For the 99.75 MW farm, using a higher rated cable (109.74 MVA) the smaller resistance when compared to the 96.02 MVA rated cable used so far (Fig. 11) produces lower losses for all the distances when compared to the 90 MW farm.

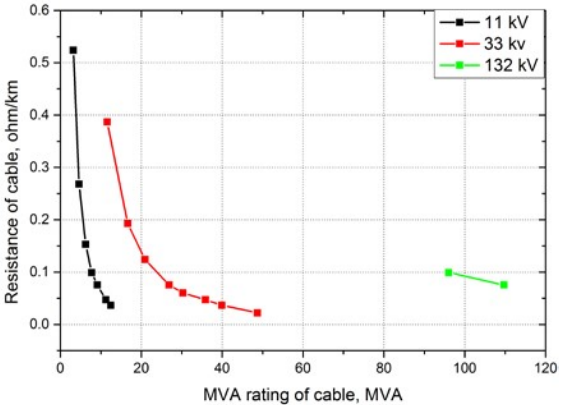


Fig. 11 Cable resistance for different cable MVA ratings

3) Transmission system cost analysis: Since there are uncertainties with respect to the cost of the different equipment and because some of these costs may be project-specific, only relative costs of the different cases with respect to a base case will be discussed in this paper. Fig. 10 shows the relative costs of the system which have been normalised against the base case of a 0.75 MW farm 10 km from the shore using a transmission voltage of 11 kV. Note that the same colour map has been used in Fig. 10 (b), (d) and (f) that compare the relative costs.

The techno-economic analysis reveals several interesting points for discussion. As expected, the cost of the transmission system will generally increase with both rated voltage and power. However, the results in Fig. 10 reveal that is rule is not always true. For systems around 30 – 50 MW installed capacity, 33 kV and 132 kV transmissions are technically feasible. However, although 33 kV equipment is generally cheaper than equipment rated for 132 kV, the relative cost will actually be higher. This can be attributed to the fact that the cable costs contributes significantly to the total cost and that the 30-50 MVA cable at 33 kV costs more than the 132 kV cable with the same MVA rating.

For the three transmission voltages considered, the cost of the substation platform and the subsea cable contributed between 94% and 98% (11 kV system), 88% and 97% (33 kV system) and 78 and 94% of the total cost of the transmission system infrastructure. The cost of other equipment, like the switchgear, reactive power compensation and transformers, increases with an increase in their MVA and voltage ratings. This explains why the contribution of cables and platform to the total cost reduces as the voltage level and farm size increase.

The subsea cable link contributes the most to the total transmission system infrastructure cost for larger MEC farms further offshore. For smaller farms closer to the shore though, the platform cost was found to be significantly higher than the cable costs. Therefore, there is potential to reduce the cost of the first commercial scale MEC arrays by investing in cost reduction of platforms/substations. As discussed in Section II, there are several options currently being developed for use in MRE. By moving away from surface piercing platforms, which require large and expensive foundations, there is potential to reduce this cost.

VIII. CONCLUSIONS

A comprehensive assessment of electrical network options is a vital part of developing commercial scale MEC farms. The work presented in this paper contributes to the research by presenting a techno-economic analysis framework for selecting the optimum transmission system for a generic MEC farm. The approach is illustrated using a wave generation example to demonstrate the impact of technical feasibility and performance on the overall cost of the system.

This information will be useful for MEC farm developers to decide the optimal transmission system configuration for their farm. Future research will expand the analysis presented in this paper to include operation and maintenance costs within the analysis. Applying the framework to a larger number of case studies will help to characterise performance based on the input parameters (rated power and distance to shore) and standardise design decisions.

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APPENDIX

TABLE A.I

CABLE PARAMETERS – 11 KV

Rating (MVA)	3.18	4.59	6.23	7.72	9.14	11.24	12.48
R (Ω/km)	0.524	0.268	0.153	0.0991	0.0754	0.047	0.0366
L (mH/km)	0.43	0.38	0.35	0.33	0.33	0.31	0.3
C (µF/km)	0.23	0.29	0.35	0.42	0.48	0.59	0.66

TABLE A.II

TRANSFORMER PARAMETERS – 11 KV

Rating (MVA)	0.8	1.6	3.15	6.3	8	10	12.5
R (pu)	1.2087	0.4738	0.2218	0.0915	0.0732	0.0561	0.0453
L (pu)	5.8132	3.0889	2.2111	1.187	1.06	0.8982	0.7987

TABLE A.III

CABLE PARAMETERS – 33 KV

Rating (MVA)	11.55	16.63	20.92	26.86	30.29	35.84	39.95
R (Ω/km)	0.387	0.193	0.124	0.0754	0.0601	0.047	0.0366
L (mH/km)	0.48	0.42	0.39	0.36	0.36	0.34	0.32
C (µF/km)	0.14	0.17	0.19	0.23	0.26	0.28	0.32

TABLE A.IV

TRANSFORMER PARAMETERS – 33 KV

Rating (MVA)	6.3	10	20	25	30	45	60
R (pu)	0.0976	0.0561	0.0233	0.017	0.0145	0.0083	0.0061
L (pu)	1.2661	0.8982	0.4995	0.3996	0.3664	0.2443	0.1999

TABLE A.V

CABLE PARAMETERS – 132 KV

Rating (MVA)	96.02	109.73952
R (Ω/km)	0.0991	0.0754
L (mH/km)	0.47	0.44
C (µF/km)	0.13	0.14

TABLE A.VI

TRANSFORMER PARAMETERS – 132 KV

Rating (MVA)	10	20	30	45	60	70	80	90	100
R (pu)	6.24	2.56	1.58	0.90	0.64	0.62	0.52	0.45	0.39
L (pu)	99.81	54.94	39.97	26.65	20.82	21.42	18.74	16.66	14.99
all values x10^{-2}									

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