Journal of
Marine Science
and Engineering

MDPI

Article

Offshore Wind Power Integration into Future Power Systems: Overview and Trends

Ana Fernández-Guillamón [1,†], Kaushik Das [2,†] and Nicolaos A. Cutululis [2,†] and Ángel Molina-García [1,†,*]

1 Department of Electrical Eng, Universidad Politécnica de Cartagena, 30202 Cartagena, Spain; ana.fernandez@upct.es
2 Department of Wind Energy, Technical University of Denmark, 4000 Roskilde, Denmark; kdas@dtu.dk (K.D.); niac@dtu.dk (N.A.C.)
* Correspondence: angel.molina@upct.es; Tel.: +34-968-32-5462
† These authors contributed equally to this work.

Received: 10 October 2019; Accepted: 2 November 2019; Published: 7 November 2019

Abstract: Nowadays, wind is considered as a remarkable renewable energy source to be implemented in power systems. Most wind power plant experiences have been based on onshore installations, as they are considered as a mature technological solution by the electricity sector. However, future power scenarios and roadmaps promote offshore power plants as an alternative and additional power generation source, especially in some regions such as the North and Baltic seas. According to this framework, the present paper discusses and reviews trends and perspectives of offshore wind power plants for massive offshore wind power integration into future power systems. Different offshore trends, including turbine capacity, wind power plant capacity as well as water depth and distance from the shore, are discussed. In addition, electrical transmission high voltage alternating current (HVAC) and high voltage direct current (HVDC) solutions are described by considering the advantages and technical limitations of these alternatives. Several future advancements focused on increasing the offshore wind energy capacity currently under analysis are also included in the paper.

Keywords: offshore wind energy; HVAC; HVDC; P2X; hydrogen storage; CAES

1. Introduction

Energy demand has been increasing non-stop during the last decades [1]. Nowadays, fossil fuel sources (i.e., coal, oil and natural gas) provide around 85% of the world energy demand, according to the BP Energy Outlook of 2019 [2]. However, with the Paris climate agreement established in December 2015, this energy scenario is about to change [3]. This climate agreement aims to restrict maximum increase in the global average temperature below 2 °C above pre-industrial levels [4]. To fulfill this goal, greenhouse gas (GHG) emission trends should drastically change [5]. Consequently, the use of fossil fuels should be reduced, as they are considered as the main source of GHG emissions [6]. Actually, global GHG emissions are dominated by the emissions of CO_2 due to the combustion of fossil fuels, which has been increasing continuously since 1990 [7]. The power sector should be decarbonized by 2050 to meet the Paris agreement target [8]. Furthermore, Liddle and Sadorsky estimated that increasing by 1% the share of non-fossil fuel electricity generation can reduce by up to 0.82% the CO_2 emissions [9]. This environmental worry is one of the reasons to promote the integration of renewable energy sources (RES) into power systems [10]. Moreover, RES can also mitigate the energy dependence on fossil fuels imported from other countries [11]. Apart from the economic costs of these fossil fuel imports, decreasing energy dependence increases electricity supply security [12]. The International Energy Agency defines electricity supply security as the uninterrupted availability of energy sources at an affordable price [13]. However, political stability, market liberalization and foreign affairs are nowadays linked to energy supply security [14]. As a consequence, it is important to be energy-independent to guarantee the energy security of a country [15].

While RES provide an acceptable solution for these two problems, they also face many challenges as their integration increases into the grids, mostly based on their intermittency, variability and uncertainty due to their dependency on weather conditions [16]. Actually, they are usually considered as 'non-dispatchable' sources [17]. This fact makes them hard to integrate into power systems [18], as transmission system operators (TSOs) have to deal with not only the uncontrollable demand but also uncontrollable generation [19,20]. RES include bioenergy, geothermal energy, hydropower, ocean energy (tide and wave), PV, thermal solar energy and wind energy (onshore and offshore) [21]. Some of them (such as wind and solar installations) are connected to the grid through power electronic converters, reducing the rotational inertia of the system as they replace conventional generation units [22,23]. This fact compromises the frequency stability and alters the transient response [24]. As a result, several frequency control strategies have been proposed in the specific literature [25–30]. Other alternatives to increase the RES share in power systems and avoid the aforementioned problems are to complement one source with another (for instance, wind with solar and/or hydropower) [31–33] or to use storage systems (such as flywheels, pumped hydroelectric storage, batteries, hydrogen, etc.) [34,35].

Among these renewable technologies, wind is one of the most economic, prominent and matured RES technologies [36,37]. In fact, since 2001, global cumulative installed wind capacity has shown an exponential growth, as can be seen in Figure 1a. Among the total wind capacity, 23 GW came from offshore installations in 2018, compared to 1 GW in 2007, refer to Figure 1b [38]. Despite offshore wind energy dating back to the 1990s, its popularity started around ten years ago [39]. This increase is due to the current interest of the wind energy industry in offshore wind power [40]. For instance, offshore wind energy investments surpassed onshore investments in Europe in 2016, as presented in [41]. Moreover, nearly 40% of the total wind capacity is expected to come from offshore wind energy in Europe in 2030 [42,43].

In addition, offshore wind energy presents many advantages compared to onshore wind power plants, especially related to wind energy potential [44,45]: (i) Offshore mean wind speeds are higher and wind power variability is also lower than onshore wind power; (ii) their visual and acoustic impact is usually lower than onshore; subsequently (iii) larger wind turbines (WTs) can be installed [46]. Actually, on the European coasts, the available offshore wind energy is about 350 GW [47]; the USA's shores present an offshore wind power potential of more than 2000 GW [48]; the offshore wind resource in China is about 500 GW in water depth under 50 m [49]; and the east and west Indian coasts have an offshore wind potential of 4.4 GW and 6.7 GW, respectively [50].

Furthermore, offshore wind speed usually increases with distance from the shore, thus increasing the power generated, as it depends on the cube of the wind speed [51]. However, higher installation and maintenance costs of offshore wind power plants (OWPP) far from the shore balance the benefits of higher energy production [52]. Indeed, OWPP are around 50% more expensive than onshore wind power plants [53], but their costs are expected to decline up to 35% by 2025 [54]. The global weighted average levelized cost of energy (LCOE) in 2018 was 20% lower than in 2010. These cost reductions can be a result of [55]:

- The evolution in wind turbine technology, installation and logistics
- The economies of scale in operations and maintenance
- The improved capacity factors due to higher hub heights, better wind resources and larger rotor diameters

This paper analyzes and reviews different aspects of offshore wind power plants, including several future alternatives to increase the offshore wind power capacity. The rest of the paper is organized as follows: Section 2 presents the current status of offshore wind power plants (WTs and OWPP sizes, water depth, distance from shore and electrical transmission to shore). Future advancements possible for larger offshore wind power plant integration are analyzed in Section 3. Finally, Section 4 gives the conclusions.

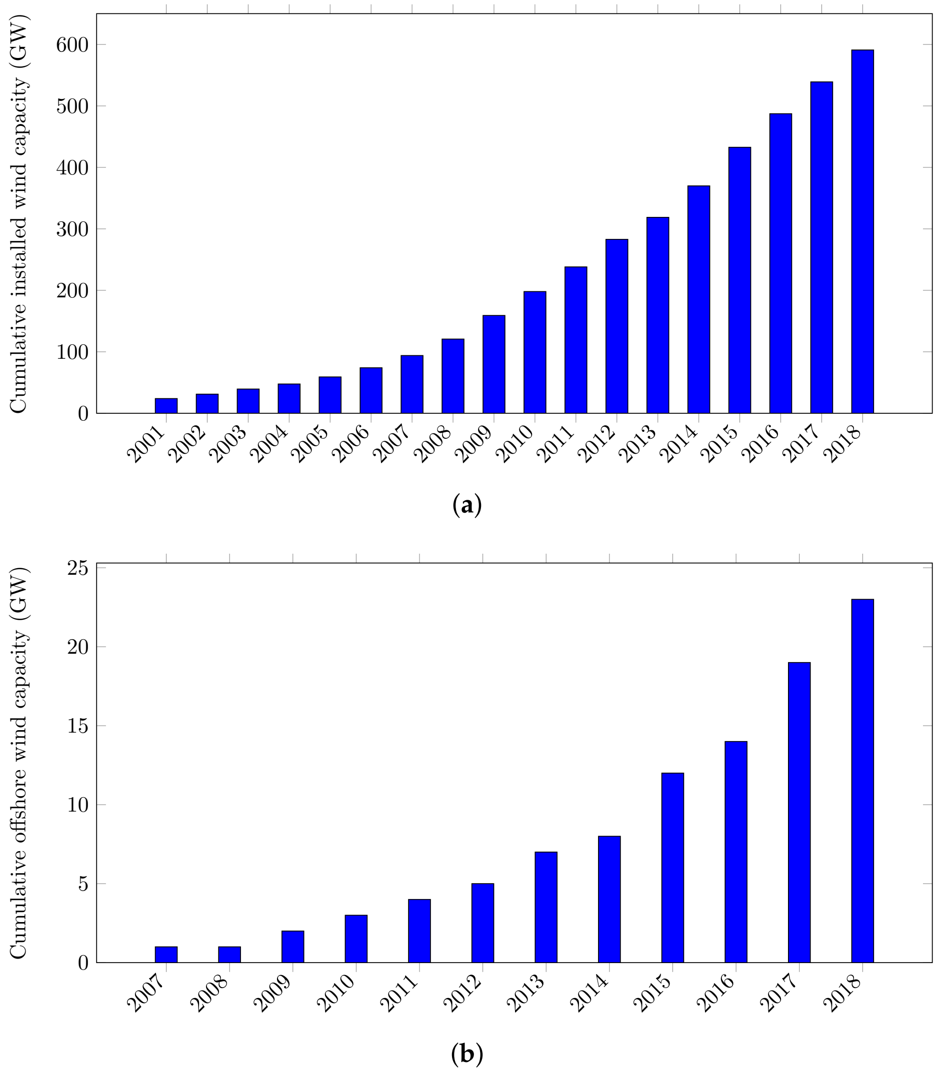

Figure 1. Global cumulative wind capacity in GW. (**a**) Global cumulative wind capacity: Onshore and offshore. (**b**) Global cumulative offshore wind capacity.

2. Current Status of Offshore Wind Power Plants

2.1. Preliminaries: Classification of Wind Turbines

WTs are usually classified as fixed speed wind turbines (FSWTs) and variable speed wind turbines (VSWTs) [56]. FSWTs work at the same rotational speed regardless of the wind speed [57]. VSWTs can operate around their optimum power point for each wind speed, using a partial or full additional power converter [58]. As a result, VSWTs are more efficient than FSWTs [59]. Moreover, WTs present different topologies depending on their generator [60]: type 1 includes a squirrel cage induction generator; type 2 includes a wound rotor induction generator; type 3 includes a doubly-fed induction generator (DFIG); and type 4 includes a full-converter synchronous generator [61]. Types 1 and 2 are FSWTs, whereas types 3 and 4 are VSWTs.

Nowadays, VSWTs are the most commonly installed WTs [62–65]. Among them, full converter generator WTs seem to be a better option than DFIG-based WTs for OWPP [66–72]. The main differences between DFIG and full-converter WTs are the following:

- The DFIG configuration needs a gearbox, generator and partial-scale power converter (around 30%), as shown in Figure 2a. The gearbox couples the blades with the generator, increasing the rotational speed from the rotor hub to the induction machine [73–75]. The stator is directly connected to the grid, whereas the rotor is connected to the power converter [76]. As a result, the converter only covers the power produced by the rotor of the DFIG [77].
- The synchronous generator of a full-converter WT is excited by an external DC source or by permanent magnets [78]. In this case, the hole generator is connected to the grid through a power converter [79]. Hence, all the generated power from a WT can be regulated accordingly [80]. They have low maintenance costs and negligible rotor losses [81]. Moreover, some type 4 WTs have no gearbox, as depicted with a dotted line in Figure 2b, using a direct driven multipole generator [82].

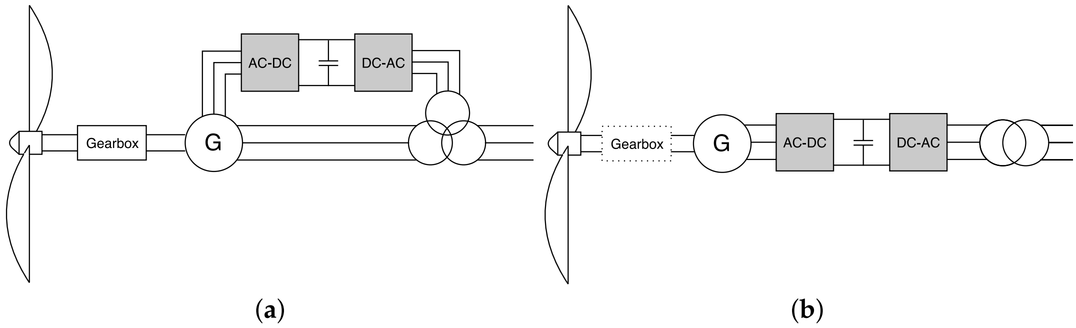

Figure 2. Variable speed wind turbines types. (**a**) Doubly-fed induction generator (DFIG) wind turbine. (**b**) Full-converter wind turbine.

2.2. Offshore Trends: Turbine Capacity, Wind Power Plant Capacity, Depth and Distance from the Shore

In Europe, the rated capacity of offshore WTs has been continuously increasing during the last decade. For instance, in 2017, the average rated capacity of WTs was 5.9 MW, compared to 3 MW in 2010 and 4.8 MW in 2016 [83]. In 2018, new offshore WTs were 6.8 MW on average, 15% larger than in 2017. Comparing 2018 to 2010, the average WT increase is more than 200%. Moreover, two 8.8 MW offshore WTs were installed in the United Kingdom in 2018, those being the largest WTs installed of the world. The commercial model of those WTs was V164-8.8 MW from MHI Vestas Offshore [84]. However, nowadays there are larger commercial offshore WTs, up to 12 MW, as presented in [85]. Table 1 shows the 10 largest WTs currently available. All of them have a rated power over 8 MW, rotor diameters between 150 and 200 m and are equipped with synchronous generators (type 4).

Table 1. Biggest wind turbines currently available.

Rated Power (MW)	Manufacturer	Reference	Diameter (m)	Generator
8.0	Siemens Gamesa	SG 8.0-167 DD	167	Synchronous permanent
8.3	MHI Vestas Offshore	V164-8.3 MW	164	Synchronous permanent
8.8	MHI Vestas Offshore	V164-8.8 MW	164	Synchronous permanent
9.0	MHI Vestas Offshore	V164-9.0 MW	164	Synchronous permanent
9.5	MHI Vestas Offshore	V164-9.5 MW	164	Permanent magnet
10.0	AMSC	wt10000dd SeaTitan	190	HTS synchronous
10.0	MHI Vestas Offshore	V164-10.0MW	164	Permanent magnet
10.0	Swiss Electric	YZ150/10.0 YZ170/10.0 YZ190/10.0	150 170 190	Synchronous permanent
10.0	Siemens Gamesa	SG 10.0-193 DD	193	Synchronous permanent
12.0	General Electric	GE HALIADE-X	220	Synchronous permanent

Regarding OWPP capacity, it has also increased dramatically in the last 10 years (around 700%), in line with the increase of average offshore WT capacity. In fact, average OWPP capacity was 79.6 MW in 2007. In contrast, 561 MW was the average capacity for OWPPs in 2018 [84]. This means that considering the average WT and OWPP capacities of the year 2018, each OWPP has between 80 and 85 WTs. On the other hand, OWPP depth and distance to the shore have not increased that much in recent years. At the end of 2013, the average water depth of OWPPs was 16 m with an average distance to the shore of 29 km [86]. In 2018, the average water depth of OWPPs under construction was 27.1 m, with an average distance to shore of 33 km. This means that water depth has increased by 170% and distance to shore by around 110%. There are some OWPPs that should be mentioned: Hornsea One (UK) and EnBW Hohe See (Germany) are the OWPPs located farthest from the shore (103 km away); Kincardine Pilot (Scotland), a floating demonstration project, has a water depth of 77 m [84]; and Hywind (Scotland), the first fully operational floating wind farm, with water depths varying between 95 and 129 m [87].

2.3. Offshore Wind Power Electrical Power Transmission

For the electrical power transmission from the OWPP plant to the shore, there are two possibilities: (i) High voltage alternating current (HVAC) and (ii) high voltage direct current (HVDC). Figure 3 depicts an overview of the current state of offshore wind power energy transmission to the shore.

$$\text{OWPP transmission} \begin{cases} \text{HVAC} \\ \text{HVDC} \begin{cases} \text{LCC} \\ \text{VSC} \\ \text{DRU} \end{cases} \end{cases}$$

Figure 3. Offshore wind power plant transmission.

2.3.1. High Voltage AC

HVAC transmissions were mostly used for OWPPs until the year 2010 [88]. Their easy protection system design and the use of transformers to change between different voltage levels were the main reasons to use them [89]. However, the high capacitance of submarine HVAC cables combined with the low resistivity of sea water caused different electromagnetic dynamic and transient problems from those of conventional overhead lines, such as distortion of the voltage's shape due to resonance problems [90,91]. This high capacitance also leads to substantial charging currents, subsequently reducing the active power transmission capacity and transmitting reactive power in long distances [92]. A possible solution could be to install reactive power compensation units along the HVAC submarine cables, but they are expensive devices and it is a difficult task to carry out [93]. an alternative found in the literature is to add compensation units only at both ends (onshore and offshore) of the underwater cables, which improve the current profile along them [94,95]. However, their effect is very limited for distances over 60–75 km [96,97]. With the aforementioned considerations, the topology for HVAC transmission from OWPPs is depicted in Figure 4 [98,99]. It consists of:

- An offshore substation to increase the offshore voltage level (usually from 30–36 kV) to the transmission voltage level at 132–400 kV.
- Three-core HVAC submarine transmission cables.
- Reactive compensation units on both ends (offshore and onshore), such as static VAR compensators (SVCs) or static synchronous compensators (STATCOMs).
- An onshore substation, if the onshore interconnecting grid voltage is different from the offshore transmission system rated voltage.

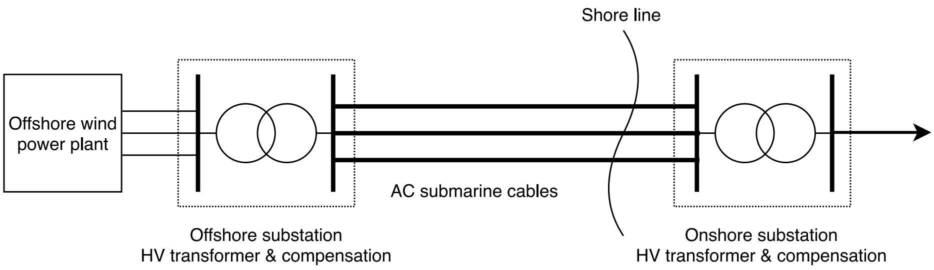

Figure 4. Offshore wind power plant high voltage alternating current (HVAC) transmission system.

As can be seen, the OWPP grid is synchronously coupled to the main onshore grid. This is another problem of HVAC links for OWPPs, as all faults in either the grid or the OWPP are propagated to the other one [100].

2.3.2. High Voltage DC

High voltage direct current (HVDC) transmission is considered as the best solution to OWPPs located far away from the land [101]. Actually, some studies conclude that HVDC links are economically viable for distances above 50–70 km [102]. A graphical comparison of costs between HVAC and HVDC transmission systems can be seen in Figure 5 [103].

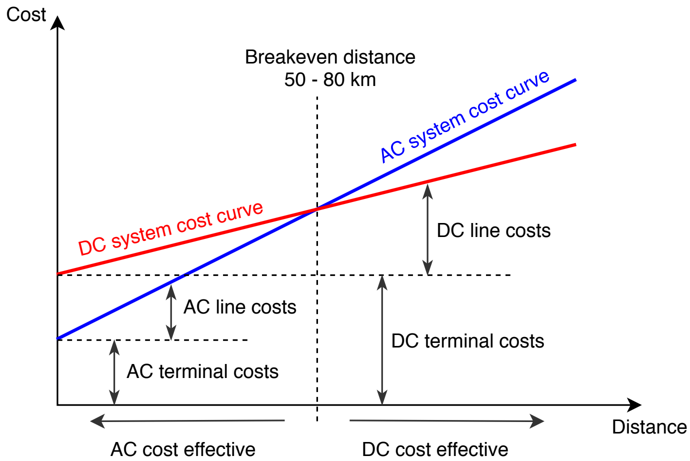

Figure 5. AC and DC system costs based on the transmission distances.

Figure 6 shows the main elements of an HVDC connection, and consists of [104,105]:

- An offshore substation to increase the voltage level to the level of the transmission line.
- AC/DC rectifier.
- AC and DC filters to cancel the low order harmonics. Furthermore, the AC filters supply some of the reactive power used by the converter, whereas the DC filters avoid the generation of circulating AC currents in the cable.
- DC current filtering reactance. This removes the possibility of a current interruption under minimum load circumstances, limiting DC fault currents and also reducing current harmonics in the DC cable.
- DC cables.
- DC/AC converter.
- An onshore substation.

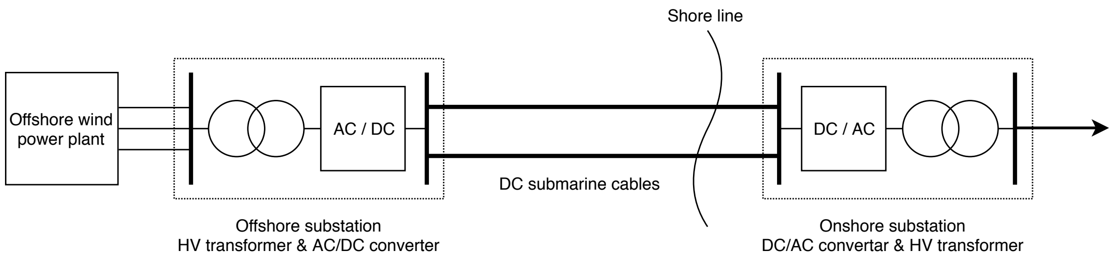

Figure 6. Offshore wind power plant HVDC transmission system.

In contrast to the HVAC topology presented in Figure 4, the HVDC link electrically decouples both the OWPP and the onshore grid, avoiding the propagation of possible disturbances between them [106,107].

Two different HVDC technologies are currently under use: Line-commutated converters (LCCs) based on thyristors and voltage-source converters (VSCs) based on insulated gate bipolar transistors (IGBTs) [108]. Among them, there is not a clear consensus about which technology is better: Some authors consider that LCCs are superior to VSCs in terms of reliability, cost and efficiency [26], whereas others affirm that the VCS–HVDC transmission system is the most promising technology [109]. a comparison between both HVDC technologies is summarized in Table 2 [110]. Recently, another technology called the diode rectifier unit (DRU) has been under discussion, though has not been implemented yet [111].

Table 2. Comparison between line-commutated converter (LCC) and voltage-source converter (VSC) HVDC technologies.

Technology	LCCs	VSCs
Semiconductor	Thyristor	IGBT
Control	Turn on	Turn on/off
Power control	Active	Active & Reactive
AC filters	Yes	No
Blackstart capability	No	Yes

Line-Commutated Converters

Traditionally, HVDC transmission systems have been based on LCCs, which use thyristors as the base technology. Actually, LCC is a trusted and mature technology [112] that links a mainland with some islands (e.g., in Northern Europe [113]). However, solutions based on thyristors usually involve the injection of some harmonics. For example, a twelve-pulse thyristor bridge, which is made up of two six-pulse bridges; the fifth and seventh harmonics can be canceled [114]. The LCC–HVDC transmission system is based on this twelve-step bridge [115,116].

The main drawbacks of the LCC–HVDC link are [116–120]:

- It can only transfer power between (at least) two active grids. As a result, an auxiliary start-up system is necessary in the OWPP.
- It demands reactive power, which needs to be supplied through reactive support devices.
- Despite most harmonics being canceled by using a twelve-pulse bridge, others still remain, thus needing additional filters.
- It requires voltage support for the OWPP AC bus. Two possible solutions can be found to overcome this requirement: (i) Installing a dedicated STATCOM, which increases considerably the overall cost or (ii) controlling the turbine inverters individually, which is technically challenging.
- The inverter is susceptible to commutation failures, especially when connected to weak AC power systems.

Blasco et al. suggest that the filter's design depends on the harmonic characteristics of the AC grid and the active power exchanged by the LCC–HVDC link, thus needing a detailed AC power system analysis [121].

Voltage-Source Converters

Since 2005, VSC–HVDC technology has been used in offshore applications. It is based on IGBTs [122]. The main characteristics of the VSC–HVDC link are summarized as [123–125]:

- It can control active and reactive power simultaneously.
- It can feed island-mode, weak AC and passive networks.
- Its station requires less space than that of an LCC (about 60% less).
- The cables are lighter.
- It does not require reactive power compensation.
- It can transmit power from zero to full-rating bidirectional, enabling OWPP start-up (black start operation) and working at low wind speeds.

Despite all these advantages, VSC–HVDC presents higher commutation losses and costs compared to the LCC–HVDC. Moreover, it can only handle limited voltage and power levels [126].

Diode Rectifier Unit

During the last years, DRU–HVDC has been under discussion. A DRU includes several diodes, a transformer and a smoothing reactor [127]. As DRU can only convert AC to DC [128], a hybrid topology combining DRU and VSC/LCC must be used, introducing the DRU as the offshore rectifier and the LCC/VSC as the onshore converter [129]. The main advantages of DRU–HVDC compared to LCC–HVDC and VSC–HVDC are [130–133]:

- Reduction of volume (80%) and weight (66%) of the platform.
- Smaller footprints.
- Reduction of power losses up to 20%.
- Reduction of total cost up to 30%.
- Capacity increased by 33%.
- Higher reliability and efficiency.
- Modular design and full encapsulation.
- Reduced operation and maintenance costs.

However, several problems have to be solved before implementing a DRU–HVDC connection [132–135]:

- As the DRU is a non-controllable passive device, the OWPP AC system must be regulated and controlled by the WT, thus requiring different WT and OWPP schemes.
- The onshore converter (LCC/VSC) controls the HVDC voltage. Subsequently, the DRU output DC voltage must be higher than the minimum voltage value to start conducting and transmit the power to the onshore station.
- Passive filters or active compensation devices are needed to remove the harmonic currents injected by the DRU.
- Voltage and frequency control stages are needed in the offshore grid for DRU commutation.
- A DRU is not able to provide auxiliary active power for the WT and OWPP substation, being then a drawback to the self-start of WTs.
- A DRU is not able to provide reactive power, needing power converters or other devices to compensate it.

3. Potential Future Advancements for Offshore Wind Energy

In 2018, ENTSO-E and ENTSO-G published their Ten Year Network Development Plan (TYNDP) scenarios. It was the first time that both European electrical and gas TSOs collaborated together. The TYNDP 2018 covers from 2020 to 2040 [136]. In 2030–2040, it is expected that between 45 and 75% of the overall European demand will be covered by RES, especially by hydro, wind and solar power. Actually, in the North Sea and Baltic Sea regions, the offshore wind power capacity is estimated to reach between 40 and 59 GW in 2030, and between 86 and 127 GW in 2040, according to the TYNDP. Other authors propose similar offshore wind power capacity scenarios in these regions; for instance, scenarios were modeled and optimized by Koivisto and Gea-Bermudez [137]. Greenpeace published in 2015 their 'Energy [R]evolution' forecast, where 148 GW of offshore wind capacity is expected to be installed in Europe in 2050 [138]. In the US, the Department of Energy considers that 22 GW of OWPPs can be installed by 2030, increasing up to 86 GW by 2050 [139]; according to the scenarios presented by the Energy Resources Institute of India for 2050, it could have 170 GW installed of offshore wind energy by then [140]; and the Chinese scenarios propose to install 200 GW of OWPPs (150 GW near offshore wind and 50 GW far offshore wind) by 2050 [141,142]. By these means, OWPPs seem to have an important energy role in the future worldwide.

However, onshore wind and other conventional fossil fuel technologies are currently cheaper than offshore wind energy [143]. As a consequence, different alternatives are being researched to reduce further costs of offshore wind power development:

- Power-to-X conversion (P2X)
- North Sea Wind Power Hub: The Hub-and-Spoke project
- Offshore storage options

These initiatives are discussed in detail in the following.

3.1. Power-to-X Conversion

P2X is based on converting power (electricity) to diverse substances (X) [144]. The different alternatives available in the P2X conversion are [145,146]:

- Power-to-heat (P2H): The electrical generation excess is linked to a heat device (electric boiler, heat pump), avoiding any intermediate energy carrier and subsequently increasing the global efficiency.
- Power-to-liquid (P2L): Different alternatives can be found in the specific literature, including the production of syngas through hydrogenation of CO_2 and reverse water gas shift; co-electrolysis of CO_2 and H_2O; or directly through the electro-reduction of CO_2 to methanol.
- Power-to-chemicals (P2C): From the syngas obtained with the power-to-liquid conversion, several compounds can be produced accordingly.
- Power-to-gas (P2G): Hydrogen is obtained from an electrolysis process and the possible subsequent conversion to methane with CO_2.
- Power-to-mobility (P2M): The electrical generation excess is used by the mobility sector through electric vehicles with an electric motor of 90% efficiency instead of an internal combustion engine (efficiency of 20%) or fuel cell (efficiency of 50%).
- Power-to-power (P2P): Electricity is converted into chemical or mechanical energy, which is stored and later reconverted into electric power.

These transformations are expected to be very relevant in future power systems, as the generated electricity excess can be stored in different ways and later used as, for instance, fuel for power plants [147]. Hence, the system's flexibility would be enhanced [148]. By these means, high capacity P2X plants could increase the RES supply by providing supply security in terms of storage facilities [149]. Moreover, as explained in [150], the P2X conversion provides a real link between different sectors, promoting the transition towards a future urban smart energy system. As an example, Figure 7 depicts the power-to-heat conversion joint [151]. an exhaustive analysis of 128 P2X demo projects in operation in Europe is discussed in [152]. These projects aim to gain experience with system integration of P2X components. Moreover, Denmark is interested in the conversion of electricity to hydrogen and liquid fuels through P2X solutions. Thus, they can become a front-runner in this technology as large Danish companies already work with it [153].

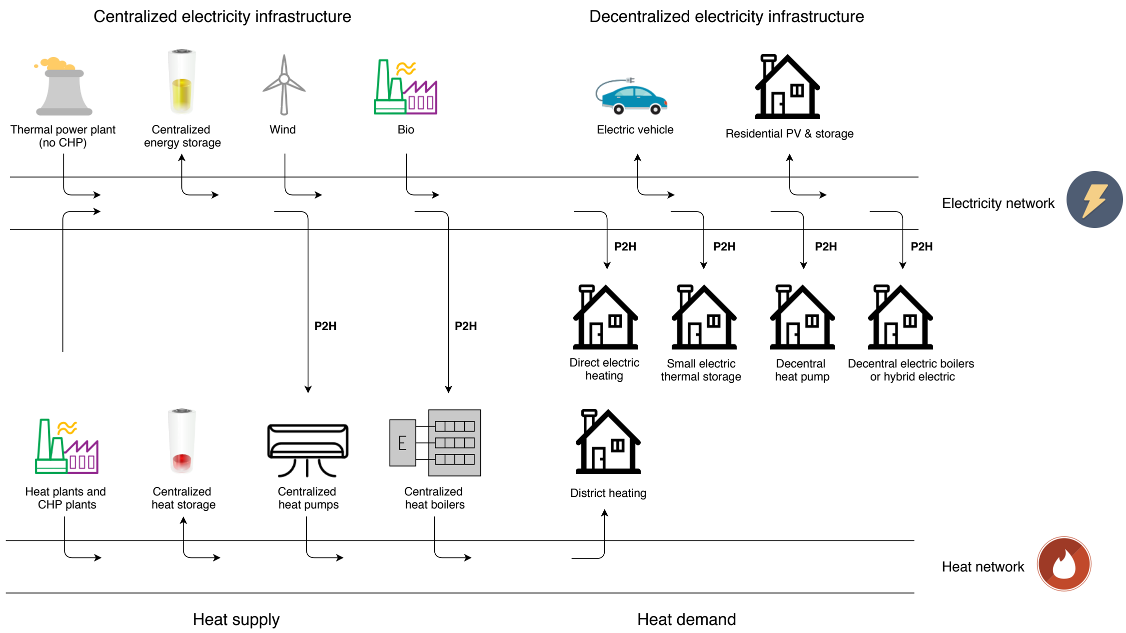

Figure 7. Power-to-heat conversion.

Several authors have already analyzed these technologies combined with the wind resource. Different flexibility options for wind power plants are analyzed in [154], concluding that the P2H solutions provide the most cost-effective scenarios with the lowest CO_2 emissions. Pursiheimo et al. focused on the feasibility of the P2G technology in Nordic countries to achieve a 100% RES system. The main applications of P2G are focused on supplying gas to transport and industrial sectors [155]. Furthermore, the use of P2G has been proved in Denmark to be a successful tool to complement wind power plants [156]. However, both investment costs of facilities and energy losses (due to the low efficiency in the conversion process) are high. Hence, the hydrogen produced from wind power also has a high cost [157]. For instance, in [158] different energy applications of hydrogen (P2P, P2G, P2M) are considered for a hybrid offshore wind–hydrogen power plant in France, obtaining negative profits due to the high investment costs in both wind and hydrogen infrastructures. Other authors conclude that the combination of a wind–hydrogen power plant should be considered to sell hydrogen directly, as re-powering hydrogen for electricity is extremely expensive [159]. Consequently, future works should be focused on reducing investment and maintenance costs for such power conversion solutions.

3.2. North Sea Wind Power Hub: The Hub-and-Spoke Project

To meet the Paris Agreement and the GHG reduction goals (refer to Section 1) in the countries around the North Sea, the North Sea Wind Power Hub (NSWPH) consortium was created. TenneT (a Dutch–German electricity TSO), Port of Rotterdam (the biggest port in Europe), Energinet (a Danish TSO) and Gasunie (a European energy infrastructure company) are the partners of the consortium [160]. NSWPH aims to facilitate the deployment of large scale OWPPs in the North Sea, evaluating and developing the Hub-and-Spoke project. The project consists on several central platforms, called hubs, which are in charge of supporting the power transport infrastructure by using the P2X conversion instead of the offshore converter platforms used currently. According to TenneT, the offshore wind power capacities will be in the range of 70 to 150 GW by the year 2040 and up to 180 GW by 2045 [161], similar values to those proposed in the TYNDP. Two main challenges are identified in NSWPH, (*i*) a strong power transmission infrastructure and (*ii*) high flexibility requirements. Mainly due to onshore surface constraints, onshore wind power plants and PV installations are not enough to decarbonize the power systems of this area [162]. The hub-and-spoke concept proposed by NSWPH is made up of several modular hubs located in different zones of the North Sea, which connect OWPPs with bordering North Sea countries. This can be seen in the figure of page 6 of [163]. By using high capacity DC cables, the power generated by OWPPs is transmitted to onshore grids in different locations connected in a smart and coordinated manner. These DC connections also provide high interconnection capacity among the different countries. Moreover, the hub-and-spoke concept can promote onshore OWPP integration through P2G transformation. Power systems thus become flexible through such P2X conversion [163].

Apart from defining the hub-and-spoke project, the NSWPH consortium also aims to demonstrate the technical feasibility of the project. So far, the consortium have concluded that [164]:

- The optimal capacity of the OWPP is estimated to be between 10 and 15 GW.
- Hub substructures can be based on four different foundation types: Ciasson island, sand island, platform and gravity-based structure. A comparison among them is presented in Table 3, as presented in [164].
- Both the spatial requirements and investment costs of the hubs are similar regardless of being all-electric, all-hydrogen or combining electricity and hydrogen:
  - All-electric hub-and-spoke: The electricity generated by the OWPP is transmitted to the shore.
  - All-hydrogen hub-and-spoke: The electricity generated by the OWPP is transformed offshore into hydrogen, and transported through pipelines to the shore.
  - Combined electricity and hydrogen hub-and-spoke: combines the two previous concepts.

Table 3. Hub substructures under consideration.

	Caisson Island	Sand Island	Platform	Gravity Based Structure
Water depth limit (m)	<25	<40	<45	>100
Construction time (years)	3–4	6–8	3–4	3–4
Size limit (GW)	6	>36	2	<6 (each WTs)
Maturity	Middle	Middle	High	Units – High/Linking – Middle
Footprint on seabed	High	High	Low	Middle

Moreover, the lifetime savings between CAPEX (capital expenditure) and OPEX (operational expenditures) for a 12 GW hub-and-spoke project (Denmark (2 GW), Germany (6 GW) and the Netherlands (4 GW)) could rise up to 2.5 billion €, without considering the P2X conversion, compared to a radial approach. This reduction is due to the lack of additional interconnection capacity between those countries. A study compared the LCOE between hub-and-spoke projects and radial approaches, concluding that the LCOE was able to be reduced for hub sizes between 6 and 12 GW, but limited for capacity hubs between 24 and 36 GW. Furthermore, electricity prices and emissions were also reduced. The total cost saving of a hub-and-spoke project compared to a no-hub project was then estimated to be between 15 and 20 billion € [165]. The main drawback of the hub-and-spoke project is that it would take more than 10 years of development and construction to become operational. Moreover, policies, regulatory framework and market design should be reconsidered to ensure a stable market. As the Paris Agreement must be fulfilled by 2050, these issues should be urgently reconsidered in order to carry out multiple hub-and-spoke projects by then [166].

3.3. Offshore Storage Options: Hydrogen and Compressed-Air Energy Storage

As electrical generation has to be immediately sold to supply the electrical consumption, and due to the stochastic nature of RES, energy storage emerges as an important solution for these sources [167]. However, as traditional energy storage technologies are difficult to use in a marine environment, new alternatives are being developed to store offshore energy. Wang et al. provide a comprehensive review on existing marine renewable energy storage solutions [168].

3.3.1. Hydrogen Energy Storage

The surplus of electricity produced by OWPP can be stored as hydrogen, and used later to generate power in fuel cells or as fuel in hydrogen vehicles [169]. Most alternatives available are based on the P2X technology, as previously described in Section 3.1.

An example of such alternatives can be found in the Deep Purple project which is based on the important CO_2 emissions from Norwegian oil and gas production. The project involves TechnipFMC, SINTEF, Subsea Valley and Maritim Forening Sogn og Fjordane, which develop the concept and new technology. It has received funding from the Research Council of Norway [170]. The Deep Purple project aims to convert electricity from OWPP to hydrogen and store such energy on the seabed. The hydrogen can then be used for several purposes [171,172]:

- Supply stable and renewable power to oil and gas installations
- Supply stable and renewable power to remote islands
- Provide a coastal hydrogen infrastructure to maritime sector
- Provide local production of power, hydrogen and oxygen to fist farming

It is expected to have a full-scale pilot by 2025 in Norway [173]. Figure 8 depicts an overview of the Deep Purple project.

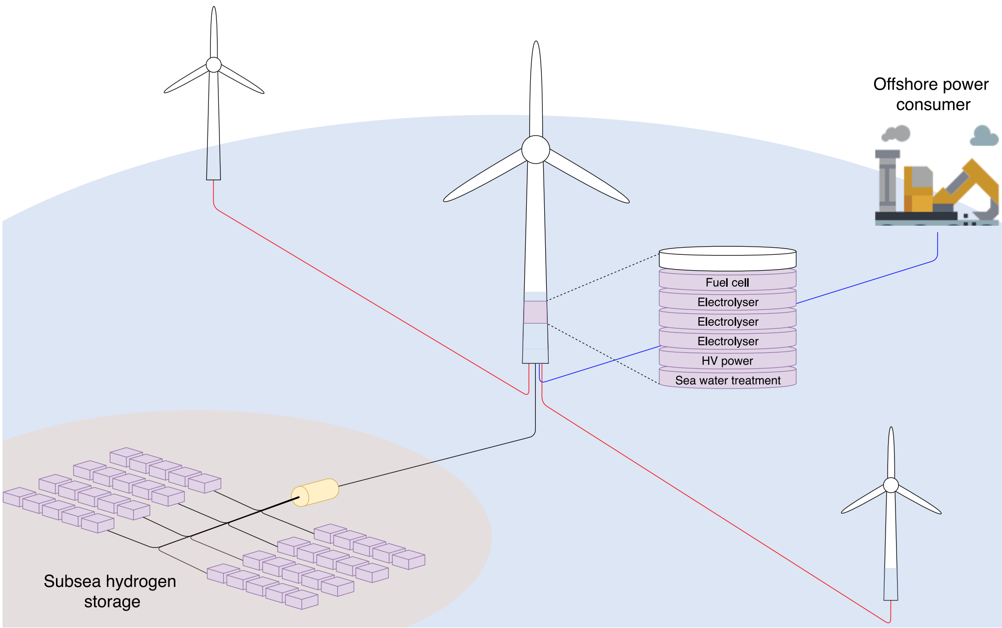

Figure 8. Deep Purple project.

3.3.2. Compressed Air Energy Storage

Compressed air energy storage (CAES) systems are a solution to energy storage based on the compression of air [174]. According to [175], the integration of CAES with wind and solar power generation can increase the RES share rate, as CAES is reported as less expensive than other storage systems, and to be large and powerful enough to store energy on a utility scale level [176]. Moreover, due to the high installation and capital cost of undersea transmission cables, offshore CAES can increase the cable's capacity factor, potentially lowering the average cost of offshore wind power while increasing the reliability and economic value of delivered power [177].

The TAKEOFF Business Incubator (University of Malta) has already patented the a storage technology called FLASC, with the aim of integrating large-scale energy storage into OWPPs. This solution is tailor-made for the offshore market, exploiting existing infrastructure and supply-chains, see Figure 9 [178]. FLASC uses compressed air for energy storage purposes, relying on the hydrostatic pressure of the deep-sea areas to maintain a stable pressure in the compressed air storage. As it uses existing infrastructure, it is considered a cost-effective solution. In [179,180], the multi-system integration and the working principle of the FLASC storage technology are described. This solution can also be used in order to: (i) Convert the intermittent RES supply into a stepped out one, simplifying their grid integration by allowing the TSO to schedule operations at specific time intervals, see Figure 10a; (ii) control the ramp rate of the generated power in case of sudden natural condition changes, see Figure 10b.

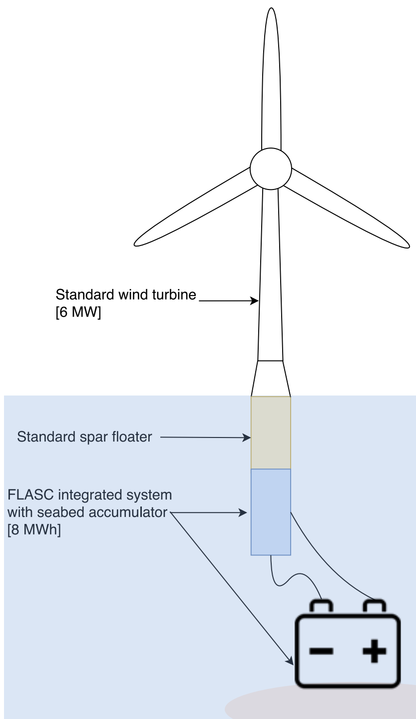

Figure 9. FLASC storage for offshore wind power plants (OWPPs).

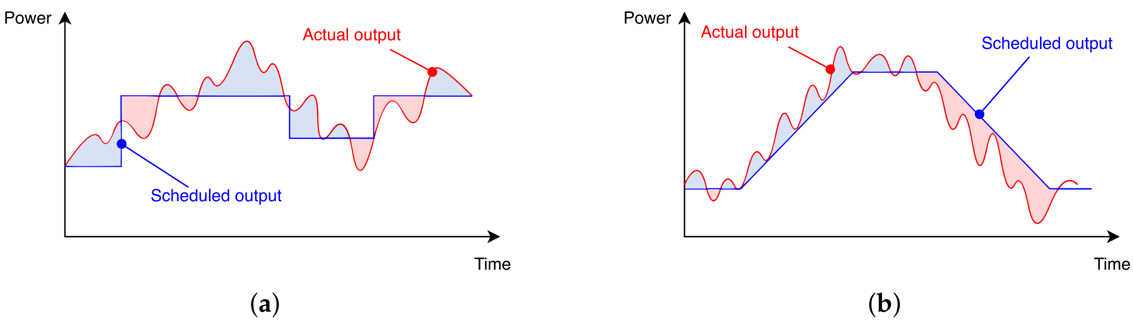

Figure 10. Further applications of FLASC storage technology. (**a**) Stepped out power control. (**b**) Ramp rate control.

A small-scale prototype was installed in Malta's Grand Harbor in May 2018. After one year, the testing campaign was completed. Results confirmed a consistently high thermal efficiency across a variety of meteorological conditions and operating regimes after hundreds of charging cycles. The prototype was removed and decommissioned, and nowadays the FLASC team is focused on developing a large-scale demonstrator in the open sea [181,182].

4. Conclusions

Future power scenarios include offshore wind energy as an important generation source. According to this framework, this paper discusses and reviews some aspects of offshore wind power plants for a massive integration into power systems. In the last decade, several characteristics such as offshore wind turbines, wind power plants, water depth and distance to shore have increased 230%, 700%, 170% and 110%, respectively. In the same way, electrical transmission has also evolved from HVAC to HVDC solutions. Moreover, HVDC technology currently offers three different possibilities: LCCs (based on thyristors), VSCs (based on IGBTs) and DRU (based on diodes). LCCs and VSCs have already been used, whereas DRU has not been implemented yet. The advantages and drawbacks of each technology have been extensively discussed in the paper. Different future advancements currently under development are also described: P2X conversion, the hub-and-spoke project as well as hydrogen and compressed air energy storage. The P2X conversion can enhance the power system's flexibility by converting the electricity surplus to other substances; however, its investment and maintenance costs should first be reduced to be economically viable. The hub-and-spoke project aims to facilitate the huge integration of offshore wind power plants in the North Sea; the total cost saving of this project, compared to a common offshore wind power plant, is estimated to be between 15 and 20 billion €. However, it is expected to take more than 10 years to become operational. Both hydrogen and compressed air energy storage systems appear as an alternative to conventional storage technologies due to the difficulty of using these traditional storage systems in the marine environment.

Author Contributions: Data curation, A.F.-G.; methodology and formal analysis, K.D. and N.A.C.; Resources A.F.-G.; Supervision, Á.M.-G.; Writing—original draft A.F.-G. and Á.M.-G.; and Writing—review and editing, K.D. and N.A.C.

Funding: This research received no external funding.

Acknowledgments: This work was supported by 'Ministerio de Educación, Cultura y Deporte' of Spain (grant numbers FPU16/04282 and EST18/00738).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
CAES	Compressed air energy storage
DC	Direct current
DFIG	Doubly fed induction generator
DRU	Diode rectifier unit
FSWTs	Fixed speed wind turbines
GHG	Greenhouse gasses
HVAC	High voltage alternating current
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistors
LCCs	Line-commutated converters
LCOE	Levelized cost of energy
OWPP	Offshore wind power plant
P2X	Power-to-X
PV	Photovoltaic

RES	Renewable energy sources
STATCOM	Static synchronous compensator
SVC	Static VAR compensator
TSO	Transmission system pperator
TYNDP	Ten Year Network Development Plan
VSCs	Voltage-source converters
VSWTs	Variable speed wind turbines
WPP	Wind power plants
WTs	Wind turbines

References

1. Wang, W.; Huang, X.; Tan, L.; Guo, J.; Liu, H. Optimization design of an inductive energy harvesting device for wireless power supply system overhead high-voltage power lines. *Energies* **2016**, *9*, 242. [CrossRef]
2. BP Energy Outlook. 2019 Edition. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf (accessed on 29 October 2019).
3. Clémençon, R. The two sides of the Paris climate agreement: Dismal failure or historic breakthrough? *J. Environ. Dev.* **2016**, *25*.[CrossRef]
4. Rogelj, J.; Den Elzen, M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature* **2016**, *534*, 631. [CrossRef] [PubMed]
5. Falkner, R. The Paris Agreement and the new logic of international climate politics. *Int. Aff.* **2016**, *92*, 1107–1125. [CrossRef]
6. Woo, J.; Choi, H.; Ahn, J. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. *Transp. Res. Part D Transp. Environ.* **2017**, *51*, 340–350. [CrossRef]
7. Crippa, M.; Oreggioni, G.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Lo Vullo, E.; Solazzo, E.; Monforti-Ferrario, F.; Olivier, J.G.J.; Vignati, E. *Fossil CO2 & GHG Emissions of All World Countries—2019 Report*; Publications Office of the European Union: Luxembourg, 2019.
8. Creutzig, F.; Agoston, P.; Goldschmidt, J.C.; Luderer, G.; Nemet, G.; Pietzcker, R.C. The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2017**, *2*, 17140. [CrossRef]
9. Liddle, B.; Sadorsky, P. How much does increasing non-fossil fuels in electricity generation reduce carbon dioxide emissions? *Appl. Energy* **2017**, *197*, 212–221. [CrossRef]
10. Huber, M.; Dimkova, D.; Hamacher, T. Integration of wind and solar power in Europe: Assessment of flexibility requirements. *Energy* **2014**, *69*, 236–246, doi:10.1016/j.energy.2014.02.109. [CrossRef]
11. Pacesila, M.; Burcea, S.G.; Colesca, S.E. Analysis of renewable energies in European Union. *Renew. Sustain. Energy Rev.* **2016**, *56*, 156–170. [CrossRef]
12. Da Silva, R.C.; de Marchi Neto, I.; Seifert, S.S. Electricity supply security and the future role of renewable energy sources in Brazil. *Renew. Sustain. Energy Rev.* **2016**, *59*, 328–341. [CrossRef]
13. What is Energy Security? Available online: https://www.iea.org/topics/energysecurity/whatisenergysecurity/ (accessed on 24 September 2019).
14. Chalvatzis, K.J.; Ioannidis, A. Energy supply security in the EU: Benchmarking diversity and dependence of primary energy. *Appl. Energy* **2017**, *207*, 465–476. [CrossRef]
15. Leonavičius, V.; Genys, D.; Krikštolaitis, R. Public perception of energy security in Lithuania: Between material interest and energy independence. *J. Balt. Stud.* **2018**, *49*, 157–175. [CrossRef]
16. Wang, X.; Palazoglu, A.; El-Farra, N.H. Operational optimization and demand response of hybrid renewable energy systems. *Appl. Energy* **2015**, *143*, 324–335. [CrossRef]
17. Weitemeyer, S.; Kleinhans, D.; Vogt, T.; Agert, C. Integration of Renewable Energy Sources in future power systems: The role of storage. *Renew. Energy* **2015**, *75*, 14–20. [CrossRef]
18. Teng, F.; Mu, Y.; Jia, H.; Wu, J.; Zeng, P.; Strbac, G. Challenges on primary frequency control and potential solution from EVs in the future GB electricity system. *Appl. Energy* **2017**, *194*, 353–362. [CrossRef]

19. Zhang, W.; Fang, K. Controlling active power of wind farms to participate in load frequency control of power systems. *IET Gener. Transm. Distrib.* **2017**, *11*, 2194–2203. [CrossRef]
20. Fernandez-Guillamon, A.; Vigueras-Rodriguez, A.; Molina-Garcia, A. Analysis of power system inertia estimation in high wind power plant integration scenarios. *IET Renew. Power Gener.* **2019**.. [CrossRef]
21. Owusu, P.A.; Asumadu-Sarkodie, S. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**, *3*, 1167990. [CrossRef]
22. Toulabi, M.; Bahrami, S.; Ranjbar, A.M. An Input-to-State Stability Approach to Inertial Frequency Response Analysis of Doubly-Fed Induction Generator-Based Wind Turbines. *IEEE Trans. Energy Convers.* **2017**, *32*, 1418–1431. [CrossRef]
23. Fernández-Guillamón, A.; Villena-Lapaz, J.; Vigueras-Rodríguez, A.; García-Sánchez, T.; Molina-García, Á. An Adaptive Frequency Strategy for Variable Speed Wind Turbines: Application to High Wind Integration Into Power Systems. *Energies* **2018**, *11*, 1436. [CrossRef]
24. Delille, G.; Francois, B.; Malarange, G. Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia. *IEEE Trans. Sustain. Energy* **2012**, *3*, 931–939. [CrossRef]
25. Sakamuri, J.N.; Altin, M.; Hansen, A.D.; Cutululis, N.A. Coordinated frequency control from offshore wind power plants connected to multi terminal DC system considering wind speed variation. *IET Renew. Power Gener.* **2016**, *11*, 1226–1236. [CrossRef]
26. Cardiel-Alvarez, M.A.; Rodriguez-Amenedo, J.L.; Arnaltes, S.; Montilla-DJesus, M.E. Modeling and control of LCCs rectifiers for offshore wind farms connected by HVDC links. *IEEE Trans. Energy Convers.* **2017**, *32*, 1284–1296. [CrossRef]
27. Dreidy, M.; Mokhlis, H.; Mekhilef, S. Inertia response and frequency control techniques for renewable energy sources: A review. *Renew. Sustain. Energy Rev.* **2017**, *69*, 144–155. [CrossRef]
28. Li, Y.; Xu, Z.; Østergaard, J.; Hill, D.J. Coordinated control strategies for offshore wind farm integration via VSCs-HVDC for system frequency support. *IEEE Trans. Energy Convers.* **2017**, *32*, 843–856. [CrossRef]
29. Rodriguez-Amenedo, J.L.; Arnaltes, S.; Cardiel-Alvarez, M.A.; Montilla-DJesus, M. Direct voltage and frequency control of an offshore wind farm connected through LCCs-HVDC link. In Proceedings of the 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, Poland, 11–14 September 2017; pp. 1–10.
30. Fernández-Guillamón, A.; Gómez-Lázaro, E.; Muljadi, E.; Molina-García, Á. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109369. [CrossRef]
31. Deng, Y.Y.; Haigh, M.; Pouwels, W.; Ramaekers, L.; Brandsma, R.; Schimschar, S.; Grözinger, J.; de Jager, D. Quantifying a realistic, worldwide wind and solar electricity supply. *Glob. Environ. Chang.* **2015**, *31*, 239–252. [CrossRef]
32. Thomaidis, N.S.; Santos-Alamillos, F.J.; Pozo-Vázquez, D.; Usaola-García, J. Optimal management of wind and solar energy resources. *Comput. Oper. Res.* **2016**, *66*, 284–291. [CrossRef]
33. Barbosa, L.d.S.N.S.; Bogdanov, D.; Vainikka, P.; Breyer, C. Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America. *PLoS ONE* **2017**, *12*, e0173820. [CrossRef]
34. Shivashankar, S.; Mekhilef, S.; Mokhlis, H.; Karimi, M. Mitigating methods of power fluctuation of photovoltaic (PV) sources—A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1170–1184. [CrossRef]
35. Ren, G.; Liu, J.; Wan, J.; Guo, Y.; Yu, D. Overview of wind power intermittency: Impacts, measurements, and mitigation solutions. *Appl. Energy* **2017**, *204*, 47–65. [CrossRef]
36. Cardozo, C.; van Ackooij, W.; Capely, L. Cutting plane approaches for frequency constrained economic dispatch problems. *Electr. Power Syst. Res.* **2018**, *156*, 54–63. [CrossRef]
37. Snow, M.; Snow, R. The Ascent of Wind Power in Nova Scotia: Pubnico Point Wind Farm. *Int. J. Renew. Energy Sour.* **2018**, *3* , 6–9.
38. GLOBAL WIND REPORT 2018. Available online: https://gwec.net/wp-content/uploads/2019/04/GWEC-Global-Wind-Report-2018.pdf (accessed on 7 October 2019).
39. Esteban, M.D.; Diez, J.J.; López, J.S.; Negro, V. Why offshore wind energy? *Renew. Energy* **2011**, *36*, 444–450. [CrossRef]
40. Gatzert, N.; Kosub, T. Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks. *Renew. Sustain. Energy Rev.* **2016**, *60*, 982–998. [CrossRef]

41. Wind Europe. *Wind in Power: 2016 European Statistics*; Wind Europe: Brussels, Belgium, 2017.
42. Chaudhary, S.K.; Teodorescu, R.; Rodriguez, P. Wind farm grid integration using vsc based hvdc transmission-an overview. In Proceedings of the 2008 IEEE Energy 2030 Conference, Atlanta, GA, USA, 17–18 November 2008; pp. 1–7.
43. Wind Europe. *Wind Energy in Europe: Scenarios for 2030*; Wind Europe: Brussels, Belgium, 2017.
44. Morgan, E.C.; Lackner, M.; Vogel, R.M.; Baise, L.G. Probability distributions for offshore wind speeds. *Energy Convers. Manag.* **2011**, *52*, 15–26. [CrossRef]
45. Pichugina, Y.L.; Banta, R.M.; Brewer, W.A.; Sandberg, S.P.; Hardesty, R.M. Doppler lidar–based wind-profile measurement system for offshore wind-energy and other marine boundary layer applications. *J. Appl. Meteorol. Climatol.* **2012**, *51*, 327–349. [CrossRef]
46. Badger, M.; Badger, J.; Nielsen, M.; Hasager, C.B.; Peña, A. Wind class sampling of satellite SAR imagery for offshore wind resource mapping. *J. Appl. Meteorol. Climatol.* **2010**, *49*, 2474–2491. [CrossRef]
47. Pérez-Collazo, C.; Greaves, D.; Iglesias, G. A review of combined wave and offshore wind energy. *Renew. Sustain. Energy Rev.* **2015**, *42*, 141–153. [CrossRef]
48. AWEA. U.S. Offshore Wind Industry. STATUS UPDATE—OCTOBER 2019. Available online: https://www.awea.org/Awea/media/Resources/Fact%20Sheets/Offshore-Fact-Sheet-Oct-2019.pdf (accessed on 30 October 2019).
49. Dai, J.; Yang, X.; Wen, L. Development of wind power industry in China: A comprehensive assessment. *Renew. Sustain. Energy Rev.* **2018**, *97*, 156–164. [CrossRef]
50. Nagababu, G.; Kachhwaha, S.S.; Savsani, V. Estimation of technical and economic potential of offshore wind along the coast of India. *Energy* **2017**, *138*, 79–91. [CrossRef]
51. Kalmikov, A. Wind power fundamentals. In *Wind Energy Engineering*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 17–24.
52. Kaldellis, J.; Kapsali, M. Shifting towards offshore wind energy—Recent activity and future development. *Energy Policy* **2013**, *53*, 136–148. [CrossRef]
53. Morthorst, P.E.; Kitzing, L. Economics of building and operating offshore wind farms. In *Offshore Wind Farms*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 9–27.
54. GWEC. Global Wind Energy Outlook. 2016. Available online: http://files.gwec.net/register/success/?file=/files/GlobalWindEnergyOutlook2016 (accessed on 11 September 2019).
55. IRENA. Renewable Power Generation Costs in 2018. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf (accessed on 28 October 2019).
56. Kumar, D.; Chatterjee, K. A review of conventional and advanced MPPT algorithms for wind energy systems. *Renew. Sustain. Energy Rev.* **2016**, *55*, 957–970. [CrossRef]
57. Naidu, N.S.; Singh, B. Grid-interfaced DFIG-based variable speed wind energy conversion system with power smoothening. *IEEE Trans. Sustain. Energy* **2016**, *8*, 51–58. [CrossRef]
58. Njiri, J.G.; Soeffker, D. State-of-the-art in wind turbine control: Trends and challenges. *Renew. Sustain. Energy Rev.* **2016**, *60*, 377–393. [CrossRef]
59. Bhukya, J.; Mahajan, V. The controlling of the DFIG based on variable speed wind turbine modeling and simulation. In Proceedings of the IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 4–6 March 2016; pp. 1–6.
60. Yan, R.; Saha, T.K.; Modi, N.; Masood, N.A.; Mosadeghy, M. The combined effects of high penetration of wind and PV on power system frequency response. *Appl. Energy* **2015**, *145*, 320–330. [CrossRef]
61. Liang, X. Emerging power quality challenges due to integration of renewable energy sources. *IEEE Trans. Ind. Appl.* **2016**, *53*, 855–866. [CrossRef]
62. Edrah, M.; Lo, K.L.; Anaya-Lara, O. Impacts of high penetration of DFIG wind turbines on rotor angle stability of power systems. *IEEE Trans. Sustain. Energy* **2015**, *6*, 759–766. [CrossRef]
63. Syahputra, R.; Soesanti, I. DFIG Control Scheme of Wind Power Using ANFIS Method in Electrical Power Grid System. *Int. J. Appl. Eng. Res.* **2016**, *11*, 5256–5262.
64. Ma, Y.; Cao, W.; Yang, L.; Wang, F.F.; Tolbert, L.M. Virtual synchronous generator control of full converter wind turbines with short-term energy storage. *IEEE Trans. Ind. Electron.* **2017**, *64*, 8821–8831. [CrossRef]
65. Artigao, E.; Honrubia-Escribano, A.; Gomez-Lazaro, E. Current signature analysis to monitor DFIG wind turbine generators: A case study. *Renew. Energy* **2018**, *116*, 5–14. [CrossRef]

66. Liserre, M.; Cardenas, R.; Molinas, M.; Rodriguez, J. Overview of multi-MW wind turbines and wind parks. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1081–1095. [CrossRef]
67. Blasco-Gimenez, R.; Añó-Villalba, S.; Rodríguez-D'Derlée, J.; Bernal-Pérez, S.; Morant, F. Connection of Off-Shore Wind Farms Using Diode Based HVDC Links. In *Wind Energy Conversion Systems*; Springer: Cham, Switzerland, 2012; pp. 431–464.
68. Nanou, S.I.; Papathanassiou, S.A. Grid code compatibility of VSCs-HVDC connected offshore wind turbines employing power synchronization control. *IEEE Trans. Power Syst.* **2016**, *31*, 5042–5050. [CrossRef]
69. Ruddy, J.; Meere, R.; O'Donnell, T. Low Frequency AC transmission for offshore wind power: A review. *Renew. Sustain. Energy Rev.* **2016**, *56*, 75–86. [CrossRef]
70. Jallad, J.; Mekhilef, S.; Mokhlis, H. Frequency regulation strategies in grid integrated offshore wind turbines via VSCs-HVDC technology: A review. *Energies* **2017**, *10*, 1244. [CrossRef]
71. Meere, R.; Ruddy, J.; McNamara, P.; O'Donnell, T. Variable AC transmission frequencies for offshore wind farm interconnection. *Renew. Energy* **2017**, *103*, 321–332. [CrossRef]
72. Sivalingam, K.; Sepulveda, M.; Spring, M.; Davies, P. A Review and Methodology Development for Remaining Useful Life Prediction of Offshore Fixed and Floating Wind turbine Power Converter with Digital Twin Technology Perspective. In Proceedings of the 2nd International Conference on Green Energy and Applications (ICGEA), Singapore, 24–26 March 2018; pp. 197–204.
73. Justo, J.J.; Mwasilu, F.; Jung, J.W. Doubly-fed induction generator based wind turbines: A comprehensive review of fault ride-through strategies. *Renew. Sustain. Energy Rev.* **2015**, *45*, 447–467. [CrossRef]
74. Teng, W.; Ding, X.; Zhang, X.; Liu, Y.; Ma, Z. Multi-fault detection and failure analysis of wind turbine gearbox using complex wavelet transform. *Renew. Energy* **2016**, *93*, 591–598. [CrossRef]
75. Wang, L.; Zhang, Z.; Long, H.; Xu, J.; Liu, R. Wind turbine gearbox failure identification with deep neural networks. *IEEE Trans. Ind. Inform.* **2016**, *13*, 1360–1368. [CrossRef]
76. Yang, B.; Jiang, L.; Wang, L.; Yao, W.; Wu, Q. Nonlinear maximum power point tracking control and modal analysis of DFIG based wind turbine. *Int. J. Electr. Power Energy Syst.* **2016**, *74*, 429–436. [CrossRef]
77. Serrano-González, J.; Lacal-Arántegui, R. Technological evolution of onshore wind turbines—A market-based analysis. *Wind Energy* **2016**, *19*, 2171–2187. [CrossRef]
78. Chen, Z.; Guerrero, J.M.; Blaabjerg, F. A review of the state of the art of power electronics for wind turbines. *IEEE Trans. Power Electron.* **2009**, *24*, 1859–1875. [CrossRef]
79. Blaabjerg, F.; Liserre, M.; Ma, K. Power electronics converters for wind turbine systems. *IEEE Trans. Ind. Appl.* **2011**, *48*, 708–719. [CrossRef]
80. Blaabjerg, F.; Ma, K. Future on power electronics for wind turbine systems. *IEEE J. Emerg. Sel. Top. Power Electron.* **2013**, *1*, 139–152. [CrossRef]
81. Wei, Q.; Wu, B.; Xu, D.; Zargari, N.R. A medium-frequency transformer-based wind energy conversion system used for current-source converter-based offshore wind farm. *IEEE Trans. Power Electron.* **2016**, *32*, 248–259. [CrossRef]
82. Hansen, A.D.; Iov, F.; Blaabjerg, F.; Hansen, L.H. Review of contemporary wind turbine concepts and their market penetration. *Wind Eng.* **2004**, *28*, 247–263. [CrossRef]
83. Wind Europe. *Annual Offshore Statistics in 2017*; Wind Europe: Brussels, Belgium, 2018.
84. Wind Europe. *Annual Offshore Statistics in 2018*; Wind Europe: Brussels, Belgium, 2019.
85. Windturbines database. Available online: https://en.wind-turbine-models.com/turbines (accessed on 30 September 2019).
86. Wind Europe. *European Offshore Statistics in 2013*; Wind Europe: Brussels, Belgium, 2014.
87. Equinor—the world's leading floating offshore wind developer. Available online: https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html (accessed on 3 September 2019).
88. Van Eeckhout, B.; Van Hertem, D.; Reza, M.; Srivastava, K.; Belmans, R. Economic comparison of VSCs HVDC and HVAC as transmission system for a 300 MW offshore wind farm. *Eur. Trans. Electr. Power* **2010**, *20*, 661–671. [CrossRef]
89. Bozhko, S.V.; Blasco-Gimenez, R.; Li, R.; Clare, J.C.; Asher, G.M. Control of offshore DFIG-based wind farm grid with line-commutated HVDC connection. *IEEE Trans. Energy Convers.* **2007**, *22*, 71–78. [CrossRef]
90. Perveen, R.; Kishor, N.; Mohanty, S.R. Off-shore wind farm development: Present status and challenges. *Renew. Sustain. Energy Rev.* **2014**, *29*, 780–792. [CrossRef]

91. Li, J.; Zhang, M.; Zhu, J.; Yang, Q.; Zhang, Z.; Yuan, W. Analysis of superconducting magnetic energy storage used in a submarine HVAC cable based offshore wind system. *Energy Procedia* **2015**, *75*, 691–696. [CrossRef]
92. Mitra, P.; Zhang, L.; Harnefors, L. Offshore wind integration to a weak grid by VSCs-HVDC links using power-synchronization control: A case study. *IEEE Trans. Power Deliv.* **2013**, *29*, 453–461. [CrossRef]
93. Reed, G.F.; Al Hassan, H.A.; Korytowski, M.J.; Lewis, P.T.; Grainger, B.M. Comparison of HVAC and HVDC solutions for offshore wind farms with a procedure for system economic evaluation. In Proceedings of the 2013 IEEE Energytech, Cleveland, OH, USA, 21–23 May 2013; pp. 1–7.
94. Guidi, G.; Fosso, O. Investment cost of HVAC cable reactive power compensation off-shore. In Proceedings of the 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), Florence, Italy, 9–12 September 2012; pp. 299–304.
95. Hur, D. Economic considerations underlying the adoption of HVDC and HVAC for the connection of an offshore wind farm in Korea. *J. Electr. Eng. Technol.* **2012**, *7*, 157–162. [CrossRef]
96. Sharma, R.; Rasmussen, T.W.; Jensen, K.H.; Akamatov, V. Modular VSCs converter based HVDC power transmission from offshore wind power plant: Compared to the conventional HVAC system. In Proceedings of the 2010 IEEE Electrical Power & Energy Conference, Halifax, NS, Canada, 25–27 August 2010; pp. 1–6.
97. Chen, H.; Johnson, M.H.; Aliprantis, D.C. Low-frequency AC transmission for offshore wind power. *IEEE Trans. Power Deliv.* **2013**, *28*, 2236–2244. [CrossRef]
98. Negra, N.B.; Todorovic, J.; Ackermann, T. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. *Electr. Power Syst. Res.* **2006**, *76*, 916–927. [CrossRef]
99. Stoutenburg, E.; Jacobson, M. Optimizing offshore transmission links for marine renewable energy farms. In Proceedings of the OCEANS 2010 MTS/IEEE SEATTLE, Seattle, WA, USA, 20–23 September 2010; pp. 1–9.
100. Bresesti, P.; Kling, W.L.; Hendriks, R.L.; Vailati, R. HVDC connection of offshore wind farms to the transmission system. *IEEE Trans. Energy Convers.* **2007**, *22*, 37–43. [CrossRef]
101. Gomis-Bellmunt, O.; Liang, J.; Ekanayake, J.; King, R.; Jenkins, N. Topologies of multiterminal HVDC-VSCs transmission for large offshore wind farms. *Electr. Power Syst. Res.* **2011**, *81*, 271–281. [CrossRef]
102. Legorburu, I.; Johnson, K.R.; Kerr, S.A. Multi-use maritime platforms-North Sea oil and offshore wind: Opportunity and risk. *Ocean Coast. Manag.* **2018**, *160*, 75–85. [CrossRef]
103. Zhang, Y.; Ravishankar, J.; Fletcher, J.; Li, R.; Han, M. Review of modular multilevel converter based multi-terminal HVDC systems for offshore wind power transmission. *Renew. Sustain. Energy Rev.* **2016**, *61*, 572–586. [CrossRef]
104. De Alegría, I.M.; Martín, J.L.; Kortabarria, I.; Andreu, J.; Ereño, P.I. Transmission alternatives for offshore electrical power. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1027–1038. [CrossRef]
105. Rourke, F.O.; Boyle, F.; Reynolds, A. Marine current energy devices: Current status and possible future applications in Ireland. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1026–1036. [CrossRef]
106. Chou, C.J.; Wu, Y.K.; Han, G.Y.; Lee, C.Y. Comparative evaluation of the HVDC and HVAC links integrated in a large offshore wind farm—An actual case study in Taiwan. *IEEE Trans. Ind. Appl.* **2012**, *48*, 1639–1648. [CrossRef]
107. Colmenar-Santos, A.; Perera-Perez, J.; Borge-Diez, D.; dePalacio Rodríguez, C. Offshore wind energy: A review of the current status, challenges and future development in Spain. *Renew. Sustain. Energy Rev.* **2016**, *64*, 1–18. [CrossRef]
108. Erlich, I.; Shewarega, F.; Feltes, C.; Koch, F.W.; Fortmann, J. Offshore wind power generation technologies. *Proc. IEEE* **2013**, *101*, 891–905. [CrossRef]
109. Kucuksari, S.; Erdogan, N.; Cali, U. Impact of Electrical Topology, Capacity Factor and Line Length on Economic Performance of Offshore Wind Investments. *Energies* **2019**, *12*, 3191. [CrossRef]
110. Sellick, R.; Åkerberg, M. Comparison of HVDC Light (VSCs) and HVDC Classic (LCCs) site aspects, for a 500MW 400kV HVDC transmission scheme. In Proceedings of the 10th IET International Conference on AC and DC Power Transmission (ACDC 2012), Birmingham, UK, 4–5 December 2012.
111. Saborío-Romano, O.; Bidadfar, A.; Göksu, Ö.; Zeni, L.; Cutululis, N.A. Power Oscillation Damping from Offshore Wind Farms Connected to HVDC via Diode Rectifiers. *Energies* **2019**, *12*, 3387. [CrossRef]
112. Sau-Bassols, J.; Prieto-Araujo, E.; Galceran-Arellano, S.; Gomis-Bellmunt, O. Operation and control of a Current Source Converter series tapping of an LCCs-HVDC link for integration of Offshore Wind Power Plants. *Electr. Power Syst. Res.* **2016**, *141*, 510–521. [CrossRef]

113. ENTSO-E. STATISTICAL FACTSHEET 2018. 2019. Available online: https://docstore.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2018_web.pdf (accessed on 26 August 2019).
114. Hart, D.W. *Power Electronics*; Tata McGraw-Hill Education: New York, NY, USA, 2011.
115. Oni, O.E.; Davidson, I.E.; Mbangula, K.N. A review of LCCs-HVDC and VSCs-HVDC technologies and applications. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 6–8 June 2016; pp. 1–7.
116. Barnes, M.; Van Hertem, D.; Teeuwsen, S.P.; Callavik, M. HVDC systems in smart grids. *Proc. IEEE* **2017**, *105*, 2082–2098. [CrossRef]
117. Adapa, R. High-wire act: Hvdc technology: The state of the art. *IEEE Power Energy Mag.* **2012**, *10*, 18–29. [CrossRef]
118. Liu, H.; Sun, J. Small-signal stability analysis of offshore wind farms with LCCs HVDC. In Proceedings of the 2013 IEEE Grenoble Conference, Grenoble, France, 16–20 June 2013; pp. 1–8.
119. Liu, H.; Sun, J. Voltage stability and control of offshore wind farms with AC collection and HVDC transmission. *IEEE J. Emerg. Sel. Top. Power Electron.* **2014**, *2*, 1181–1189.
120. Hamlaoui, H.; Francois, B. Interest of storage based STATCOM systems to the power quality enhancement of thyristors based LCCs HVDC links for offshore wind farm. In Proceedings of the 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 20–22 February 2018; pp. 1702–1707.
121. Blasco-Gimenez, R.; Aparicio, N.; Ano-Villalba, S.; Bernal-Perez, S. LCCs-HVDC connection of offshore wind farms with reduced filter banks. *IEEE Trans. Ind. Electron.* **2012**, *60*, 2372–2380. [CrossRef]
122. Callavik, M.; Bahrman, M.; Sandeberg, P. Technology developments and plans to solve operational challenges facilitating the HVDC offshore grid. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–6.
123. Henry, S.; Denis, A.; Panciatici, P. Feasibility study of off-shore HVDC grids. In Proceedings of the IEEE PES General Meeting, Minneapolis, MN, USA, 25–29 July 2010; pp. 1–5.
124. Glasdam, J.; Hjerrild, J.; Kocewiak, Ł.H.; Bak, C.L. Review on multi-level voltage source converter based HVDC technologies for grid connection of large offshore wind farms. In Proceedings of the 2012 IEEE International Conference on Power System Technology (POWERCON), Auckland, New Zealand, 23–26 October 2012; pp. 1–6.
125. Torres-Olguin, R.E.; Molinas, M.; Undeland, T. Offshore wind farm grid integration by VSCs technology with LCCs-based HVDC transmission. *IEEE Trans. Sustain. Energy* **2012**, *3*, 899–907. [CrossRef]
126. Prieto-Araujo, E.; Bianchi, F.D.; Junyent-Ferre, A.; Gomis-Bellmunt, O. Methodology for droop control dynamic analysis of multiterminal VSCs-HVDC grids for offshore wind farms. *IEEE Trans. Power Deliv.* **2011**, *26*, 2476–2485. [CrossRef]
127. Seman, S.; Trinh, N.T.; Zurowski, R.; Kreplin, S. Modeling of the diode-rectifier based HVDC transmission solution for large offshore wind power plants grid access. In Proceedings of the International Workshop on Large-Scale Integration of Wind Power into Power Systems, Vienna, Austria, 15–17 November 2016.
128. Hoffmann, M.; Rathke, C.; Menze, A.; Hemdan, N.G.; Kurrat, M. AC Fault Analysis of DRU-VSCs Hybrid HVDCTopology for Offshore Wind Farm Integration. In Proceedings of the VDE/IEEE Power and Energy Student Summit, Kaiserslautern, Germany, 2–4 July 2018.
129. Ramachandran, R.; Poullain, S.; Benchaib, A.; Bacha, S.; Francois, B. AC Grid Forming by Coordinated Control of Offshore Wind Farm connected to Diode Rectifier based HVDC Link-Review and Assessment of Solutions. In Proceedings of the 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, Latvia, 17–21 September 2018; pp. 1–10.
130. Prignitz, C.; Eckel, H.G.; Achenbach, S.; Augsburger, F.; Schön, A. FixReF: A control strategy for offshore wind farms with different wind turbine types and diode rectifier HVDC transmission. In Proceedings of the 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, BC, Canada, 27–30 June 2016; pp. 1–7.
131. Li, R.; Yu, L.; Xu, L. Offshore AC Fault Protection of Diode Rectifier Unit-Based HVdc System for Wind Energy Transmission. *IEEE Trans. Ind. Electron.* **2018**, *66*, 5289–5299. [CrossRef]
132. Li, R.; Yu, L.; Xu, L. Operation of offshore wind farms connected with DRU-HVDC transmission systems with special consideration of faults. *Glob. Energy Interconnect.* **2018**, *1*, 608–617.

133. Saborío-Romano, O.; Bidadfar, A.; Sakamuri, J.N.; Göksu, Ö.; Cutululis, N.A. Primary Frequency Response from Offshore Wind Farms Connected to HVdc via Diode Rectifiers. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019; pp. 1–6.
134. Cardiel-Alvarez, M.A.; Arnaltes, S.; Rodriguez-Amenedo, J.L.; Nami, A. Decentralized control of offshore wind farms connected to diode-based HVDC links. *IEEE Trans. Energy Convers.* **2018**, *33*, 1233–1241. [CrossRef]
135. Chang, Y.; Cai, X. Hybrid Topology of a Diode-Rectifier-based HVDC System for Offshore Wind Farms. *IEEE J. Emerg. Sel. Top. Power Electron.* **2018**, *7*, 2116–2128. [CrossRef]
136. TYNDP 2018. Available online: https://tyndp.entsoe.eu/ (accessed on 20 September 2019).
137. Koivisto, M.; Gea-Bermudez, J. *NSON-DK Energy System Scenarios—Edition 2*; DTU Wind Energy: Roskilde, Denmark, 2018.
138. Greenpeace; GWEC. Energy [r]evolution. 2015. Available online: https://storage.googleapis.com/planet4-philippines-stateless/2019/05/09ccb4ca-energy-revolution-asean.pdf (accessed on 21 September 2019).
139. U.S. Department of Energy. WindVision: A New Era for Wind Power in the United States. Available online: https://www.energy.gov/sites/prod/files/2015/03/f20/wv_executive_summary_overview_and_key_chapter_findings.pdf (accessed on 29 October 2019).
140. TERI; WWF. The Energy Report—India 100% Renewable Energy by 2050. 2013. Available online: http://awsassets.wwfindia.org/downloads/the_energy_report_india.pdf (accessed on 29 October 2019).
141. IEA; ERI. Technology Roadmap: China Wind Energy Development Roadmap 2050. 2011. Available online: https://www.china.tu-berlin.de/fileadmin/fg57/SS_2012/Umwelt/IEAchina_wind_2050.pdf (accessed on 29 October 2019).
142. China National Renewable Energy Centre. China Wind, Solar and Bioenergy Roadmap 2050. 2014. Available online: https://fch.cl/wp-content/uploads/2015/06/6.4-China-Wind-Solar-and-Bioenergy-Roadmap-2050-Short-Version.pdf (accessed on 29th October 2019).
143. Varela-Vázquez, P.; del Carmen Sánchez-Carreira, M.; Rodil-Marzábal, Ó. A novel systemic approach for analysing offshore wind energy implementation. *J. Clean. Prod.* **2019**, *212*, 1310–1318. [CrossRef]
144. De Vasconcelos, B.R.; Lavoie, J.M. Recent advances in Power-to-X technology for the production of fuels and chemicals. *Front. Chem.* **2019**, *7*, 392. [CrossRef]
145. Sternberg, A.; Bardow, A. Power-to-What?–Environmental assessment of energy storage systems. *Energy Environ. Sci.* **2015**, *8*, 389–400. [CrossRef]
146. Blanco, H.; Faaij, A. A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1049–1086. [CrossRef]
147. Lewandowska-Bernat, A.; Desideri, U. Opportunities of power-to-gas technology in different energy systems architectures. *Appl. Energy* **2018**, *228*, 57–67. [CrossRef]
148. Koj, J.C.; Wulf, C.; Zapp, P. Environmental impacts of power-to-X systems-A review of technological and methodological choices in Life Cycle Assessments. *Renew. Sustain. Energy Rev.* **2019**, *112*, 865–879. [CrossRef]
149. Schnuelle, C.; Thoeming, J.; Wassermann, T.; Thier, P.; von Gleich, A.; Goessling-Reisemann, S. Socio-technical-economic assessment of power-to-X: Potentials and limitations for an integration into the German energy system. *Energy Res. Soc. Sci.* **2019**, *51*, 187–197. [CrossRef]
150. Nastasi, B.; Basso, G.L. Power-to-gas integration in the transition towards future urban energy systems. *Int. J. Hydrogen Energy* **2017**, *42*, 23933–23951. [CrossRef]
151. Bloess, A.; Schill, W.P.; Zerrahn, A. Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. *Appl. Energy* **2018**, *212*, 1611–1626. [CrossRef]
152. Wulf, C.; Linßen, J.; Zapp, P. Review of power-to-gas projects in Europe. *Energy Procedia* **2018**, *155*, 367–378. [CrossRef]
153. Hydrogen and Liquid Electricity Could Become Denmark's next Business Adventure. Available online: https://investindk.com/insights/hydrogen-and-liquid-electricity-could-become-denmarks-next-business-adventure (accessed on 2 October 2019).
154. Pilpola, S.; Lund, P.D. Different flexibility options for better system integration of wind power. *Energy Strategy Rev.* **2019**, *26*, 100368. [CrossRef]
155. Pursiheimo, E.; Holttinen, H.; Koljonen, T. Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. *IET Renew. Power Gener.* **2017**, *11*, 1695–1706. [CrossRef]

156. Hou, P.; Enevoldsen, P.; Eichman, J.; Hu, W.; Jacobson, M.Z.; Chen, Z. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark. *J. Power Sour.* **2017**, *359*, 186–197. [CrossRef]
157. Hosseini, S.E.; Wahid, M.A. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renew. Sustain. Energy Rev.* **2016**, *57*, 850–866. [CrossRef]
158. Loisel, R.; Baranger, L.; Chemouri, N.; Spinu, S.; Pardo, S. Economic evaluation of hybrid off-shore wind power and hydrogen storage system. *Int. J. Hydrogen Energy* **2015**, *40*, 6727–6739. [CrossRef]
159. Schuster, M.; Walther, T. Valuation of combined wind power plant and hydrogen storage: A decision tree approach. In Proceedings of the 2017 14th International Conference on the European Energy Market (EEM), Dresden, Germany, 6–9 June 2017; pp. 1–6.
160. North Sea Wind Power Hub. Available online: https://northseawindpowerhub.eu/ (accessed on 30 August 2019).
161. North Sea Wind Power Hub. Available online: https://www.tennet.eu/our-key-tasks/innovations/north-sea-wind-power-hub/ (accessed on 30 August 2019).
162. North Sea Wind Power Hub. 1. The Challenge. Urgent Action Is Needed to Reach a Low-Carbon Society in Time. Available online: https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_1-TheChallenge.pdf (accessed on 30 August 2019).
163. North Sea Wind Power Hub. 2. The Vision. The Hub-and-Spoke Concept as Modular Infrastructure Block to Scale Up Fast. Available online: https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_2_The-Vision.pdf (accessed on 30 August 2019).
164. North Sea Wind Power Hub. 3. Modular Hub-and-Spoke: Specific Solution Options. Case Studies Have Demonstrated Technical Feasibility. Available online: https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_3-Specific-solution-options.pdf (accessed on 30 August 2019).
165. North Sea Wind Power Hub. 4. The Benefits. The Modular Hub-and-Spoke Concept Has Substantial Societal Benefits and thus the Potential to Incentivise All Involved Stakeholders. Available online: https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_4-The-benefits.pdf (accessed on 30 August 2019).
166. North Sea Wind Power Hub. 5. Requirements to Develop. Ensure Industry Can Progress. Available online: https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_5-Requirements-to-develop.pdf (accessed on 30 August 2019).
167. Parra, D.; Norman, S.A.; Walker, G.S.; Gillott, M. Optimum community energy storage for renewable energy and demand load management. *Appl. Energy* **2017**, *200*, 358–369. [CrossRef]
168. Wang, Z.; Carriveau, R.; Ting, D.S.K.; Xiong, W.; Wang, Z. A review of marine renewable energy storage. *Int. J. Energy Res.* **2019**, *43*, 6108–6150. [CrossRef]
169. Shatnawi, M.; Al Qaydi, N.; Aljaberi, N.; Aljaberi, M. Hydrogen-Based Energy Storage Systems: A Review. In Proceedings of the 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), Paris, France, 14–17 October 2018; pp. 697–700.
170. Subsea Energy Storage. Available online: https://www.gceocean.no/news/posts/2018/september/subsea-energy-storage/ (accessed on 5th September 2019).
171. HYON Joins Offshore Wind-to-Hydrogen Project. Available online: https://www.offshorewind.biz/2019/06/07/hyon-joins-offshore-wind-to-hydrogen-project/ (accessed on 3rd September 2019).
172. Deep Purple. Available online: https://energyvalley.no/wp-content/uploads/2019/04/Deep-Purple-.pdf (accessed on 3rd September 2019).
173. 'Deep Purple' Seabed Hydrogen Storage for Offshore Wind Plan. Available online: https://www.rechargenews.com/wind/1802829/deep-purple-seabed-hydrogen-storage-for-offshore-wind-plan (accessed on 3rd September 2019).
174. Katsaprakakis, D. Energy storage for offshore wind farms. In *Offshore Wind Farms*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 459–493.
175. Venkataramani, G.; Parankusam, P.; Ramalingam, V.; Wang, J. A review on compressed air energy storage—A pathway for smart grid and polygeneration. *Renew. Sustain. Energy Rev.* **2016**, *62*, 895–907. [CrossRef]
176. Bouman, E.A.; Øberg, M.M.; Hertwich, E.G. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). *Energy* **2016**, *95*, 91–98. [CrossRef]

177. Li, B.; DeCarolis, J.F. A techno-economic assessment of offshore wind coupled to offshore compressed air energy storage. *Appl. Energy* **2015**, *155*, 315–322. [CrossRef]
178. FLASC. Available online: https://www.offshoreenergystorage.com/ (accessed on 4 September 2019).
179. FLASC. Available online: https://www.offshoreenergystorage.com/multi-system-integration/ (accessed on 4 September 2019).
180. FLASC. Available online: https://www.offshoreenergystorage.com/flasc-working-principle/ (accessed on 4 September 2019).
181. FLASC Prototype Official Launch. Available online: https://www.offshoreenergystorage.com/flasc-prototype-official-launch/ (accessed on 4 September 2019).
182. FLASC 1st Generation Prototype Testing Completed. Available online: https://www.offshoreenergystorage.com/flasc-1st-generation-prototype-testing-completed/ (accessed on 4th September 2019).