North Sea Offshore Network and Energy Storage for Large Scale Integration of Renewables

Ole Christian Spro [*]
SINTEF Energy Research
Sem Sælandsvei 11, 7034 Trondheim, Norway
Raymundo E. Torres-Olguin [†]
SINTEF Energy Research
Sem Sælandsvei 11, 7034 Trondheim, Norway
Magnus Korpås [◊]
Dept. of Electric Power Engineering, Norwegian University of Science and Technology (NTNU)
O.S. Bragstads plass 2E, 7034 Trondheim, Norway

Abstract

This review investigates different aspects of the realization of a North Sea offshore grid. The North Sea region has several characteristics that make large-scale integration of renewable energy sources attractive, such as large wind resources and huge hydro reservoirs in the North. A meshed offshore grid with underwater storage can contribute to facilitate sufficient flexibility in the system. The technical review reveals some aspects that need more research, particularly regarding the protection schemes. Furthermore, offshore storage solutions are under development. However, most other aspects are covered by readily available solutions. The greatest challenges seem to lie within standardization, cost-benefit sharing and harmonization of regulatory regimes of the surrounding countries. Nevertheless, several studies have shown highly promising economic benefits of establishing an offshore grid in the North Sea compared to traditional planning of point-to-point connections only.

Keywords: offshore grid, HVDC, grid integration, renewable, energy storage, North Sea

1 Introduction

The integration of renewable power generation implies new challenging issues for the grid such as variability of energy input, frequency response, system power balancing and power market design. Moreover, renewable resources are often located far from the load centers. For future scenarios new transmission infrastructure and energy storage is needed. Consequently, the grid will be more flexible and the security of supply will be ensured. Depending on the grid layout, distance from load centers and geography, few power grids today will support renewable integration above 10%-30% without an elevated risk of outages [1-4]. To increase the renewable penetration either grid extensions or storage should be added to the system. Optimally, a combination of the two are implemented [4]. The North Sea region could very well be a first mover towards integrated grid and storage planning for high renewable penetration levels. The grid will connect the Northern European mainland, the UK and Scandinavia, with the goals of:

- Harvesting offshore wind
- Interconnect Europe's energy markets to enhance security, stabilize prices and increase cost efficiency
- Provide large scale hydro balancing power to markets with high penetration of variable renewable production
- Implement deep-water energy storage to balance fluctuations

In addition, the offshore grid can connect to energy consuming facilities in the North Sea, such as oil and gas platform at the Norwegian sector, and thus reduce regional CO_2 emissions further. For reference, the total emission for the power generation of the Norwegian oil and gas sector equaled more than 9 million tons CO2-eqvuivalents for 2010. The power comes mainly from open cycle gas turbines with an average efficiency of approximately 33%, about half of what a modern onshore gas plant can achieve today [5].

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[*] Research Scientist, corresponding author, OleChristian.Spro@sintef.no, +47 92446028, Sem Sælandsvei 11, 7034 Trondheim, Norway
[†] Research Scientist
[◊] Professor

2 Possibilities and synergies of a North Sea offshore grid

Several scenarios have been developed the last years which indicates a large potential for offshore wind development in the medium term. Capacity estimates for 2030, originally taken from the Trade Wind project [6], shows that 94.6 GW installed wind power capacity in the North Sea by 2030 could be possible. The total capacity is divided into 3.0 GW in Belgium, 5.6 GW in Denmark, 25.4 GW in Germany, 43.3 MW in UK, 12.0 GW in the Netherlands and 5.4 MW in Norway. To make use of this huge potential in the North Sea there is a need for new transmission and balance capacity.

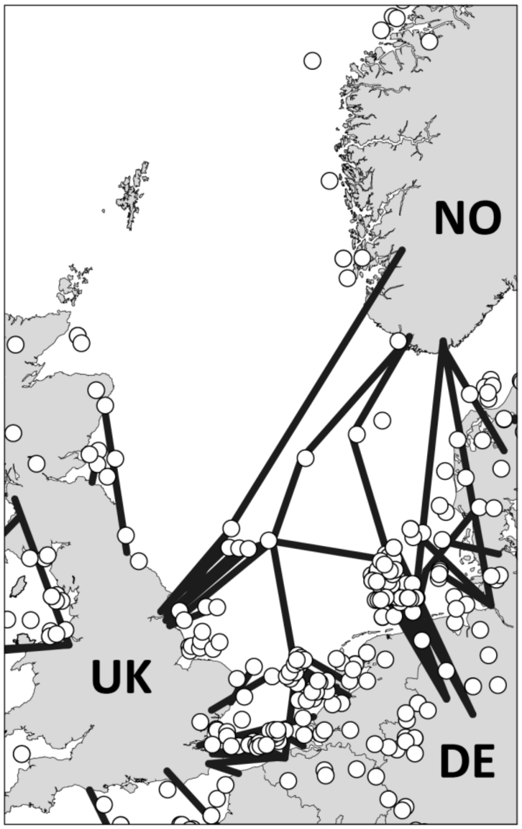

Figure 1. A meshed grid layout for a future North Sea offshore grid. Lines indicate cables, white dots represent current or future wind farms.

To construct the required long term storage capacity the northern European system will need on a long-term basis, would be a huge and expensive endeavor. As a natural first step, researchers are looking into using Norway's hydro power to balance out variable renewable sources. The CEDREN HydroBalance project has found the balance capacity potential of southern parts of Norway to be at least 20GW [7]. Using this resource in collaboration with neighboring countries could unlock a big portion of the renewable potential. Such a solution can be to be cost-effective and possibly the cheapest large-scale solution available [6]. Depending on how this large dispatchable source is used in the energy grid, there are different estimates on how much new renewable capacity could be added. The hydro power can be used to cover up the gap between the load and generation on days without wind or sun. A study from IEA estimates that Europe needs about 100GW of new dispatchable capacity between 2016-2035 to sustain the grid reliability while supporting the 250 GW increase in renewable capacity [8]. The hydro power could therefore cover a fifth of this capacity demand/requirement. Yet, the time period where there is a minimum production from renewables is a small fraction of the year. For the remaining time, the hydro power could exploit its inherent high flexibility as reserve capacity to counter imbalances in wind production due to forecasting error. Forecasting error depends on many factors, which will not be covered here. Studies indicate that the 20GW hydro capacity could cover the reserve requirements for 60-250GW of new wind capacity depending on forecasting error and grid reliability level [9, 10].

Out of the 20 GW additional capacity, the main scenario in the report looks at an expansion of 11.2 GW in total, from which 5.2 GW is new pumped hydro power and 6.0GW is new traditional hydro capacity. Further development of existing and new sites could increase the total power to 20GW. A survey among different Norwegian stakeholders shows the will and interest in using Norway as a balance power in the Northern Sea area. Yet, concern was expressed on the lack of a national policy and needed regulations. Without a national strategy the risk is perceived to be too high to start initiatives on planning and building export balance power for future offshore grid scenarios [6].

Due to the expected renewable increase in the European area, large grid investments are being planned. Three reports on grid expansion have been investigated from European Climate Foundation (ECF), Eurelectric, and European Network of Transmission System Operators for Electricity (ENTSO-E) [6]. Special attention is directed towards inter-country connection. The 10-year development plan from ENTSO-E states an expected 10,500 km new HVDC inland or subsea cables will be built for the pan-European area. The subsea cables represent a market of 23 billion Euros. Further, it is stated that the North Sea offshore grid "is expected to be profitable on the long-term." ["Norwegian Hydropower balancing needs" 6]. Still, investors must be found for such a project. Normally, infrastructure projects of this magnitude are at least co-financed by governments.

3 Availability of offshore network components

3.1 Converters and transmission

Due to intrinsic characteristics regarding reactive power consumption, HVAC cables have quite stringent distance limitations. Hence, HVAC is unsuited for large scale use in offshore grids. HVDC is able to overcome the challenges of long-distance transmission. Therefore, for offshore applications where distances are substantial, HVDC is the most attractive solution in terms of investment and operating costs. In fact, HVDC transmission distance is only limited by the cost and the conduction losses of the cable. HVDC has low transmission losses, but power losses in the DC stations are higher than for equivalent AC systems. An important advantage is that HVDC provides full power flow control [11].

For HVDC grids there are two competing converter technologies, namely the current source converter (CSC) and the voltage source converter (VSC). Line commutated converter (LCC) is a CSC technology suitable for the transmission of bulk power. Its reliability and availability has been demonstrated for many years on land installations [12]. However, the LLC has certain drawbacks in large filtering needs, increased footprint and operational issues [13]. The VSC is advantageous over the CSC regarding these issues. For this reason VSC technology is often the preferred choice for an offshore grid [14]. Still, it is uncertain if the future offshore grid will only consist of a single converter technology or if they will coexist.

The main topologies of VSC can be classified as follows: Two-level VSC, Three-level VSC and Modular multi-level VSC (MMC) [15, 16]. The MMC is the most recent HVDC solution and to some extent can be considered the state-of-the-art topology for high-power and high-voltage applications. The MMC reduces power losses and reduces the harmonic content in the voltage and current waveforms [17].

The control systems for LLC and VSC converters have been thoroughly studied over the years. An overview of the control of an LLC is found in [18] with further reading found in [19]. As for VSC control the most common method is vector control. Relevant aspects of VSC vector control and HVDC systems can be found in [20, 21]. The control of the MMC converter is a reasonably new area of research and improvements are still being made. Still, the high level control of a MMC is similar to the VSC and can be viewed to operate largely in the same manner.

Examples of realized HVDC projects, cost estimate data and further information about offshore transmission technology can be found in an ENTSO-E report made by the NSCOGI (North Seas Countries' Offshore Grid Initiative) [22].

3.2 Control system for multi terminal HVDC (MT-HVDC) systems

In the operation of MT-HVDC system, one of the most critical issues is the dependency between voltage control and power balance [23]. The power injections in DC grids are completely regulated by the power converters. However, the transferred power of each line cannot be controlled directly, but is rather determined by the voltage at the nodes. Thus congestions may occur in a DC grid. Precise and automated control of node voltages enables possibilities for power balancing between different converters. Several methodologies to balance the power and control the voltage have been studied in the literature. There are two main control philosophies: centralized or distributed approach.

Centralized control includes master-slave control (fig 2a) and voltage-margin control (fig 2b), and are considered to be easy to implement. In master-slave control, the master node, also known as the slack bus, is responsible for maintaining the DC voltage at its own node. The other nodes operate as constant power nodes. To ensure operation within the technical limits of the converter, the master node must be oversized. Also, the system reliability depends heavily on the master node or the fast communication between nodes. The result is a vulnerable system. Many of these aspects are also true for voltage-margin control. Thus, the easy implementation of centralized systems comes at a cost of reliability and oversizing [21, 24].

For the philosophy of distributed voltage control in a MTDC system, each terminal is assigned a linear relationship between its DC voltage and the power flowing through its terminals (fig 2c&d). This is more known as droop control. In this way, the terminals share the task of maintaining the system voltage as well as the duty of instantaneous power balancing in the power grid. Further, the power transfer for the individual lines is controlled through changing the respective droop constants offset of the converters [25]. Additionally, with this topology there is no longer a need for fast communication between nodes as the control is based on local measurements. In conclusion, the distributed control can still control the power flow while providing higher system reliability compared to a centralized control system. Figure 2 shows PV characteristics for each voltage and power control described above, including a modification of the droop control.

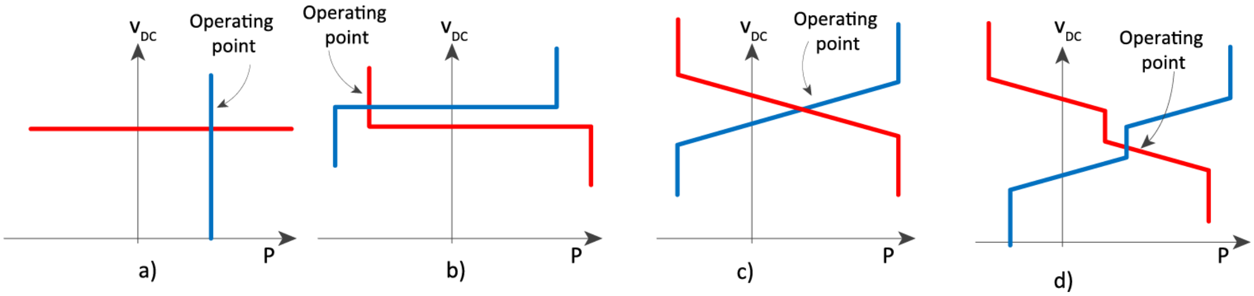

Figure 2. P-V characteristics of voltage and power control methods for multi terminal DC grids. a) master/slave mode b) voltage margin control c) DC droop control d) dead-band droop control

3.3 Protection system

DC power system protections are still under development. Moreover, the use of VSCs in offshore grids represents a challenge since VSCs are vulnerable to DC faults. This is due to their inherent antiparallel diodes. Undoubtedly, the protection system is one of the major challenges in the application of the DC grids [26]. A new protection scheme for DC grids must be developed due to the more demanding protection system requirements compared to AC. The response must be faster since DC transmission lines have very small series impedances which are unable to effectively limit the rise time of the fault current. In MT-DC systems, the protection needs a high selectivity since the DC voltage not only drops in the transmission line where the fault occurs, but also in the rest of the lines. DC grids have small series impedances which make them unable to limit the rise time of the DC current when the voltage collapses. If the fault occurs close to one of the converters, it is difficult to identify which protection unit that must be deployed since there will be over-currents with similar magnitudes within the MT-DC system. Preferably, fault location methods must be based on local measurements [27]. Protection system must therefore be able to identify and isolate only the faulted DC line. However, detection methods typical for AC systems may not be suitable for DC grids.

Most of the research in DC protection has been done in the development of high-voltage DC circuit breakers. The development of DC breakers has been a great challenge due to the demanding requirements. The breaker must have a fast response, create a zero-crossing to interrupt the current, dissipate a large amount of energy, and withstand the voltage response of the system after the interruption. There are three types of DC circuit breakers: resonant-based circuit breakers, solid-state-based circuit breakers, and the recently introduced hybrid DC breaker. [28-32]. Of the three, the hybrid breaker shows the most promising performance. Figure 3 shows a schematic of the hybrid DC breaker.

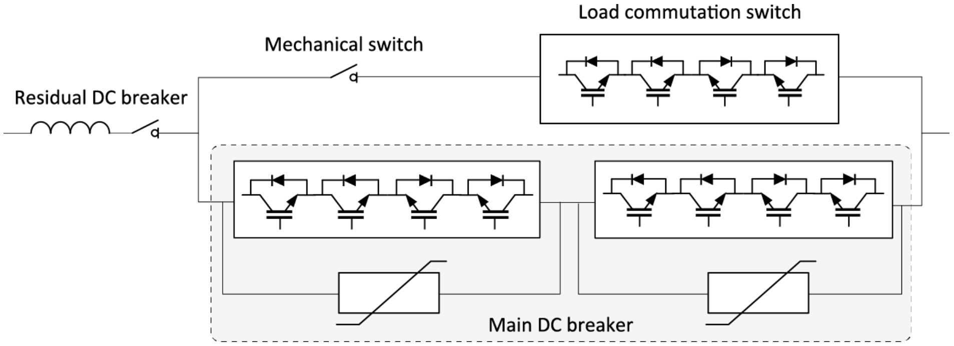

Figure 3. Schematic showing the parts that make up a hybrid DC breaker.

3.4 Cables

Nowadays, there are three main types of DC cables available in the market: self-contained fluid filled cables (SCFF), mass-impregnated cables (MI), and extruded insulation cables (XLPE). The extruded cables, which use cross-linked polyethylene as an insulator, are the most attractive solution for several reasons. XPLE cables are lighter, have smaller banding radius, and do not need an oil duct system. XPLE cables are available up to ±320 kV and 900 MW [33]. XPLE cables are normally used for VSC-based HVDC. In the Cigré model it is proposed to use XPLE cables up to ±400 kV and 1500 MW. A new generation HVDC transmission system with XLPE cables operating at up to 525kV and 2600MW power level was launched in the summer of 2014. The evolution trend of XLPE DC cables is shown in table 1 [34].

Table 1. Development in XLPE cable technology showing a significant increase in capacity over the last two decades.

Year	1997	2000	2001	2004	2010	2014
Max. voltage [kV]	10	80	150	150	320	525
Max. Power [MW]	3	60	220	350	800	2600

However, the future North Sea Offshore Network may contain LCC-based HVDC for which the XPLE cables cannot be used. Hence, SCFF cables and MI cables should be considered. SCFF cables are commercially available up to 600 kV [35]. MI cables are available up to 500 kV and 1000 MW.

3.5 DC transformers

Similar to the AC grid, an offshore DC grid is expected to grow organically over a long time frame. To allow for different DC voltages operating in the offshore grid, DC transformers must be developed. DC-DC converters topologies can be effectively classified in two groups: non-isolated DC-DC converters and isolated DC-DC converters, of which the isolated topology would be the most relevant for an HVDC grids [36, 37]. Availability on the market of DC-DC converters for high power applications as standard products is rather limited. In the literature, several prototypes have been presented spanning from tens of kWs to a few MWs and with an AC operating frequency in the kHz range using several topologies [36, 38-42].

3.6 Offshore Platforms

Offshore HVDC converters and associated equipment require offshore platform to house them. There are few examples of HVDC equipment on an offshore platform. For instance, Troll-A, which is a gas and drilling platform, and Borwin Alpha, the first HVDC station of the world installed on an offshore platform. In regards to foundation, installation and maintenance, the offshore wind industry is leading the way. It is expected that the development within the offshore wind industry will develop the needed solutions for future offshore platforms for the North Sea offshore grid.

3.7 Offshore energy storage

Even though balance power from mainland Norway is a considerable addition to the Northern European system, it cannot cover the whole demand. Offshore storage solutions can make up a large contribution to the North Sea offshore grid. Traditionally, onshore pumped storage and compressed air projects can experience long lead times due to public acceptation and/or long regulatory processes (e.g. environmental impact studies). Offshore solutions are expected to outperform the onshore counterpart on these subjects.

The North Sea offshore grid will be a large-scale system with numerous connected wind farms connected to multiple countries. Such a system should only focus on large scale storage. However the storage time will be limited by the cost of the system. While hydro power can provide up to seasonal storage, pumped storage projects traditionally provides storage for shorter time spans.

Large-scale energy storage needs technologies capable of providing high power for long duration at low cost. Consequently, the only suitable available technologies are compressed air energy storage (CAES) and hydroelectric storage [43]. Although some emerging battery technologies may provide energy balancing services as well, typical system capacities and storage sizes are an order of magnitude smaller than above mentioned storage systems with significantly higher capital costs [44]. The most important requirement for offshore energy storage is the immense magnitude of stored energy required to transform waste intermittent wind resources to a constantly available power supply.

CAES systems could be placed offshore, utilizing underground formations, sub-sea tanks or even depleted oil reservoirs as their storage reservoirs. The turbine house could be situated above sea level while a riser system would connect it to the sub-sea well; much like the oil industry does today. The turbine house at sea level would facilitate maintenance. One reference shows that CAES might be price competitive with hydro storage already today [44]. Another promising fact about CAES is that since summer 2014, a Canadian company has been running the world's first underwater CAES prototype outside the city of Toronto. In addition, an agreement is already in place to sell the commercialized version to the grid operator on Aruba. This presently makes CAES the most mature offshore storage technology.

Several concepts exist for placing pumped hydro storage offshore. In 2007 DNV GL published a concept called the energy island, which is an offshore pumped storage plant in shallow waters. Both SubHydro and MIT have developed concepts of placing large tanks equipped with turbines on the sea bed for pumped storage operation [45, 46]. Regardless of the tanks being vented or not, the turbines produce energy by letting water in to the tanks and energy is stored by pumping the water out. Modern PHS usually has a round-trip efficiency of above 80%, which is higher than CAES solutions. Still, larger prototypes are needed to validate these concepts.

There is a large need for more research on offshore storage, particularly on the system level. Present studies have focused on optimal grid layout for the North Sea grid. However, these investigations have been without looking at suitable deployment of offshore storage solutions. Thus, storage placing, storage sizing, control strategy and capacity needs are currently unknown. For future scenarios, the deployment of offshore storage solutions can be considered to be in competition with onshore storage solutions or flexible generation capacities. So deployment will happen only if the return on investment for offshore storage is larger than the alternatives. Going offshore often results in added costs, yet if the need for storage becomes significant in the future then subsidies or regulation could favor offshore storage solutions. E.g. lack of suitable onshore area could force projects to go offshore.

4 Standardization and harmonization between regulation, grid codes and markets

Nowadays each HVDC system has been bespoke to maximize the investment of the shareholders since all connections are point-to-point configuration. So, the need for standardization has been postponed. The need for standardization is emphasized by several actors. [14, 47].

This is especially important for the voltage level. In HVDC systems, DC voltage level is the most important parameter to be considered for standardization since two converters could be connected only if their DC voltages are slightly different. As in AC systems, several levels might be possible. However, this implies the use of DC transformers for converting from one level to another. This will lead to more power losses and add extra installation cost. Further, a certain degree of standardization should be made for control, protection, and communication systems. This approach will allow for different manufactures to develop and supply solutions in competition, which would lower costs. At the same time, the different solutions would be able to operate together without unwanted oscillations or other operational issues.

The realization of a meshed offshore grid in the North Sea implies that the surrounding countries are able to coordinate infrastructure development, which will require a high level of cooperation between all the parties involved. Several previous analyses have shown that an offshore grid in the North Sea could be economically beneficial compared to point-to-point connections only. However, the lack of a regulatory regime facilitating the development of an offshore grid with offshore renewable projects in the North Sea have been identified as a main obstacle in several studies, such as the EU-projects OffshoreGrid [48] and WindSpeed [49].

Another substantial challenge for offshore grids is the connection between different European markets for electricity exchange. A lack of coordination between the current, different market structures will constitute a barrier for an optimal exchange of electricity between the North Sea area and continental Europe. Additionally, a meshed offshore grid based on DC will introduce new issues from a market point of view, since the power flow to/from the different landfall points are controlled by the respective converter stations.

The NSCOGI group (North Sea Countries Offshore Grid Initiative) published their reports on grid, regulatory and markets barriers in Dec. [50]. NSCOGI emphasize that international cooperation will crucial to realize offshore grid developments, and that the differences in planning regimes are difficult but not impossible to overcome.

5 Concluding Remarks

The North Sea region has several characteristics that make large-scale integration of renewable energy sources attractive, such as high offshore wind speeds and huge hydro reservoirs in the North. A meshed offshore grid with underwater storage can contribute to facilitate sufficient flexibility in the system, but challenges remain with respect to technology availability, standardization, cost-benefit sharing and harmonization of regulatory regimes of the surrounding countries. Nevertheless, several studies have shown highly promising economic benefits of offshore grids in the North Sea compared to traditional planning of point-to-point connections only.

Future works should include techno-economical evaluations of different North Sea offshore grid and storage opportunities to provide infrastructure and balancing for high penetration levels of renewable energy in Europe.

Table 2. Overview of reviewed components for a future North Sea offshore grid. Each component group is rated according to the EU H2020 programme definition of Technology Readiness Level (TRL) after the authors' own views.

Offshore grid component	Approximate TRL (1-9)	Authors' remarks
Converters	8	LLC and VSC technology is a mature technology, and commercial products are available also for high voltage levels. MMC converters are commercialized while being developed further. The EU funded project, *Best Paths*, will by 2019 verify the operation of multi terminal HVDC nets with MMCs with real lab experimentation. However, there is little operational experience of converters offshore.
MT-HVDC control system	1-9	Multi-terminal systems are currently in operation in the world, some with long operating experience. Again there is no practical experience with offshore systems. Research continues to identify control concepts. The EU funded project, *Best Paths*, (see converters comment) also aim at verifying the operation of large systems with different technology suppliers.
Protection system	1-6	Prototypes of DC breakers have been verified and are offered by commercial entities. Still, many aspects of the protection scheme are not yet solved, e.g. fault detection and measurement deployment strategies. EU funded project, *ProOfGrids*, is one of the large research efforts targeting HVDC protection schemes. Yet there is room for more research effort on this field.
Cables	9	Three different cable technologies exist and are available commercially, all of which have been deployed and operated for long periods of time. With current development progress suitable technology for the offshore grid is already available or will be available in near future.
DC transformers	4	A few prototypes have been built in laboratories up to the MW class. Higher ratings and commercialization of the technology is required for future offshore grid needs.
Offshore platforms	8-9	Examples exist of offshore platforms carrying converter stations. Some cost reduction may be realized through the current and future activity in the offshore wind industry.
Offshore storage	1-7	An underwater CAES prototype system is currently operating in a real application situation. However, it is uncertain if that technology is suitable for the North Sea. Several concepts exist for pumped storage, yet no there are no known prototypes. More research is needed on the need and value of adding offshore storage to the North Sea offshore grid, as well as developing the concepts.

Acknowledgements

This article is in a large degree based on information from the SINTEF projects NSON (grant number 228981/E20) and HydroBalance (CEDREN), both of which receive partial funding from the Norwegian Research Council.

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