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Review article

Energy storage systems for services provision in offshore wind farms

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ABSTRACT

Offshore wind energy is growing continuously and already represents 12.7% of the total wind energy installed in Europe. However, due to the variable and intermittent characteristics of this source and the corresponding power production, transmission system operators are requiring new short-term services for the wind farms to improve the power system operation and security of supply. For this purpose, the incorporation of energy storage systems to provide those services with no or minimum disturbance to the wind farm is a promising alternative. Taking into account the rapid progress of the energy storage sector, this review assesses the technical feasibility of a variety of storage technologies for the provision of several services at distinct locations of a point-to-point high-voltage direct-current connected offshore wind farm. In pursuit of this goal, a novel multidimensional systematic assessment is presented. The results provide a comprehensive representation of the present state of the art and indicate potential research avenues for the enhancement of the technical viability of the technology.

1. Introduction

With the growing concern about climate change and the consequent electrification of various sectors, renewable energy sources are becoming increasingly important in the electricity market, and are now the only alternative to fossil fuels that do not produce emissions or involve radioactive waste.

According to the International Energy Agency, wind energy is the energy source with the fifth highest production in the world, with 2030.02 TWh in 2022, and has followed a constant growth trend in Europe since 1990 [1]. Part of this growth is due to the development of offshore wind farms (OWF) from 2011, producing more than 134.3 TWh in 2021. From 2015 to 2023, installed offshore wind capacity nearly doubled in the countries that belong to the European Network of Transmission System Operators for Electricity [2], reaching an offshore to onshore wind capacity ratio of 15.22% in 2023, as shown in Fig. 1.

Nevertheless, this increase in wind energy challenges the stability and reliability of the power system [3]. When wind energy was first introduced, the requirements from grid operators were more relaxed than for other distributed generators. Additionally, wind turbines were initially equipped with induction machines that were not able to control the reactive power consumption.

Later, power-electronics based technologies such as doubly-fed induction generators or full power electronics interfaced generators allowed grid voltage regulation. However, their inherent characteristics decouple the electrical and mechanical systems [4], decreasing the global inertia of the grid, and thereby increasing the rate of change of frequency in case of power imbalances, which could even result in network collapse [5].

As the volume of installed wind power increased, transmission system operators began to implement stricter requirements to limit the disturbances to the grid operation from this technology, such as fault ride-through requirements [6]. Consequently, operators are increasingly asking for more short-term ancillary services [6].

Additionally, the intermittency of wind still presents a large challenge, making the operation of the power system a far more complex task and increasing the vulnerability of the grid [7]. Furthermore, due to the currently prevalent grid-following strategy of wind turbines, black-start capabilities and operation in weak grids are limited [3].

Several solutions in the literature include short-term wind forecast improvements, turbine deceleration and de-loading methods, and the implementation of energy storage systems (ESS) [8]. However, the possibility of employing the latter is progressively increasing, and even though the economic barriers to these technologies generally still need

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Abbreviations

AC	Alternate current
BESS	Battery energy storage system
BSR	Black start restoration
CAES	Compressed air energy storage
DC	Direct current
ESS	Energy storage system
FBES	Flow battery energy storage
FES	Flywheel energy storage
FPC	Frequency primary control
FSC	Frequency secondary control
HES	Hydrogen energy storage
HVDC	High-voltage direct current
IFS	Inertial frequency support
LVRT	Low-voltage ride-through
MMC	Modular multilevel converter
OfAC	Offshore AC grid location
OfCO	Offshore converter location
OfDC	Offshore HVDC link location
OfWT	Offshore wind turbine location
OnAC	Onshore AC grid location
OnCO	Onshore converter location
OnDC	Onshore HVDC link location
OWF	Offshore wind farm
PFS	Power fluctuation suppression
PHS	Pumped hydro storage
POD	Power oscillation damping
PS/TS	Peak shaving/time shifting
SCES	Supercapacitor energy storage
SMES	Superconducting magnetic energy storage
TC	Transmission curtailment
VS	Voltage support

to be overcome, the technical viability is moving closer to reality. Nevertheless, some key questions still need to be fully answered, such as where can ESS be integrated in an OWF? Which services can they provide? Which options are the most viable today and which can be promising lines of research for the future?

As a contribution to answering these questions, this work briefly introduces the possible ESS technologies and the services that they can provide, and then compares their effectiveness while considering different deployment locations within a point-to-point high-voltage direct current (HVDC) connected OWF. A novel multidimensional systematic methodology is proposed to explore the technical feasibility of the provision of distinct services through diverse ESS at various locations within the HVDC-OWF using a comprehensive review of the existing literature.

The proposed method consists of three phases. First, a systematic assessment of the literature is performed, culminating in three color-coded tables providing a clear portrayal of the state of the art. These findings not only provide information about what is or is not feasible, but also identify the insufficiently researched areas. The second phase consists of a quantitative compilation of previous results as a 3D array, which takes into consideration the interdependencies between dimensions. The versatility of each ESS, service and location is represented by a final score based on the obtained multidimensional array.

Finally, a sensitivity analysis is performed showing the improvements if any insufficiently researched area is investigated, highlighting the research avenues with the greatest potential to contribute to the technical viability of each field.

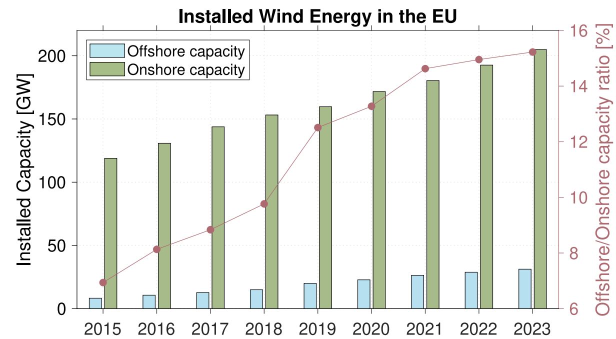


Fig. 1. Installed offshore and onshore wind capacity in EU and offshore/onshore capacity ratio.

The adaptability of the proposed method allows for its application to more complex configurations, such as multiterminal or meshed HVDC grids. With constantly evolving technology, this approach serves as a clear roadmap for the assessment and understanding of the technology interdependencies. Thus, the proposed methodology goes beyond the immediate scope of this review. It becomes a useful tool for researchers and engineers to explore the emerging technologies with accuracy and foresight.

The study is structured as follows. Sections 2 and 3 briefly describe the different services and ESS that will be subsequently assessed. Section 4 explains the topology of the OWF to analyze, along with the locations where any ESS can be placed. The methodology for the analysis is presented in Section 5. Then, the color-coded tables, the results from the 3D array, and the sensitivity analysis are discussed in Section 6, concluding the review with a summary of the main outcomes in Section 7.

2. Services to be provided

This section details the services that can be provided in a point-to-point HVDC-connected OWF. Apart from the already existing grid services defined by national grid codes, several additional services have been defined in this assessment. While some services aim to counteract the natural drawbacks of wind energy technologies, such as minimizing the power output intermittency, others are direct current (DC) services inspired by existing alternate current (AC) grid services. Table 1 lists the analyzed services, which have been categorized into three groups: (i) services provided to the AC network, (ii) services that are not directly linked with the nature of the system, and (iii) services provided to the DC side.

Table 1
Services to be provided by the offshore wind farm.

Services according to where they are provided		
AC side	IFS	Inertial frequency support
	FPC	Frequency primary control
	FSC	Frequency secondary control
	POD	Power oscillation damping
	AC-VS	AC voltage support
	AC-LVRT	AC low-voltage ride-through
	AC-BSR	AC black start restoration
Both sides	PFS	Power fluctuation suppression
	PS/TS	Peak shaving/Time shifting
	TC	Transmission curtailment
DC side	DC-VS	DC voltage support
	DC-LVRT	DC low-voltage ride-through
	DC-BSR	DC black start restoration

2.1. AC services

These are services that are specifically related to the operation of an AC grid, which are generally defined in national grid codes. Although these services definitions and requirements are not consistent between grid codes, this section gathers the services that might be required by/for an OWF and summarizes their main purpose and key features.

2.1.1. Inertial frequency support

Inertia limits the rate of change of frequency due to power imbalances and is important for limiting the frequency change until control action can be taken. Inertia is the fastest acting frequency response, acting immediately until the other control responses can initiate. Inertial frequency support (IFS) is typically provided intrinsically by synchronous generators with large rotating mass, although this service can be provided synthetically with fast-acting control. The frequency nadir (the minimum point of the frequency transitory response) is usually reached within a few seconds, so any IFS must be provided within hundreds of milliseconds and provided for at least several seconds [9,10].

2.1.2. Frequency primary control

Maintaining the frequency within a certain range is paramount to the functioning of a power system. When a frequency deviation occurs, due to a mismatch in load and generation or a fault, control actions must be taken to maintain the frequency within acceptable ranges. These are typically classified into different services depending on the response time and duration of activation, although there is no universal agreement on the specifics of each. In this work, the first control response is classified as frequency primary control (FPC), also known as frequency containment reserve. This service is typically activated within several seconds and fully activated within 30 s and the service is provided for a duration of approximately 15 min [11,12]. In this service, the generation set-points are unchanged, but the control will change the generator production proportionally to the frequency deviation, reaching a new frequency steady-state equilibrium point preferably close to the nominal frequency of the grid [13]. See [14] for more information about this service.

2.1.3. Frequency secondary control

Since frequency disturbances can last longer than the required time for FPC, and additional frequency events may occur, additional frequency response is needed. After the initial primary response, frequency secondary control (FSC) takes over frequency control. This service is also referred to as frequency restoration reserve, and can be automatic or manual. This service begins within several minutes, with full activation up to a maximum of the FPC duration [11]. Although the specifications vary for different regions, provision of FSC usually lasts for a duration of approximately 15 min [15,16]. Therefore, the amount of energy required by this service may not be fully compensated by some ESS with low energy densities.

2.1.4. Power oscillation damping

Low-frequency oscillations can occur following a disturbance, for several reasons. These oscillations usually occur in the region from 0.1–2 Hz [13], and, if not damped, can cause power system failure and blackout. These oscillations are typically solved using flexible AC transmission system devices and automatic voltage regulators with power system stabilizers. The latter may use active power, reactive power or a combination of both to address the oscillations; active power being the one that contributes most to damping according to [17]. There are three main ways in which power oscillation damping (POD) can be addressed in a topology such as the one examined in this work: reactive power modulation at the grid-connected inverter; active power modulation at the wind farm; and a combination of both [18]. The ESS may serve as an additional, rapid source of active power for damping, playing an important role in the dissipation of low-frequency oscillations.

2.1.5. AC voltage support

This service, also known as reactive power control, is intended to maintain the AC voltage amplitude within a certain range. In contrast to frequency, voltage is a local variable and can be varied at each node in the power system. The optimal voltage level at each node is usually determined by a power flow analysis. As the name reactive power control suggests, AC voltage support (AC-VS) is performed by the injection/absorption of reactive power. The various methods of implementing this service have been extensively discussed in [13]. It is important to note that this service does not require an active power reserve.

2.1.6. AC low-voltage ride-through/fault support

Low-voltage ride-through (LVRT) is one of the services increasingly required for new wind farms connected to the grid. This service refers to the ability of a wind farm to remain connected during low voltage in the AC grid, due to a fault [19]. The disconnection of a wind farm during a fault, causing a voltage dip, can exacerbate the situation and create a larger voltage drop, potentially causing frequency degradation and full system failure. However, wind farms connected to power electronics are able to provide reactive power to bolster the voltage during faults. Such voltage support does not require active power (other than to account for losses in the power electronics), and so the main role of energy storage in relation to this service is to prevent shut-down or disconnection of the wind farm.

2.1.7. AC black start restoration

Black start restoration (BSR) is the process of restoring a power system after complete or partial shutdown. A generation node participating in a black start must be capable of generating power without help from a grid, and support re-energization of the power system. This involves regulation of the frequency and voltage of the system. The power required for black start restoration varies according to the system, but can be up to tens of megawatts and may be required to be active for hours, with a response time of minutes as a maximum [20].

2.2. AC and DC services

This section discusses services that are not specific to AC or DC grids, but are still relevant and necessary for the proper operation of the entire system. These services differ from the rest by regulating the supplied power or energy, instead of other physical magnitudes such as frequency or voltage, which are normally related to the network to which they belong.

2.2.1. Power fluctuation suppression

Wind farms that use control schemes to maximize energy production will generate power outputs that are heavily dependent on the wind speed, which in itself varies greatly. This can create rapid power fluctuations, reflected in oscillations of frequency and voltage, which negatively affect system stability. Such fluctuations are in the order of a minute [21]. Therefore, any ESS that can provide power fluctuation suppression (PFS) requires rapid activation, but is not required to act for a particularly long time.

2.2.2. Peak shaving/time shifting

Peak shaving/time shifting (PS/TS) refers to optimizing load consumption and power generation to be matched more closely on a day-to-day timescale. Due to its variable nature, peak wind power does not always match the peak load. Allowing for storage of wind power for use during peak load time is known as peak-shaving [22]. Time shifting is very similar in that it involves storing the energy during peak wind power for use during peak demand [23]. There is naturally a unique role for energy storage in this service, although it requires energy storage with a sufficient capability to provide energy for up to several hours.

2.2.3. Transmission curtailment

Generated power above and beyond the rated capacity of transmission lines cannot always be transmitted to loads [23]. Transmission infrastructure is expensive and takes a long time to upgrade, thereby requiring times of generation curtailment during high wind. This curtailed power is essentially lost if not stored, providing another unique opportunity for energy storage. There are no specific requirements for time or energy stored for transmission curtailment (TC).

2.3. DC services

This section describes the services relevant to this analysis that are directly related to the DC links. For an OWF as described later in Section 4, both the DC-link in the wind turbine and the HVDC line are considered.

2.3.1. DC voltage support

The active power flow in an HVDC system can be controlled by controlling the DC voltage, similar to using the frequency for an AC system [13]. To maintain scheduled power flows and prevent damage to equipment, the DC voltage must be kept within a certain range. Therefore, DC voltage support (DC-VS) can be classified as a DC service. Some authors recommend that DC voltage control can be separated into discrete time-based activation stages, such as with primary, secondary, and tertiary reserves for AC frequency [24]. Therefore, the duration of such DC voltage control can vary from milliseconds to minutes, and the power in consideration can also vary drastically. However, the DC voltage responds very rapidly to changes in active power, and so a system capable of controlling the DC voltage should be able to respond in the order of tens of milliseconds [13].

2.3.2. DC low-voltage ride-through/fault support

Unlike the AC counterpart, faults on the DC side cannot be mitigated by providing reactive power. In the context of a point-to-point OWF, little to no power can be transmitted to the onshore grid in the event of a DC fault. Therefore, for the purposes of this analysis, DC fault support is generally defined as the ability to prevent shutdown or curtailment of the wind farm during a DC fault. Due to the rapid response of DC voltage to changes in active power, the response time needed is also in the tens of milliseconds range.

2.3.3. DC black start restoration

After a system blackout, the DC-link in a point-to-point OWF needs to be re-energized before transmission of power can resume. This energizing can originate from the attached AC grid, or internally from an energy source within the point-to-point system. If the OWF can be re-energized before the AC grid in the event of a total blackout, the OWF can provide blackstart support to the AC grid. The energy required for energization mainly comes from the capacitances in the system, and is likely to be performed within several seconds [25]. These capacitances are mainly in the converters and the capacitance of the HVDC cables, which will greatly depend on the power rating of the system and the line lengths.

3. Energy storage systems

In this section, energy storage systems are discussed. ESS can be classified in several ways. The most common classification from the literature is based on the mode of energy storage, which is shown in Fig. 2. Another mode of classification by the European Network of Transmission System Operators for Electricity is based on technical requirements, where ESS are categorized as two groups, i.e., synchronous and non-synchronous electrical energy storage modules [26]. In the synchronous electricity storage module, the transfer of electrical energy is through one or more synchronous machines that are connected to the system; while in the non-synchronous classification, the interconnection is through an asynchronous machine or power electronics, which does not naturally contribute to the global inertia of the network. Furthermore, the focus of this multidimensional assessment will be on the most developed and relevant storage technologies for OWF, which, for the sake of clarity, are highlighted in green in Fig. 2.

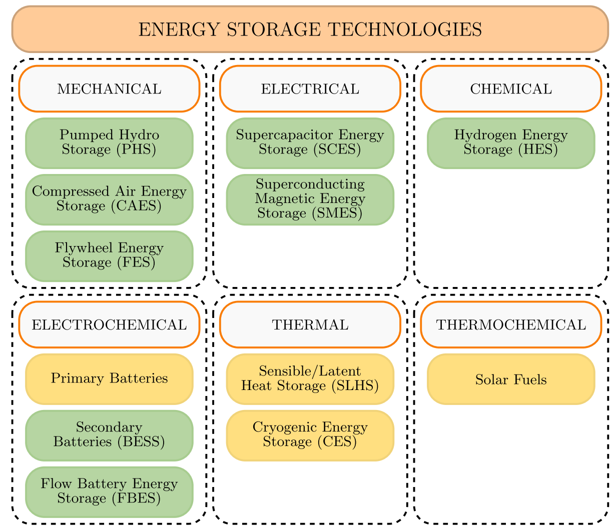


Fig. 2. Energy storage systems classification based on the form of energy storage. Technologies considered in this analysis highlighted in green; otherwise colored in yellow.

A brief summary of the ESS selected for this assessment is given below, highlighting the information relevant to the assessment. For more detailed information about each type, see review articles such as [22,27–30].

3.1. Pumped hydro storage

Conventional pumped hydro storage (PHS) is a popular, mature storage technology in wind power management [31]. It is the main energy storage technology, with 164.7 GW installed capacity around the world in 2021 [32]. Pumping water from a lower reservoir to a higher reservoir stores energy, while discharging involves using the stored water from the upper reservoir as a traditional hydroelectric plant. PHS has a power rating of 10-1000 MW and energy capacity rating of 500-8000 MWh [21]. The cycle efficiency of PHS is estimated to be in the range of 70-85% and the lifetime exceeds 40 years. PHS systems are limited by the availability of suitable sites, high capital investment and long construction time. Although alternative concepts such as [33,34] exist, the consideration of all possibilities is impractical for a rigorous assessment. Thus, only the classical concept of this storage is evaluated.

3.2. Compressed air energy storage

Compressed air energy storage (CAES) is also a mature technology with several working examples in operation [35]. In CAES, the energy is stored as compressed air in pressurized storage space. This might be in underground structures such as caverns, abandoned mines, or emptied oil reservoirs, as well as human-made pressure vessels. CAES has a high power and energy capacity rating (ranging from 580 MWh to 2860 MWh) [21], and offers energy efficiency of around 71% [36]. Nonetheless, when directly compared with gas, heat and electricity, CAES has a lower power density, and has specific site requirements. Furthermore, its discharge time is comparatively longer, with a shorter cycling time [37].

3.3. Flywheel energy storage

Flywheel energy storage (FES) is an electromechanical technology that stores energy as kinetic energy. To charge the flywheel, the electrical machine is operated as a motor, accelerating the flywheel to very high speeds, while discharging involves operation as a generator, causing the flywheel to decelerate. To store energy, the flywheel is kept rotating at a constant speed [38].

In addition to their unique properties such as excellent cycle stability, high efficiency and high power density [39], FES is applied in power quality management including providing ride-through capabilities [40], improving damping and suppressing rapid wind fluctuations [41]. However, flywheels have low energy density, a shorter operational time and high self-discharge losses [42].

3.4. Supercapacitor energy storage

Supercapacitor energy storage (SCES) systems are also known as ultracapacitors or double-layer capacitors [21]. Unlike traditional capacitors, supercapacitors have an electrolytic fluid between two electrodes instead of a solid dielectric with high capacitance and power density, making its design compact. They are highly efficient up to 90%, require virtually no maintenance and offer many pros such as fast charging, near infinite cycle stability and high power density [23]. When integrated with wind turbines, supercapacitors are typically used to help batteries optimize rapid changes providing smoothing effects during fast fluctuations. However, compared to other energy storage technologies, supercapacitors have a lower energy density and faster self-discharge [21].

3.5. Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) has three main components: the superconducting coil unit, the power supply, and refrigeration and vacuum units. The energy is stored by the magnetic field that is created by the DC current flowing through the superconducting coil. This coil is cryogenically cooled to a temperature below its critical superconducting temperature, making it almost lossless, as it offers little resistance to the current flow [27]. SMES offers a relatively fast response time (milliseconds), high power density, and high cycle efficiency [23,27]. SMES has been implemented together with wind turbines to improve power quality and increase dynamic stability. However, superconducting materials are very sensitive to temperature changes, affecting the reliability of the system [43]. It is noteworthy that SMES has not been deployed or commercialized on a large scale so far.

3.6. Hydrogen energy storage

The use of hydrogen as energy storage is suitable due to its high energy capacity. There is also great potential for integrating it with offshore wind farms, especially if the hydrogen is produced offshore. Traditionally, hydrogen has been produced from fossil fuels (grey hydrogen) or natural gas with carbon capture and storage, referred to as blue hydrogen. However, carbon dioxide emissions from grey hydrogen and the cost of carbon capture and storage have promoted the production of hydrogen through electrolysis, commonly referred to as green hydrogen production. Hydrogen can be converted to electricity using fuel cells. Fuel cells have good dynamic behavior, with rapid start-up even at partial load [21], although faster stack degradation is expected when handling rapid fluctuations [44].

Using hydrogen energy storage (HES), energy can be stored for a longer period with no self-discharge. In addition, it offers a useful life cycle of about 15 years with a cycle life of 20 000 charges and discharge cycles at 100% depth of discharge. However, hydrogen-based energy storage has overall low energy efficiency, at about 42%, due to the low efficiency of the fuel cells (60%) and electrolyzers (70%) [29].

3.7. Battery energy storage system/secondary batteries

A battery energy storage system (BESS) is a form of electrochemical energy storage that is widely used and readily available. With the increase in renewable energy production, especially wind and solar energy, integrating battery energy storage is expected to be the most cost-effective option for adding more renewable energy generation to the mix. In the context of the integration of renewable energies, BESS is useful in handling the short-term intermittency and variability effects on the grid that are characteristic of renewable energy sources [8,45]. Furthermore, there is an economic incentive to use batteries through the provision of certain “stacked” or combined services to the grid [45,46]. However, generally, BESS have limited life spans, depending on how much they discharge and the number of cycles [43].

Generally, batteries can be classified as primary and secondary batteries, where secondary batteries are also known as rechargeable batteries. These are considered to have very fast response times (in milliseconds) and can track load changes to improve system stability [23]. BESS is often the technology of choice for energy storage applications at the present time. See [45] for an overview of different battery types.

3.8. Flow battery energy storage

Flow battery energy storage (FBES) is another type of secondary battery. Conventional batteries store energy as the electrode material, whilst in flow batteries, the energy is stored as an electrolyte [47]. More information about FBES types can be found in [48].

Unlike BESS, by increasing the electrolyte’s volume in FBES, they can store large quantities of energy regardless of the size of the cell. Furthermore, redox flow batteries have been highlighted in the literature as providing high efficiency and low cost per unit of energy and cycle, prolonged working lifetimes, peak-hour load leveling and stability enhancement of the grid, when they are connected to renewable energy sources [49].

4. OWF topology

In addition to service and storage type, storage location is a relevant aspect to consider in the subsequent analyses. However, the actual challenges of storage siting are not technical issues, but the fact that there is no standard OWF, and therefore not all projects incorporate all the proposed locations. For this work, a point-to-point HVDC-connected wind farm with an AC collection grid is selected as the reference topology, which is presently the most used configuration for far OWF and the precursor of future multiterminal and meshed offshore HVDC grids. Both converters in the offshore and onshore substations are assumed to be modular multilevel converter (MMC). Type IV wind turbines are assumed, which have an available DC-link between generator side and grid side converters. Note that this review considers the DC-link of the back-to-back converter of the wind turbine as a possible location for services provision, and DC services are thus not confined solely to the HVDC transmission line, but also to this link.

The chosen ESS locations are summarized graphically in Fig. 3. The OfWT location is relevant for technologies that can be connected to the wind turbine. OfAC and OnAC indicate storage connected to the AC grid, with the former located on the offshore substation and the latter located onshore. Locations OfCO and OnCO refer to energy storage embedded in the MMC, and OfDC and OnDC pertain to storage tapped to the HVDC terminals. In all locations, the prefix “Of” refers to locations offshore, while the prefix “On” refers to locations onshore. Energy storage placement at an offshore location involves an intrinsic handicap in terms of cost and space, which has been considered in the explanation of color-coded tables development. However, its proximity to the OWF brings advantages regarding the provision of certain services and could bring further benefits in the event of future connections to meshed and multi-terminal networks, such as the proposed North Sea super grid [50].

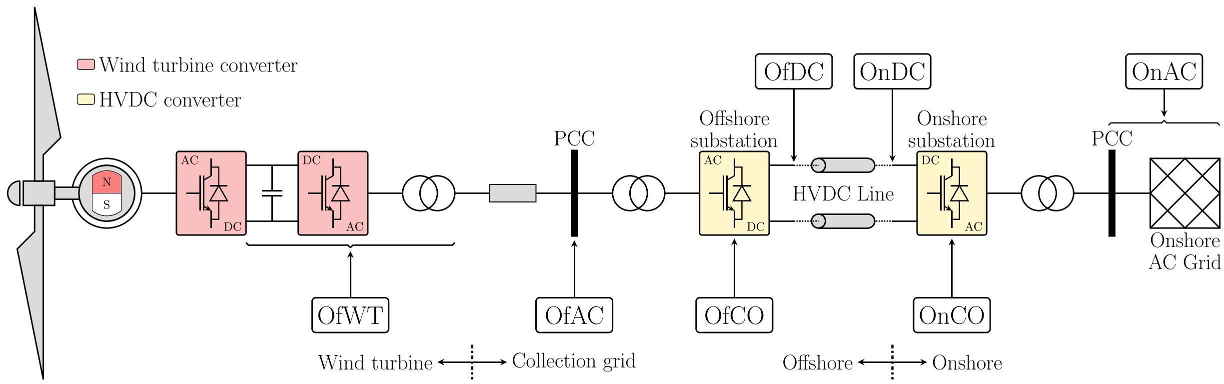


Fig. 3. Single-line diagram of a HVDC-connected OWF depicting possible locations of an ESS.

5. Methodology

The multidimensional assessment begins with the completion of three tables comparing (i) services that can be provided depending on the ESS location, (ii) where each ESS can be situated, and (iii) which services can be provided by each ESS. These tables are qualitatively filled according to the following criteria.

- If the case is technically feasible or there is already research concerning the case, it is filled as green. Note that economic feasibility is not specifically assessed.
- If the case has relatively few examples in the literature or is not investigated, but is theoretically possible and would be worthwhile to develop or study, it is colored yellow.
- If the case technically makes no sense or is not possible due to the characteristics of the ESS, service or location, it is red.
- Additionally, if the case does not provide the specific service under evaluation, but it supports the system during that contingency, it is classified as blue. If the ESS is not connected to the grid where the contingency occurs, it is also classified as blue. Note that a combination of blue and yellow may occur.

As the reader of this manuscript might notice, expressions such as "relatively" or "make sense" leave room for subjectivity. Additionally, although some technologies are widely investigated in other areas, their use in the offshore environment and in special grids such as offshore collection systems have not been analyzed in the literature. In contrast, atypical ESS concepts are described in Section 6 during the assessment. To prevent possible discrepancies between conventional and exotic concepts of the same ESS, only the former are considered in this study.

For the sake of clearness and rigor, the most controversial cases are discussed in Section 6. Moreover, some inconsistencies have been found between authors, which will also be discussed and are classified in yellow. A particular point has been considered for locations OfDC and OnDC. Presently, DC-DC converters to step-up voltage are not mature technologies (see [51] for further information). Following the criteria, these locations should be generally evaluated with a maximum color of yellow. Nevertheless, as this would affect both Tables 3 and 4, and in order not to consider this limitation twice in the quantitative evaluations, it has only been taken into account for Table 4, so the reader is encouraged to take this point into account when looking at Table 3.

Aiming to collect extra information, a 3D array has been built from previous tables. To do so, numeric values have been given to the different colors, aiming to accurately translate the information. Green, yellow and red colors are translated into the values 1, 0.5 and 0 respectively. Blue color instead is set as green multiplied by a factor of 75%, so that the combination between blue and yellow has 75% of the value of yellow. Table 2 provides a brief summary of the conversion performed.

Table 2
Conversion from colors to values for the multidimensional assessment.

Quantitative values for each color				
0.00	0.375	0.50	0.75	1.00

Once the values for each color are defined, the 3D array is built via the geometrical mean. For instance, to assess the ability to provide FPC though FBES in location OfWT, the result is $\sqrt[3]{0.75 \cdot 0.5 \cdot 1} = 0.721$, where the 0.75, 0.5 and 1 represent the blue, yellow and green colors at Tables 3–5 respectively. A geometrical mean differs from the typical arithmetical mean in that if one element is zero (red), the average will also be zero. Additionally, it penalizes those cases with low values more, even if the arithmetical average is the same.

Thanks to the 3D array, cross information between tables can be used to obtain further results. For example, questions such as "Where can each energy storage technology be implemented to provide oscillation damping?" or "Which locations are suitable to provide the highest number of services?". As the number of results that can be concluded is greater than what can be contained in a single manuscript, each storage, service and location versatility scoring is provided in Section 6.4.

6. Multidimensional assessment

A multidimensional evaluation is quantitatively performed via three tables comparing the research state and the technical feasibility of: (i) the services described in Section 2 at the specified locations in Section 4 (Table 3); (ii) the ESS introduced in Section 3 at each location (Table 4); and (iii) the services that can be provided by each ESS (Table 5). Each table is individually developed through Sections 6.1–6.3. Then, a three-dimensional quantitative assessment is performed in Section 6.4 along with a sensitivity analysis in Section 6.5 to interrelate previous assessments and to provide information about possible future trends.

6.1. Services provided at different locations

Table 3 contains information on which services can be provided depending on the location where the ESS is installed. In some cases, even though the storage technology does not directly provide a specific service, it can contribute positively to the system during the contingency, and therefore a blue color is defined. The services are grouped according to whether they are provided in the AC or DC grid. A third group is also used for those services that do not depend on the grid to which they are connected.

Power fluctuation suppression is the only green service for all locations. This is due to the fact that the ESS only has to provide the required power, independent of its location. In the case of PS/TS

Table 3
Evaluation of the services provided by an OWF compared to the possible locations of the ESS.

SERVICES vs LOCATIONS								
		ESS Locations						
		OfWF	OfAC	OfCO	OfDC	OnDC	OnCO	OnAC
DC side	DC-VS	Green	Red	Green	Green	Green	Green	Red
	DC-LVRT	Blue	Blue/Yellow	Yellow	Red	Red	Yellow	Red
	DC-BSR	Green	Blue/Yellow	Yellow	Green	Green	Yellow	Blue/Yellow
AC & DC	PFS	Green	Green	Green	Green	Green	Green	Green
	PS/TS	Yellow	Yellow	Red	Yellow	Green	Yellow	Green
	TC	Yellow	Yellow	Red	Yellow	Green	Yellow	Green
AC side	IFS	Blue	Blue	Blue	Blue	Blue	Green	Green
	FPC	Blue	Blue	Blue	Blue	Blue	Green	Green
	FSC	Blue/Yellow	Blue/Yellow	Blue/Yellow	Blue/Yellow	Blue	Green	Green
	POD	Blue	Blue	Blue	Blue	Blue	Green	Green
	AC-VS	Red	Yellow	Red	Red	Red	Red	Green
	AC-LVRT	Blue	Yellow	Blue	Blue	Blue	Blue	Green
	AC-BSR	Blue	Green	Yellow	Blue	Blue	Yellow	Green

* Voltage support (VS), Low-voltage ride-through (LVRT), Black-start restoration (BSR), Power fluctuation suppression (PFS), Peak shaving/time shifting (PS/TS), Transmission curtailment (TC), Inertial frequency support (IFS), Frequency primary control (FPC), Frequency secondary control (FSC), Power oscillation damping (POD).

Red: Practically infeasible, Not meaningful; Yellow: Theoretically possible, Insufficiently explored; Green: Technically feasible, Adequately researched; Blue: Indirectly Supportive

and transmission curtailment, the cells are generally categorized as yellow for offshore locations and green for onshore. This is due to the difficulty in placing the required amount of energy capacity in an offshore substation. Hydrogen and compressed air storage are the main technologies able to provide these services offshore, even though the latter includes geographical constraints, as the required caverns might not be available. Regarding both locations with embedded storage, there is no information in the literature about the connection of such amounts of energy capacity embedded to an MMC converter. This fact, along with the difficulty of placing the storage offshore, makes the embedded storage in the offshore converter practically infeasible for these services.

Regarding frequency regulation services, all offshore locations and the onshore storage connected to the HVDC link are set as blue, as the service is originally provided by the converter onshore and the ESS at these locations only provide the required energy. This is also true for power oscillation damping, for which the storage can deliver the amount of active energy that the onshore converter requires for damping (if damping is performed through active power). In the single case of frequency secondary control, a combination of yellow and blue is used due to the challenge of placing enough energy storage offshore. Further research on enhanced secondary batteries [52,53] could be interesting to eliminate this constraint. With respect to ESS embedded in the onshore converter and connected to the AC network, both frequency support services and power oscillation damping have been set as green, thanks to a larger available space to locate the storage and the fact that they directly supply these services.

Continuing with the last three AC services, voltage support is set as infeasible, except for locations where the ESS is connected to an AC system. As commented in Section 2.1.5, due to the general inductive behavior of the AC networks, the voltage level is controlled through the injection or absorption of reactive power. This is supplied by the converters connected in the grid, so the ESS has practically no influence over this power. Nevertheless, the addition of converter interfaced energy storage, or the connection of a synchronous generator in the AC system, adds a new source of reactive power to the system, although some storage components (e.g. batteries or flywheels) do not contribute actively to its provision/absorption. Finally, since the collection grid voltage is normally controlled by the powerful converter in the offshore substation [17], the actual effect of the extra converter on this grid voltage is difficult to assess and, to the best of the authors' knowledge, has not been widely researched.

In the case of the AC-LVRT service, the blue color has been used in locations where the storage task is to absorb the trapped energy during the transient when a fault occurs in the onshore grid [54–56]. These ESS could reduce or even replace the DC chopper used to keep the voltage under the secure upper limit. Instead of dissipating the surplus energy, as in [57], the energy is stored and used later. Energy storage connected directly to the onshore grid can support the voltage by injecting reactive current. On the other hand, the evaluation of the ESS placed in the offshore collection grid is challenging. One can argue that, similar to the rest of the technologies, the storage can absorb the generated active power during the fault period in the onshore grid. However, if the fault occurs in the collection grid, the energy storage converter can theoretically contribute with reactive power. This is subject to research with the wind turbine acting as a reactive power source [58], but the limited investigation of this service through collection grid connected energy storage justifies a yellow categorization.

For AC black start restoration, the connection of an ESS in the offshore collection grid is set as green, as it should be able to replace the generator normally used for the restoration [59–61]. Note that storage connected through a converter needs to be controlled by a grid-forming strategy. Locations with an available DC-link are in blue as, although they cannot interact directly with the AC grid, they can provide energy and stabilize the DC voltage, allowing for better grid-forming control of the AC interface converters. Again, these converters' strategy must be grid-forming [3,5,60]. In the case of ESS embedded into the substation converters, information in the literature is practically nonexistent. Theoretically, however, the storage should be able to help energize and stabilize the MMC sub-modules, allowing or improving the black-start performance of the converter.

Regarding DC services, as voltage in DC systems can be used as a power imbalance indicator (such as the role of frequency in AC grids) [17], DC voltage regulation can be compared with power fluctuation suppression. The main difference is found when the storage is connected to an AC system. The rapid dynamics of DC-links make DC voltage support infeasible if the storage is not directly connected to the link. Note that in the offshore wind turbine, the DC-link subject to control is in the back-to-back converter.

In the case of DC-LVRT, locations with embedded ESS in the converter are set as yellow because they are dependent on the MMC topology. If this converter is based on full-bridge cells, it has DC fault clearance capability [62], sometimes using part of the internal energy on the MMC's capacitors [63]. If fault clearance is achieved, the converter is even able to continue operating as a static synchronous compensator for the AC grid [64]. If the energy storage is embedded in the converter, this could support the stored energy in the sub-modules during the fault, and inject/absorb active power to/from the AC grid afterwards. If the collection grid can remain in operation thanks to the full-bridge topology of the MMC, and if the wind generators are controlled by a grid-forming strategy, the ESS in these locations could absorb part of the power generated by the turbines during the transient, improving the system performance during the contingency. Similar behavior is expected in the wind turbine, where the energy storage can absorb part of the surplus energy [55]. To conclude this service, a fault in the offshore HVDC line would rapidly bring the voltage to zero, prohibiting the injection of power from the ESS. The only exception could be the use of SMES as a current-limiting coil during contingency [65–67].

Regarding DC black start restoration, an ESS connected to a DC-link can be used in the voltage regulation during energization. On the other hand, the support of energy storage connected to the offshore collection grid could help the restoration of surrounding DC-links, although further research is needed. Finally, embedded storage in substation converters has the same role as in the AC grid restoration service, while the onshore AC system power quality could be improved during HVDC energization by a storage directly connected to the network.

6.2. ESS at different locations

Table 4 assesses the technical feasibility of placing each ESS at each location in the OWF. Starting with pumped hydro storage and CAES, both give nearly the same results. This can be attributed to the inherent nature of both technologies, which are typically characterized as synchronous ESS, with substantial energy capacities. The primary drawbacks associated with these systems include their geographical dependency and space constraints. As explained in Section 3.2, CAES may also be deployed using pressurized tanks [68] or underwater compressible containers [69]. Although their energy capacity is lower, this reduces the geographical constraints. The reader should take into account that in this study, only the standard concepts of both of these technologies are considered. In the case of pumped hydro storage, projects such as [33] using undersea water reservoirs, or energy islands as in [34], have been excluded from the scope.

Exotic wind turbine technologies with internal CAES such as in [70–72] are not considered either. Therefore, none of these technologies can be connected to the wind turbines or to the HVDC converters. Regarding the collection grid, CAES could be implemented using either already existing undersea caverns or pressurized tanks, but due to the high geographical dependency on the former, and the smaller body of research of the latter, it is considered yellow. Additionally, according to [73], offshore CAES in offshore wind farms is not techno-economically feasible at the present time and more research is needed. Finally, storage connected to the HVDC link have the same drawback as the previous locations, but with the extra need of interfacing the ESS via power electronics.

The rest of the technologies in the fourth and fifth columns of Table 4 have been set as yellow, except for superconducting magnetic storage, which can be used in the DC-link both to store energy and to act as a current ramp-rate limiter during contingencies, and without the need of a complex power electronic interface (see [65–67,74] for more details).

The ESS can be connected to the collection grid as usual in the continental grid, so they are considered green, although the offshore space constraints must always be taken into account. In case of embedded storage, the only technologies found in the literature to be integrated into the MMC are secondary batteries, supercapacitors, or a combination of both [75–78].

Regarding the location of ESS in the wind turbine, hydrogen and flow battery based storage have been set as yellow. Concerning the former, projects such as ERM Dolphyn [79] are investigating the placement of this ESS over the floating platform of the wind turbine. However, this kind of project is still under development. More information about hybridization projects for hydrogen and wind energy can be found in [80]. Flow batteries are also a theoretically feasible technology, although the research of this technology in wind turbine applications is not particularly developed [55,81]. Otherwise, the interest in BESS and supercapacitors is increasing every year, regardless the location.

In the case of flywheel and superconducting magnetic energy storage, this has been set as red due to the low amount of investigation in the literature. With regard to the former, having additional rotating masses in a wind turbine seems disadvantageous compared with the other alternatives. It must be remarked that, apart from the classical concept of flywheels within the scope of this analysis, some authors are developing the idea of moving masses inside the turbine blades to modify the total inertia of the rotor, proportionally increasing the maximum amount of stored energy at the same angular speed of the blades [82,83]. Although some authors have already published some articles about the use of superconducting storage inside a wind turbine [74,84], the implementation of this technology in the short- or medium-term seems infeasible due to some of its current characteristics, such as operation at cryogenic temperatures, or the need for protection of wind turbine components from the strong magnetic fields of this storage [85].

Table 4
Evaluation of the possibility of placing each ESS at each location in an OWF.

ENERGY STORAGE SYSTEMS vs LOCATIONS							
	ESS Locations						
	OfWT	OfAC	OfCO	OfDC	OnDC	OnCO	OnAC
PHS	Red	Red	Red	Red	Red	Red	Green
CAES	Red	Yellow	Red	Red	Red	Red	Green
HES	Yellow	Green	Red	Yellow	Yellow	Red	Green
BESS	Green	Green	Green	Yellow	Yellow	Green	Green
FBES	Yellow	Green	Red	Yellow	Yellow	Red	Green
SCES	Green	Green	Green	Yellow	Yellow	Green	Green
SMES	Red	Green	Red	Green	Green	Red	Green
FES	Red	Green	Red	Yellow	Yellow	Red	Green

Red: Practically infeasible / Not meaningful; Yellow: Theoretically possible / Insufficiently explored; Green: Technically feasible / Adequately researched

6.3. Services provided by different ESS

Table 5 aims to assess which services can be provided by each ESS. For the sake of clearness, the storage technologies are grouped into three categories: Long-term energy capacity (PHS, CAES and HES), medium-term energy capacity (BESS and FBES) and short-term energy capacity storage (SCES, SMES and FES).

6.3.1. Long-term energy capacity storage

With regard to the DC-side services, long-term storage technologies have been set as red. The typical concepts of compressed air and pumped hydro storage are connected to the AC-side and their response times are too slow to provide these services [27]. There is a lack of information about hydrogen storage regarding the control of the DC-link through this technology, which is normally connected to an AC system via a voltage source converter responsible for stabilizing the DC voltage [86,87].

It must be remarked that the response time of hydrogen storage is faster than the previous technologies, mainly, thanks to proton exchange membrane technology in the electrolyzers. According to [87], a power ramp-up of 145 MW in 250 ms can be achieved, demonstrating that this technology has potential to provide both inertial and frequency primary control. Note that inertial support has a service provision time scale of 200 ms, according to [10]. However, hydrogen storage still has issues associated with such a rapid response, such as faster stack degradation or the higher power fluctuations [44]. On the other side, alkaline electrolyte, which is a more established technology, may be suitable for frequency secondary control applications and long-term stability. More information about the differences between proton exchange membrane and alkaline electrolytes can be found in [88].

Compressed air and pumped hydro storage for frequency regulation are both generally suitable technologies. Since they are both synchronous ESS, they naturally provide inertia to the systems [89]. In addition, their power set-point can be adjusted for frequency secondary control. Nevertheless, traditional hydro storage governor response is usually not fast enough for primary control. More recent evolutions of this technology use back-to-back converters to connect the generator with the grid, allowing faster power control and providing both inertial and primary support [90]. However, issues with water pressure in the station pipes have been reported in [91], due to the fast required ramp-up power. The response time of the governor of CAES, however, is fast enough to provide frequency primary control [92–95].

Continuing with power fluctuation suppression and oscillation damping, contrary to CAES and hydrogen, pumped hydro storage has been set as yellow due to the faster response and power control capacity of this technology interfaced by power electronics [90]. On the other hand, the operation of CAES makes it unsuitable for continuous power regulation in small time scales (seconds). According to [96], this technology modulates the power output by means of opening and closing an air valve, which produces an undesired oscillatory power output for these services. In fact, the authors recommend the use of additional energy storage like supercapacitors for performance enhancement. Nevertheless, the reader should know that fluctuation suppression at larger time scales (hours) is feasible, as shown in [97,98]. Regarding hydrogen storage, both power fluctuation suppression and oscillation damping are colored in red, due to the low amount of information in the literature and the high stack degradation at rapid power set-point variations.

Compressed air and pumped hydro storage are suitable for the provision of the last three services on the AC side, as they are synchronous ESS that can use typical reactive power control, and have a high energy capacity for system restoration purposes. Hydrogen energy storage is likewise, able to regulate the reactive power set-point, thanks to the interface converter. However, its application in black-start restoration has not been sufficiently investigated and it is categorized as a promising technology in [27].

6.3.2. Medium-term energy capacity storage

The ESS discussed in this section (BESS and FBES) stand out due to their balanced characteristics in terms of energy and power capacity, which make them suitable for a wide range of applications. Note that, since both storage systems are similarly interfaced with the system, the discussion of the feasibility of one technology normally also applies to the other.

With respect to the DC services, the rapid response time for these storage technologies makes them suitable. According to [28], both technologies have the potential to respond in the order of milliseconds. This is why some authors have used flow batteries for DC voltage stabilization in [99] and for surplus energy absorption during grid fault transients in [100]. The connection of BESS through a DC-DC dual active bridge converter is investigated for medium voltage DC grids in [101]. The authors state that ESS with this converter can withstand a DC fault in the grid, controlling the current and continuing operation once the fault is cleared. In addition, they affirm that the technology

Table 5
Evaluation of the provided services by each ESS in an OWF.

SERVICES vs ENERGY STORAGE SYSTEMS									
		Energy Storage Systems							
		PHS	CAES	HES	BESS	FBES	SCES	SMES	FES
DC side	DC-VS	Practically infeasible	Practically infeasible	Practically infeasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	DC-LVRT	Practically infeasible	Practically infeasible	Practically infeasible	Technically feasible	Technically feasible	Theoretically possible	Technically feasible	Theoretically possible
	DC-BSR	Practically infeasible	Practically infeasible	Practically infeasible	Technically feasible	Technically feasible	Theoretically possible	Theoretically possible	Theoretically possible
AC & DC	PFS	Theoretically possible	Practically infeasible	Practically infeasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	PS/TS	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Practically infeasible	Practically infeasible	Practically infeasible
	TC	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Practically infeasible	Practically infeasible	Practically infeasible
AC side	IFS	Technically feasible	Technically feasible	Theoretically possible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	FPC	Theoretically possible	Technically feasible	Theoretically possible	Technically feasible	Technically feasible	Theoretically possible	Theoretically possible	Theoretically possible
	FSC	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Practically infeasible	Practically infeasible	Practically infeasible
	POD	Theoretically possible	Practically infeasible	Practically infeasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	AC-VS	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	AC-LVRT	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible	Technically feasible
	AC-BSR	Technically feasible	Technically feasible	Theoretically possible	Technically feasible	Technically feasible	Practically infeasible	Practically infeasible	Practically infeasible

* Voltage support (VS), Low-voltage ride-through (LVRT), Black-start restoration (BSR), Power fluctuation suppression (PFS), Peak shaving/time shifting (PS/TS), Transmission curtailment (TC), Inertial frequency support (IFS), Frequency primary control (FPC), Frequency secondary control (FSC), Power oscillation damping (POD).

Practically infeasible Not meaningful — Theoretically possible Insufficiently explored — Technically feasible Adequately researched could be expanded to HVDC applications. Regarding black-start restoration capability, both technologies should be able to energize both an AC and a DC system [22].

Moving to the second block of services, both secondary and flow battery energy storage have the potential to improve the integration of new renewable energy sources by smoothing possible power fluctuations [100,102]. However, degradation issues with BESS may be one of the biggest challenges of this technology. An already-built demonstration project proves the technical feasibility for PS/TS and transmission curtailment, e.g. Moss Landing Energy Storage Facility in California (USA) with 1600 MWh energy capacity and 400 MW of installed power capacity, with a planned expansion of 1400 MWh and 350 MW [103]. Similarly, a vanadium redox flow storage of 400 MWh and 100 MW has already been connected to a Dalian grid in China [104]. Due to this high level of energy capacity, both technologies are also suitable for frequency secondary control.

Continuing with frequency control services, the BESS “AES Kilroot Power Station” (5 MWh/10 MWh) in Ireland has demonstrated a response to an event within 40 ms, and it should have the ability to ramp to full power in 100 ms [105,106]. Similarly, [107] states that the inertia emulated with flow batteries show advanced behavior compared to other technologies in terms of over-shoots, under-shoots and settling time.

Regarding AC power system stabilization, flow batteries, as well as BESS, are able to damp sub-synchronous oscillations in the power grid. For example, power oscillation damping of a wind-diesel station due to the wind farm disconnection is researched in [108] using flow batteries, with satisfactory results. AC voltage control can be provided by these technologies if they are connected to the grid through a voltage source converter. This operation can be seen in [109] for flow batteries. Additionally, reactive power control of this type of converter allows them to provide voltage support during LVRT contingencies (considering the limits of the converter). The operation during either AC or DC faults has also been tested for BESS embedded in an MMC [110]; however, as previously commented in this review, the converter must contain a minimum amount of sub-modules to be able to counteract the fault current. Additionally, BESS connected to a DC microgrid has also been researched in [111], improving the quality of the DC-side voltage during an AC fault.

6.3.3. Short-term energy capacity storage

The last three technologies (SCES, SMES and FES) are highly recommended for applications that require high power densities and rapid responses; although they lack high energy capacity compared to previous storage. This prevents them from providing services such as AC grid restoration, secondary control, transmission curtailment or PS/TS [22,112].

Conversely, these storage are suitable for DC voltage support, as they can rapidly provide the extra energy required by the system to stabilize the voltage [40,113,114]. This service is normally researched in the literature as a consequence of an AC fault that destabilizes the DC grid. However, since there is no formal specification of DC-LVRT [115], there is a lack of research of this service with supercapacitor and flywheel energy storage. On the other hand, due to the ongoing investigation of the current-limiting capabilities of SMES [67], this technology has been set as green. With respect to DC-link restoration, the response time of these short-term storage could be beneficial for the regulation of the DC voltage during energization. However, due to the insufficient investigation of this service and their limited energy capacity, they have been classified as yellow.

Power fluctuation suppression for short-term intermittence and inertial frequency support are relatively well-researched topics in terms of these types of ESS [39,41,65,116]. On account of the similar characteristics of power oscillation damping and fluctuation suppression, these are also colored as green [117–119].

Some discrepancies can be found regarding frequency primary control. On the one hand, some authors state these technologies cannot provide this service [29,112]. Their main issue is the lack of stored energy to retain the power provision until the secondary control is activated. In the specific case of flywheel storage, it can be classified as a potential technology according to [22], probably due to the greater energy capacity of this technology compared with supercapacitors and SMES. On the other hand, some papers advocate the suitability of these technologies for primary control [30]; but in the majority of cases, these technologies are hybridized with another storage (normally BESS) to fulfill the energy requirements [39,120]. Moreover, supercapacitors in the DC-link of the wind turbine may be used for fluctuation suppression, to allow for rapid power output ramp-up of the generator [116].

Finally, the three technologies are able to control AC voltage and support AC faults, normally thanks to the use of power electronics to connect them to the grid, which have full control of reactive current [41,121,122] for absorbing the trapped energy upstream in the system [40,123]. As previously commented, SMES is also able to limit the fault current, as researched in [124,125].

6.4. Three-dimensional assessment

A drawback of the tables previously commented on is the ability to represent only two dimensions (services-locations, ESS-locations and services-ESS). For the sake of completeness, a 3D matrix has been built using the geometric mean (see Section 5). For example, this gives the ability to determine the “versatility” of each service, location and ESS. This research refers to versatility as the percentage of cases for which one dimension can be provided, placed or used, considering the remaining dimensions, so that a service that can be provided by all ESS at any location would have a versatility of 100%. The same example can be extrapolated to ESS and locations.

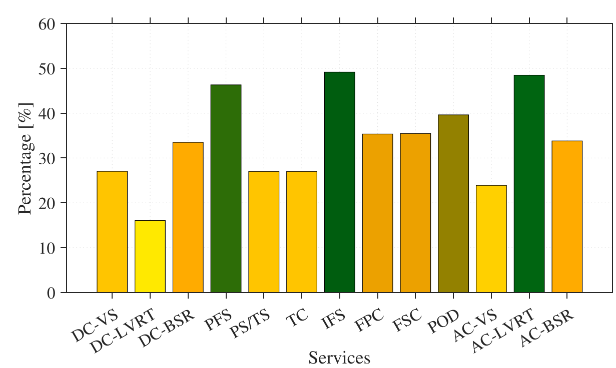


Fig. 4. Versatility of services.

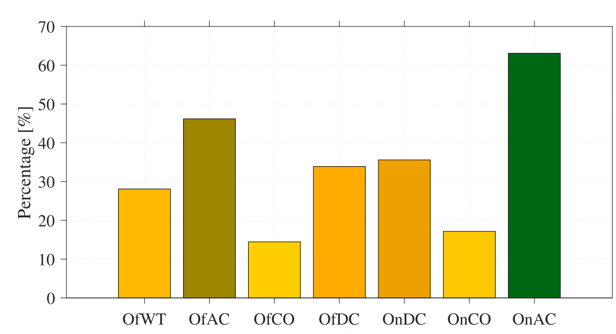


Fig. 5. Versatility of locations.

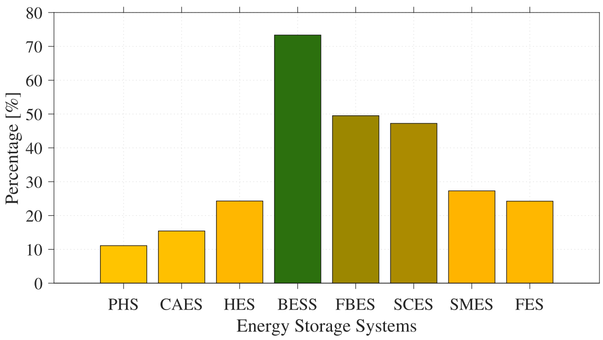


Fig. 6. Versatility of energy storage systems.

Fig. 4 depicts the technical versatility of each evaluated service. As can be noted from the greener color, fluctuation suppression, inertial support and AC-LVRT support are the services that can be provided more frequently, followed by oscillations damping and frequency regulation services. Readers interested in these services thus have several appropriate options. The reasons for these results are listed below.

- Power fluctuation suppression: Although this service can generally be provided only by medium- or short-term energy storage, it can be provided from every location in the OWF. Additionally, these types of energy storage are more likely to be connected at different places.
- Inertial frequency support: Since rapid response technologies can be controlled to emulate inertia, and slower ESS are usually synchronous storage, inertia can be provided by almost every storage device. Additionally, since DC-link-connected storage can provide power to help with the inertia (colored as blue in Table 3), the final score of this service increases to 49.16%.
- Low-voltage ride-through at AC grid: By defining this service as the possibility to remain connected and inject reactive power to the system, or as the absorption of trapped energy in the system during the contingency, the number of cases to which it applies is relatively high.

By analyzing the versatility of each location in the OWF in Fig. 5, it is clearly seen that AC-connected alternatives have been investigated intensively. In contrast, embedded energy storage in the converter has the lowest scope, since the only technologies that can be connected are secondary batteries and supercapacitors.

Finally, Fig. 6 shows that BESS is the most flexible energy storage. This technology clearly stands out from the others, as it can be placed at nearly every location and provides all of the evaluated services. In addition, lithium ion batteries are one of the most researched technologies at the present date. On the other hand, pumped hydro storage yields the lowest score since, although it is the most mature technology on the list, its implementation on an OWF is not straightforward.

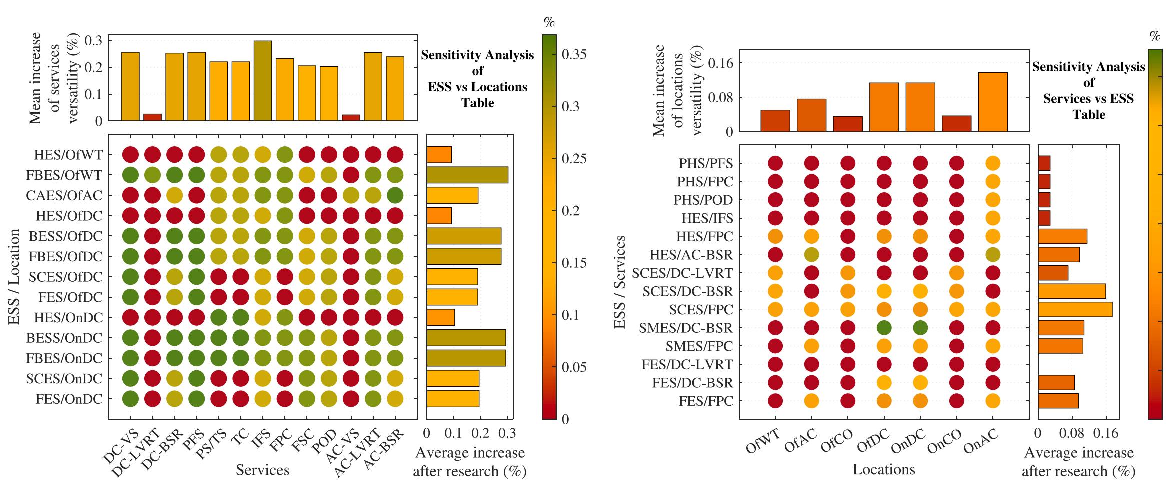
6.5. Sensitivity analysis and outlook

After the systematic evaluation in Sections 6.1–6.3, and the quantitative 3D assessment, giving a final versatility score, this section aims to perform a sensitivity analysis showing how much the final score varies if any "insufficiently explored" case (yellow color) in the systematic analysis becomes green. Thus, while previous results reveal the current state of the literature, this section seeks to quantitatively indicate the research directions with the greatest potential.

The followed methodology is based on (i) changing a single "insufficiently explored" case to "adequately researched", (ii) computing a new 3D analysis, and (iii) calculating the versatility percentage variations. This sequence is repeated for each yellow case for Tables 4 and 5, summarizing the results in Fig. 7(a) and Fig. 7(b), respectively.

Both Figs. 7(a) and 7(b) comprise a main graph and two complementary bar plots. The y-axis of the central graph names all yellow cases in the systematic analysis tables, in the form of "ESS/Location" for Fig. 7(a), and "ESS/Service" for Fig. 7(b), while the x-axis contains the remaining dimension (services and locations, respectively). As an example, if the yellow color of hydrogen storage in the wind turbine of Table 4 is researched and considered mature (first line of Fig. 7(a) called HES/OfWT), it can be seen that the versatility of the services that increases the most is PS/TS, transmission curtailment, inertial frequency support and primary control, where the latter stands out from the rest, with an increase of more than 0.3% according to the color bar on the right. Additionally, the bar plot at the top represents the average variation for each service, so it can be seen that the final scoring of services DC-LVRT and AC-LVRT has low sensitivity on average concerning changes in the systematic analysis. On the other hand, the lateral bar plot represents how much the average versatility increases on the basis of a single research status update.

Analyzing the results in Fig. 7(a), it can be seen that secondary and flow batteries have a high average sensitivity, independently of their locations. Their balanced energy and power densities make them suitable for any service, which is reflected in higher sensitivity. On the other hand, inertial support is the service that benefits the most from the research of any case, since medium- and short-term ESS



(a) Sensitivity analysis for services versatility

(b) Sensitivity analysis for locations versatility

Fig. 7. Versatility increases due to an status update in: (a) Table 4 and (b) Table 5.

with high power density and rapid response times are more likely to be placed offshore due to their characteristics. Other interesting possibilities would be the use of flow batteries connected to the DC-link of the offshore wind farm, which would be highly beneficial for the DC voltage stability and restoration; or the use of CAES in the offshore collection grid, which could replace the generally used diesel generator in the black start restoration. This can also be seen in Fig. 7(b), where the research of AC grid restoration through hydrogen storage would be positive for both offshore and onshore AC systems.

Checking locations' sensitivity, it can be noted that the research of the provision of primary control via supercapacitors storage would be beneficial at any location. However, due to its low energy density, its use would be more likely in future low-inertia networks, where the rest of the generation responds more quickly to disturbances. Besides, research on using this technology for DC voltage restoration would be beneficial for every location in the OWF. Furthermore, frequency primary control provision through hydrogen energy storage, whose potential has already been analyzed [126,127], would also increase the average versatility of several locations.

7. Conclusion

Aiming to offer a comprehensive representation of the existing literature, a multidimensional systematic analysis is presented to explore the technical feasibility of delivering diverse services utilizing distinct energy storage technologies situated at various locations within an HVDC-connected offshore wind farm. The analysis comprises three distinct phases. Firstly, three color-coded tables are filled comparing (i) services with locations, (ii) storage with locations and (iii) services with storage. This result clearly shows the already existing knowledge and the possible new research directions in terms of the technical viability of the technology. Nevertheless, these first outcomes are restricted to the two dimensions represented by a table.

The second stage aims to merge the previous results into a 3D array to consider the interdependencies between all dimensions, resulting in a quantitative score indicating which storage, location or service has the greatest potential and versatility. The analysis concludes with a sensitivity analysis based on the previous outcomes, which shows the potential improvement in each service and location if an understudied field is further researched. This study not only provides an overview of the current state of the literature but also highlights research avenues that could potentially make substantial contributions to the technical viability of the technology.

Nevertheless, there are some scope limitations to consider. First, the analysis is restricted to a technical evaluation, disregarding the current economic constraints of each technology. The authors recognize this handicap of offshore ESS in the present scenario, which narrows their suitability and limits market adoption. However, further research typically reduces costs, and the need for storage offshore, despite higher costs, may increase with the emerging plans for multi-terminal and meshed offshore HVDC grids.

Summarizing the most relevant results, it can be seen that the most balanced ESS in terms of energy and power capacity have the greatest potential. Even though these technologies do not offer the fastest response, and they are not able to store huge amounts of energy, they can provide all analyzed services. However, it must be considered that the deployment of these ESS offshore is a challenge that must be further researched. Techno-economically feasible secondary and flow battery technologies are required to enable future offshore wind farms with integrated energy storage.

The natural intermittency of wind energy is a challenge that must be overcome to allow a greater introduction of this resource into the energy mix. The evaluation has shown that power fluctuation suppression is one of the most flexible services, which can be supplied by several ESS in different time-scales. In addition, it has no limitations regarding the location of the storage.

The assessment has also revealed the wider research of storage systems in onshore AC systems. This research allows for easier implementation of an ESS at the AC offshore collection system than in other DC connections at an offshore wind farm. However, some other options can be also interesting. For instance, although energy storage embedded in the power converter (locations OfCO and OnCO in Fig. 3) has a low score, it can utilize BESS to provide power fluctuation suppression, which in addition to the modularity and reliability of the ESS at this location, makes this alternative an attractive option to be investigated.

Finally, the hybridization of different energy technologies, even though it is beyond the scope of this paper, might be crucial in overcoming the disadvantages of each individual energy storage. A symbiotic relationship between the technologies with faster responses and those with greater energy capacity could be very beneficial to provide a wider range of services and enhance their performance. In addition, the presented methodology could be extendable in future work to consider techno-economical limitations and/or analyze future multi-terminal and meshed offshore networks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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