A SYSTEMATIC REVIEW OF DC WIND FARM COLLECTOR COST-EFFECTIVENESS

Victor Timmers[1]* *, *Agustí Egea Àlvarez*[1]*, Aris Gkountaras*[2]

[1]*Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK*
[2]*Siemens Gamesa Renewable Energy, Hamburg, Germany*
**E-mail: victor.timmers@strath.ac.uk*

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Abstract

DC collection systems have been suggested to improve the cost-effectiveness of offshore wind farms but no consensus currently exists on which configurations are the most promising. This paper aims to determine the primary DC wind farm candidates for commercialisation based on cost-effectiveness and technological risk. A systematic review was performed of the literature that formally assesses the cost, losses or reliability of DC wind farm configurations. The optimal configurations were found to be dependent on the methodology and assumptions used by each study, as well as the individual wind farm characteristics. Series and series-parallel DC designs without offshore platform performed well in terms of costs, but have challenges in operation and reliability that limit the short-term opportunity for commercialisation. The standard DC parallel topology has the lowest technological risk, but the mean cost reported in the literature is similar to that of AC topologies. Standard parallel DC wind farms are the primary candidate for the first commercial DC wind farm demonstrators, but the optimal design will likely need to be determined on a case-by-case basis. Guidelines for this assessment are provided.

1 Introduction

Offshore wind is expected to play a key role in the decarbonisation of electricity networks in Europe and around the world. As the industry has matured, offshore wind farms have become larger and are located increasingly far from shore [1]. Many of these wind farms are expected to use high voltage direct current (HVDC) to reduce the transmission losses. The converters used in HVDC transmission require large offshore platforms, adding significant costs to the overall wind farm.

It has therefore been suggested that future wind farms could employ a DC internal collection system instead of the conventional AC collector. DC collection has a higher power density suited to larger wind turbine ratings and DC cables require two conductors instead of three, leading to cost savings [2]. In addition, all-DC wind farms do not require bulky 50 Hz transformers leading to space and weight savings for the offshore platform. In some designs, the offshore platform can be even be omitted entirely [3].

The main electrical components that are replaced in DC wind farm designs include the wind turbine electrical drivetrain, the inter-array cables in the collection system, the converters and associated platform, and the export cables, as shown in Fig. 1. The cost-effectiveness of each design will be determined by the costs, losses, and reliability of these components.

A large range of designs has been proposed in the literature [3], [4], [6]. There are currently no DC wind farms in operation and no consensus on the most cost-effective designs has been reached.

Previous literature reviews that cover DC wind farm designs are typically limited to describing the options for a single design aspect, such as the collector topology [4] or DC/DC converter [5]. Those that cover multiple design aspects typically only present a qualitative discussion of the relative merits based on limited sources, and do not include any detailed investigation of the cost-effectiveness [3], [6].

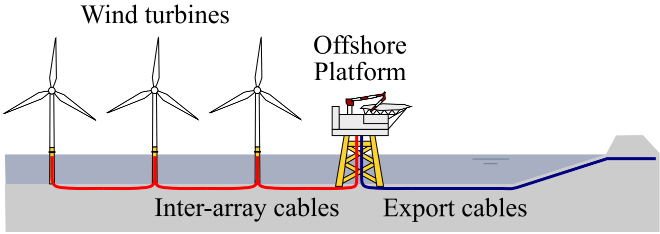


Fig. 1: Main electrical components in offshore wind farms

This systematic literature review aims to fill this gap by providing a comprehensive investigation of DC wind farm configurations proposed in the literature, following a formal systematic review procedure. This review aims to form a complete picture of DC wind farm cost-effectiveness by including assessments of the costs, losses and reliabilities reported in the literature. It also evaluates the calculation methodologies used in cost-effectiveness analyses and provides recommendations for future studies.

2 Review Methodology

This paper follows a systematic review procedure based on the guidelines set out in [7]. The systematic review was originally used in medicine and later in social science [8] and computer engineering [7] as a way to reduce the bias of individual studies and reach more robust conclusions compared to regular reviews [8]. This approach was selected for this paper due to the diversity of methodologies, conclusions, and quality of the literature on this topic.

2.1 Research Questions

The systematic review aims to answer the following research questions:

1. Which DC wind farm configurations have been evaluated in the literature?
2. What methodologies are used to calculate the cost, losses and reliability of DC wind farms and their components?
3. What are the most cost-effective DC wind farm configurations and how do they compare to AC?
4. What are the technological readiness levels and barriers to commercialisation for DC wind farms?

2.2 Search Strategy

The search strategy consisted of an initial search on Google Scholar to identify a starting set of papers. Further relevant papers were then identified by searching three databases: IEEE Xplore, SCOPUS and Web of Science. The search terms included "wind farm", any of the following performance indicators: "cost", "losses", "efficiency", "reliability" or "feasibility", and any variation of "DC collector". After the search, the starting set of papers was compared to the obtained records and the search string was amended iteratively to include all starting set papers. Please contact the authors for the full search string used. The results were limited to include peer reviewed journal articles and conference proceedings only. The systematic review procedure is shown in Fig. 2.

2.3 Screening

The search strategy resulted in 282 records, with 171 records remaining after removal of duplicates. These records were screened for eligibility, with articles excluded based on the following criteria:

1. The evaluated design does not use a DC collection system.
2. The paper does not include any assessment of the wind farm collector topology, e.g. it only considers the DC/DC converter topology.
3. The paper only considers a single design without any comparison to other options.
4. The paper does not include any formal, quantitative analysis of costs, losses or reliability.
5. The full text of the paper is not available or not in English.

Following the screening, a total of 20 publications were included in the analysis. For each article, the metadata, evaluated design aspects, performance indicators, analysis methodology, and results were extracted. Any technological challenges of the proposed designs were recorded.

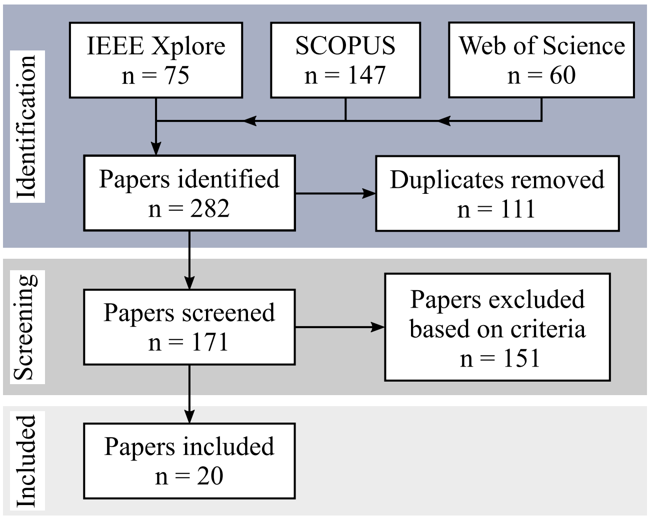


Fig. 2: Systematic review flow diagram

The quality of each of the selected studies was assessed on a scale of 0–6 by awarding up to two points for each of the following conditions:

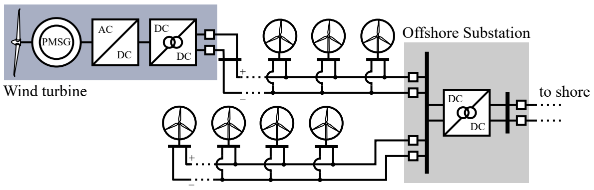
1. Is the studied configuration well-defined? Does it state which components are included in the analysis? Are the power and voltage ratings of equipment specified?
2. Is the study reproducible? Does it include a detailed description of the methodology, sources of data, and assumptions used?
3. Is the study comprehensive? Does it take into account more than one aspect of cost-effectiveness? Does it perform any sensitivity analyses?

3 DC Wind Farm Configurations

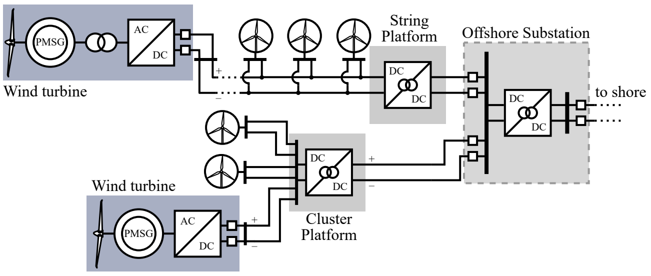
3.1 Parallel topologies

The proposed collector topologies considered in the literature can be categorised into parallel or series topologies. For each of these, several variants exist. The most commonly investigated parallel topology variants include the standard parallel [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], the centralised or cluster parallel [10], [11], [12], [13], [19], [20], [21], and the dispersed parallel [9], [10], [18], [19], [22].

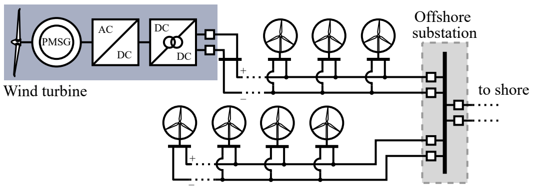
In the standard parallel topology, illustrated in Fig. 3a, each wind turbine electrical drivetrain uses a dedicated DC/DC converter with medium frequency transformer (MFT) to step up the voltage to MVDC levels of around ±20 kV to ±50 kV [13]. The wind turbines are connected in strings to one or more offshore substations where high power DC/DC converters convert the voltage to HVDC, typically ±150 kV [12], [15] or ±300 kV [11]. This design is most similar to commercial AC wind farm configurations as it connects the wind turbines in strings and uses two step-up stages, one in the turbines and one on an offshore platform [9]. This reduces the technological risk. However, it requires a large number of conversion stages [10], and is dependent on immature high power DC/DC converter technology [18].



a) standard parallel



b) centralised/cluster parallel



c) dispersed parallel

Fig. 3: DC wind farm parallel collector topologies

The centralised or cluster design, shown in Fig. 3b, uses a DC/DC converter to perform the control of multiple wind turbines. This allows the wind turbine drivetrain to be simplified. Designs have been proposed that use a 50 Hz transformer to raise the generator output voltage before converting this to DC with an active or passive rectifier [11]. Other designs use a single-stage drivetrain to directly rectify the generator output [12]. In the cluster design, each wind turbine is connected directly to the cluster platform, whereas in the centralised design, the turbines are connected in a string before the voltage is stepped up. A high power DC/DC converter on a separate offshore platform may be used to further increase the voltage up to HVDC levels if required [11]. The centralised and cluster designs have the benefit of reducing the conversion stages in the wind turbines [10], but require additional platforms for the string or cluster converters [13]. In addition, as the DC/DC converter controls multiple wind turbines, additional losses occur due to suboptimal wind energy extraction [11]. The non-standard drivetrain with a transformer before the converter is unproven and may have difficulties with control, increasing the technological risk of this configuration.

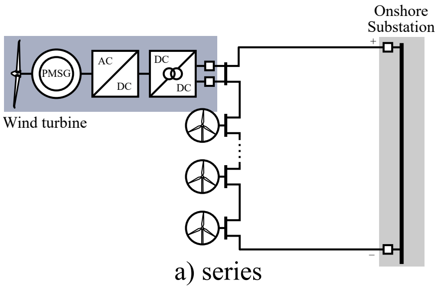
The dispersed parallel configuration, illustrated in Fig. 3c, uses a high step-up ratio DC/DC transformer in each wind turbine to boost the voltage to ±50 kV [19], ±150 kV [10], [22], or even higher. This allows the configuration to omit a central converter and large offshore platform [9]. Instead, there may be a small platform to house the protection equipment before connecting to shore. This configuration has the potential to reduce the capital costs associated with the offshore platform. However, the export voltage is limited by the step up ratio of the wind turbine converter, which may lead to higher transmission losses.

3.2 Series topologies

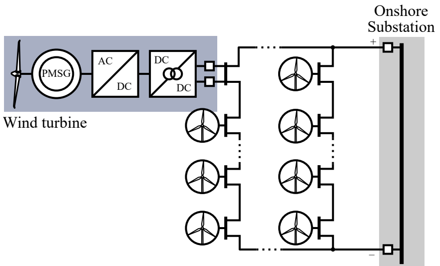
As the name implies, in series-connected DC wind farm topologies, the wind turbines are connected in series to build up the voltage to transmission levels. The most commonly investigated series variants are the standard series [21], [23], [24], [25], [28] and the series-parallel designs [9], [17], [18], [24], [25], [26], [27].

In the series design, illustrated in Fig. 4a, all wind turbines in the wind farm are connected in a single string [23]. The wind turbine drivetrains therefore need to have a DC/DC converter with MFT to provide galvanic isolation [9]. For large wind farms, the wind turbine output voltage can be relatively low, in the order of a few kV, since many wind turbines can be used to build up the voltage [25]. The benefit of this configuration is that no offshore platform and converter are required [9]. In addition, a smaller number of cables can be used to connect the wind turbines compared to parallel configurations. The main issues with the series design are its low reliability, since any fault on the cable will result in the entire wind farm disconnecting [23].

The series-parallel configuration, shown in Fig. 4b, addresses this issue by dividing the series wind farm into multiple parallel-connected strings. Both series and series-parallel wind farms have additional challenges, such as high insulation requirements [25], voltage balancing issues when wind turbines are subjected to unequal wind speeds [21], and challenges maintaining the transmission voltage when multiple wind turbines are out of service [18].



a) series



b) series-parallel

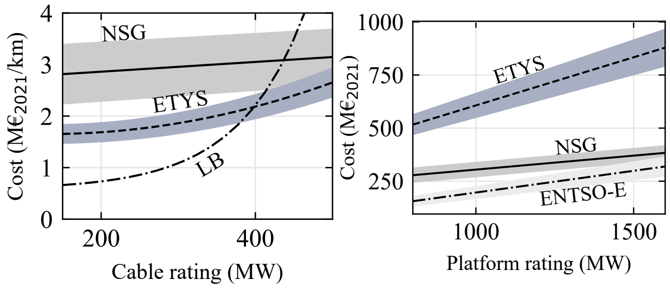
Fig. 4: DC wind farm series collector topologies

4 Calculation Methods

4.1 Cost

Publications that investigate the cost of topologies typically estimate the capital cost investment required only [17], [19], rather than a full levelized cost analysis over the wind farm lifecycle [15]. Capital costs that are considered typically include the costs of the wind turbines, cables, transformers, converters and offshore platform. More rigorous publications also tend to include the costs of the losses over the wind farm lifetime [11], [13], [23].

Most publications use equations from the literature to determine costs of the various components. Since commercial data is often difficult to come by, these are often based on the same datasets. For example, a 2003 report by Lundberg [29] is used by various papers [11], [13], [23], to calculate the costs of MVDC cables. Other sources include publications by Dicorato et al. [30] and industry figures from the UK ETYS [32], NorthSeaGrid (NSG) project [33], ENTSO-E [34], OREC [35], among others. These provide cost estimates for cables, transformers, platforms and more. Cost figures from different sources can vary significantly, as shown in Fig. 5.



(a) MVAC cables

(b) DC platform

Fig. 5: Example cost estimates of components using various data sources

The costs of DC components, such as the DC/DC converters and DC circuit breakers are generally not available. Therefore, papers instead use a bottom-up approach where they estimate the cost based on individual elements that make up larger components. For example, [11] use the costs of the semiconductors and transformers needed for the DC/DC converter to estimate its overall cost. Alternatively, papers can rely on assumptions to estimate the cost DC components as a proportion of AC component costs [13]. Due to the variability of estimation procedures it is important to detail the exact methodology and assumptions used. It is also recommended to perform sensitivity analyses for components with greater uncertainty in their cost, such as in [11], [13].

Despite the large influence of the offshore platform on overall cost, very few of the included publications quantitatively assessed the size and weight of the DC/DC converter, and the associated cost reduction of the offshore platform [12]. This may be an area of interest for future publications.

4.2 Losses

Publications that calculate the efficiency of the overall wind farm typically use datasheet information such as the resistance of cables, and transformer load and no load losses. The loss calculation can then be performed analytically [11] or through load flow simulation software [13]. Some papers only consider losses at rated power [25]. However, since wind farms do not produce rated power continuously, it is recommended to calculate the losses at varying operating conditions and wind speeds. The overall wind farm efficiency can then be calculated using a typical Weibull wind speed distribution curve [12], [13].

The efficiency of DC/DC converters will be dependent on the selected design. Some papers assume an efficiency as a proportion of existing AC/DC converters. Others perform more sophisticated calculations based on the power electronic components, either analytically [10] or by using simulation tools such as PLECS [12]. Research into DC/DC converters is ongoing, therefore, it may be an option to use efficiency measures of DC/DC converter lab prototypes [36].

4.3 Reliability

Very few publications assessed the reliability of configurations, despite the large impact this can have on cost-effectiveness. The approach used for the reliability assessments consists of using the failure rates per year for individual components and estimating the repair time and lost energy production in case of failure [17]. It is important to take into consideration how the protection will reconfigure the wind farm during equipment failure when calculating the energy lost [23], [24]. Similar to the cost estimates, the component failure rates and repair times can differ significantly depending on the sources used, as shown in Table 1. Reliable failure rate data can typically be obtained from CIGRE brochures [37], [38].

Table 1 Example failure rates and repair times using various data sources

Component	Source	Failure rate per year	Repair time (hrs)
AC	[31]	0.008/km	720
cables	[37]	0.0007/km	1440
Offshore	[24]	0.05	720
converter	[38]	0.0153	1664

5 Cost-Effectiveness Results

5.1 Cost results

Analysis of papers investigating the costs of DC wind farms shows a large range of cost estimates, from €0.3/W [19] to €3/W [15]. The disparity of estimates is mainly due to the difference in scope of the studies, and to a lesser extent because of varying wind farm characteristics, such as size, distance from shore, converter technology, etc. For example, some papers exclude the transmission system capital costs [11], others cover

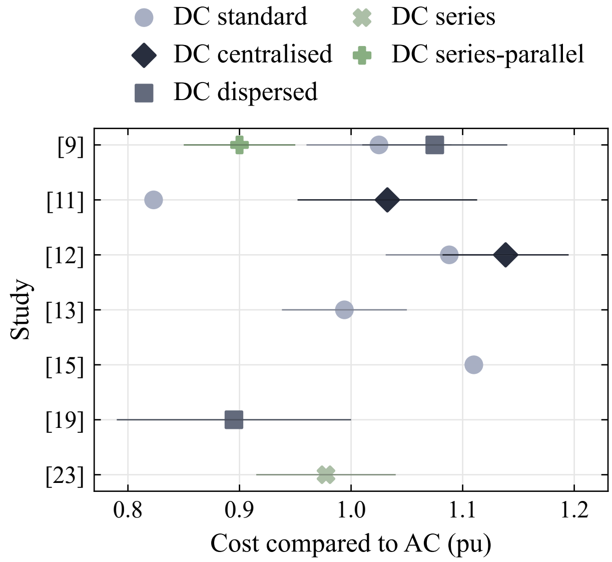


Fig. 6: Normalised cost estimates for DC wind farm configurations, using AC radial cost of each study as base

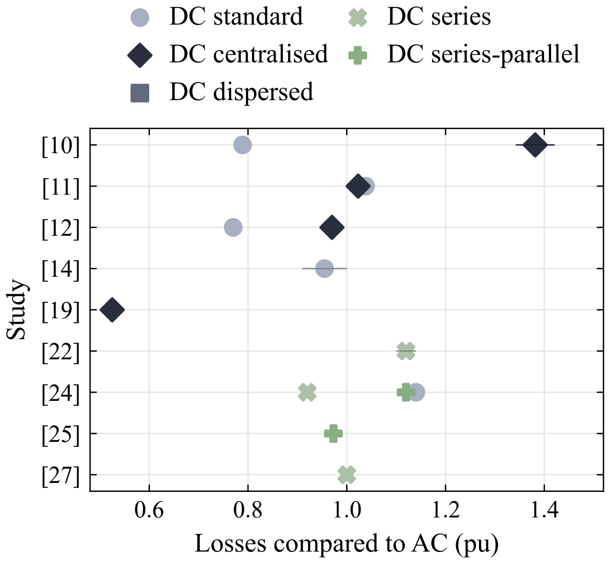


Fig. 7: Normalised loss estimates for DC wind farm configurations, using AC radial losses of each study as base

both the capital cost of the entire system and the cost associated with the losses [23]. Direct comparison is further complicated by heterogeneous reporting, with papers reporting costs using local currencies [14], in per unit values compared to AC [23], or in costs per energy produced [12].

In order to compare the costs of the various configurations, for each study the results were normalised by using the calculated AC configuration cost as a base. For studies that did not include an AC option for comparison [18], the mean cost of all tested configurations in that study was selected as the base for the per unit comparison. To increase the robustness of the comparison, only studies with a quality rating of 3 or more were included and studies that did not cover at least the costs of the wind turbines, collector system, converter and platform were excluded [25]. Furthermore, studies with unrealistic component costs that deviated by more than a factor 5 from the norm were excluded [17], [18]. The results of the analysis are shown in Fig. 6.

It can be seen from Fig. 6 that there is considerable disagreement on whether certain DC configurations provide cost savings. For example, [11] show potentially significant savings of up to 18% when using DC standard parallel collector systems compared to AC, whereas [12] find the same configuration to be 3% to 14% more expensive than AC, despite both studies following a similar calculation methodology. The main difference is the high DC circuit breaker costs included in the calculation by [12]. Other differences include the wind farm sizes (1000 MW vs 400 MW) and the wind turbine ratings (10 MW vs 5 MW).

Overall, the results show that the DC dispersed, series and series-parallel topologies have potential cost savings as they have mean costs of less than 1 pu. The centralised and cluster parallel designs, on the other hand, were found to be more expensive than AC in all included cases, making them unlikely candidates for commercialisation. The standard DC topology is most often investigated, however, its cost saving potential is uncertain as the mean cost reported in the literature is approximately 1 pu compared to AC.

5.2 *Losses results*

Similar to the cost results, analysis of the losses showed a large variation in loss estimates, from 2.1% [20] to 11.3% [26]. The variation of losses is due to the difference in scope of the studies: some studies only include the losses of the collector cables and converters, whereas others include losses in the wind turbines and the export system as well. In addition, the losses of DC/DC converters vary significantly between studies. In [26], the losses of the DC/DC converter are calculated to be 4%, compared to [20] who consider the losses to be 1.6%.

The losses of each of the configurations were normalised following the same procedure as for the costs. The results are shown in Fig. 7. It can be seen that the DC standard parallel topology has the potential to reduce the losses in the system compared to the AC topology. The series and series-parallel topologies do not show the same advantage, with mean losses close to 1 pu. The centralised and cluster configuration loss performance is very dependent on the study assumptions. Studies that take into account clustering losses [11] and multiple step up stages show high losses, whereas those that neglect clustering losses and use a single conversion stage find losses to be lower than AC [20].

5.3 *Reliability results*

The number of studies investigating the reliability of DC wind farm configurations is more limited compared to cost and efficiency. Reliability measures are typically given in terms of the average system availability index, which is the ratio of the number of hours the wind farm is operating compared to the total hours in a year. The results of the studies are shown in Fig. 8.

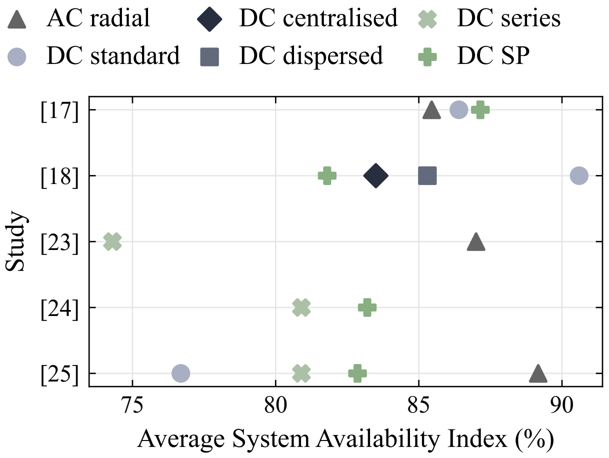


Fig. 8: Average system availability index for AC and DC wind farm configurations

The figure shows that the majority of studies agree that series and series-parallel configurations perform significantly worse than the AC radial topology. This is expected due to the large number of wind turbines being disconnected in the event of a failure. There is no consensus on the standard parallel DC configuration reliability. For example, [18] considers it to be the most reliable of the DC configurations, whereas [25] finds the opposite. There is a need for further reliability studies, especially as the DC/DC converter technology matures, to conclusively determine whether DC wind farm reliability will be significantly different than that of AC wind farms.

6 Conclusion

This systematic review has provided a comprehensive investigation of the current research into DC wind farm collector cost-effectiveness. The review extracted data from 20 studies, including proposed topologies, cost-effectiveness calculation methodologies and results.

The optimal configurations were found to be highly dependent on the calculation methodology and wind farm characteristics considered by each study. The series and series-parallel DC designs without offshore platform performed well in terms of costs but have challenges in operation and reliability that may limit the short-term prospects for commercialisation. The dispersed parallel topology also has the potential to reduce capital costs compared to AC, however more research is needed in this topology. The standard parallel DC topology has the lowest technological risk, making it the primary candidate for commercial DC wind farm demonstrators. The cost-effectiveness benefits of this configuration over AC are not assured, however, and the optimal design of future wind farms will likely need to be determined on a case-by-case basis.

7 Acknowledgements

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Victor Timmers received his B.Eng. (Hons.) and M.Sc. degrees from the University of Edinburgh in 2017 and 2018, respectively. He worked for two years as a power systems engineer in consultancy before joining the University of Strathclyde, where he is currently pursuing a Ph.D. in Electronic and Electrical Engineering.