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Review

Energy Storage Solutions for Offshore Applications

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Abstract: Increased renewable energy production and storage is a key pillar of net-zero emission. The expected growth in the exploitation of offshore renewable energy sources, e.g., wind, provides an opportunity for decarbonising offshore assets and mitigating anthropogenic climate change, which requires developing and using efficient and reliable energy storage solutions offshore. The present work reviews energy storage systems with a potential for offshore environments and discusses the opportunities for their deployment. The capabilities of the storage solutions are examined and mapped based on the available literature. Selected technologies with the largest potential for offshore deployment are thoroughly analysed. A landscape of technologies for both short- and long-term storage is presented as an opportunity to repurpose offshore assets that are difficult to decarbonise.

Keywords: energy storage; decarbonisation; offshore; batteries; hydrogen; ammonia; CAES; flywheel; supercapacitor

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1. Introduction

Greenhouse gas emission is among the leading causes of anthropogenic climate change. Offshore oil and gas extraction was responsible for 26.7% of the total Norwegian greenhouse gas emissions in 2020 [1]; 85% of the emissions was generated by gas turbines on platforms [2]. The increasing focus on sustainability in recent years promotes the uptake of renewable energy, such as offshore wind, to limit such emissions. The design and implementation of innovative energy-efficient technologies exploiting renewable sources are critical issues towards the transition to a sustainable future.

The benefits of developing offshore energy storage solutions are not limited to the decarbonisation of the oil and gas industry. The shipping industry presents the opportunity for energy generation and consumption offshore (e.g., in the form of hydrogen or ammonia), locally generated by offshore renewable energy sources (RES). The expected deployment at scale of offshore renewable generation, in addition to the need for security of supply over the seasons, calls for large-scale, safe storage. Such storage could be provided by offshore reservoirs underground. The possibility of re-using such assets for energy storage is valuable and minimally impactful on land use.

Offshore-produced renewable energy provides opportunities to reduce gas consumption in the turbines and emissions from oil platforms by replacing the need to burn natural gas for electricity generation. Further connection to renewables produced in the vicinity may reduce the investment costs. Such an approach would leverage existing plans of, for example, offshore wind farms, and remove expensive transmission links to the shore. Along with this perspective, several challenges can be identified, ranging from cheap and durable component manufacturing to advanced control strategies. The overview of technology readiness level (TRL), developing trends, power and scaling potential for various emerging solutions have been discussed in Ref [3].

Solar and wind RES exhibit a random behaviour with multiscale dynamics, ranging from seconds to yearly patterns. They also include seasonal and non-stationary phenomena. The stability of the current electricity supply, which relies on controlling the gas influx into the turbines to match the electricity demand in the platform, cannot be mimicked by RES. Given the required balance between power generation and consumption, a large penetration of RES introduces significant challenges.

Storage systems provide a necessary support service for reliable grid operations when a significant penetration of RES is achieved [4]. To date, no large-scale alternative for seasonal storage is available, and power-to-gas conversion seems to be the most promising technology [5]. This reality creates a need to deploy long- and short-term energy storage systems (ESS) on site, as illustrated in Figure 1. The inclusion of these novel configurations into existing offshore facilities is not straightforward. Offshore systems are often isolated from the mainland grid and, hence, are highly sensitive to disturbances that compromise maintaining the power, voltage and frequency balances.

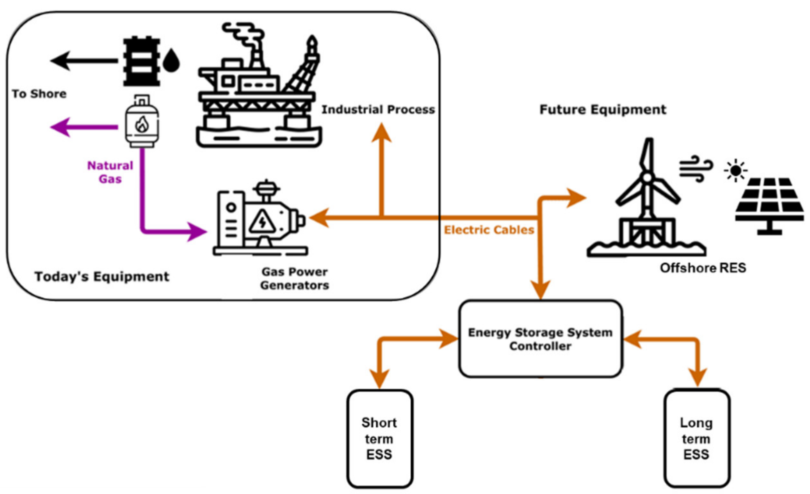

Figure 1. Integration of an offshore storage system into an oil and gas platform.

ESS are currently not widely deployed offshore. The state of the art related to offshore assets shows limited results, since the thematic had not captured enough interest until recently. Such lack of interest is due mainly to the narrative that the economy makes it more advantageous to deploy ESS on land. The preferred energy storage option currently involves large-scale battery parks installed onshore. However, the offshore deployment of RES and related ESS has received increasing attention driven by the constraints put on the land by the broad deployment of renewables. Such constraints include (i) the need for geographical proximity between energy storage and large urban areas often located near water basins and (ii) the environmental impact of large installations on landscapes.

Offshore energy storage provides the opportunity to ensure a large-scale, secure supply of energy. A rapid technological advance is needed to enable fossil-fuel-free offshore operation within the time constraints imposed by the global climate agreements and domestic strategies [6]. Many challenges need to be overcome for a swift uptake of RES offshore. The first step, which is analysed in this paper, is to ensure continuous operation of offshore assets completely emissions free. Although a deep system integration requires a thorough assessment of each case, some common ground can be established.

This paper aims to cover the literature gaps in the area by proposing a methodology to assess energy storage technologies viable for offshore applications. The work intends to be a steppingstone towards deploying large-scale energy storage solutions. The solutions could also be used on land to improve energy availability off-grid and the security of supply; thus, the work has value in a larger context than offshore. The remainder of the manuscript is structured in four sections: Section 2 outlines the methodology used; Section 3 provides a thorough overview of the state of the art; the potential of various energy solutions based on two scenarios (one including 40% renewable penetration and one more targeting 100%) is assessed in Section 4; concluding remarks are put forward in Section 5.

2. Methods

The methodology adopted to identify promising energy storage solutions for offshore applications is based on identifying energy storage requirements, performance, technologies and potential use in practical scenarios.

2.1. Offshore Energy Storage Requirements

Offshore energy storage presents several specificities compared to onshore, primarily referring to the remoteness of the fields and the limiting or non-existing connection to energy grids. The essential requirements that offshore facilities pose to system architectures were identified here based on a dialogue with relevant stakeholders. More specifically:

1. The maximum power required per platform is often in the order of tens of MWs (30–60 MW) rather than hundreds of MWs of the conventional land-based storage systems.
2. Space and weight constraints onboard are challenging.
3. Offshore installations and their load flexibility tend to be use-case specific and sometimes more challenging to predict; hence, it is difficult to identify a one-fits-all approach. Such demanding predictability is due to the large variety of offshore assets (e.g., production units typically have a lower degree of flexibility than drilling assets) and the lower margin for load aggregation.
4. Offshore assets must include features such as black-start, continuous voltage support and frequency regulation.
5. Due to the high operational costs, offshore energy storage technologies need to be sturdier and less maintenance intensive than their onshore counterparts.
6. Seasonal storage is necessary if the renewable energy supply does not match yearly demand.

2.2. Definition of the Key Performance Indicators (KPI)

Eleven KPIs, of qualitative and quantitative nature, were proposed to reflect the unique challenges that offshore storage presents. The relevance of the KPIs was ensured by discussion and prioritisation from industry experts within the Low-Emission Research Centre [7].

For ease of comparison among the technologies, all KPIs were scaled from 1 to 10, with 10 corresponding to the best performance. The range is linear for all KPIs, except for the Capacity, where a logarithmic range is adopted due to the intrinsically large size of underground stores compared to most other technologies. The KPIs are described in Table 1.

Table 1. Description of the KPIs.

KPI	Type	Description	Scale, 1–10
Mass energy density (Wh/kg)	Quant.	Amount of energy stored in a kg of storage solution.	1: ≤*5* 10: ≥*30,000*
Energy Capacity per footprint (kWh/m^2)	Quant.	Energy content of a given square metre of an energy storage solution, including the additional equipment needed to generate,	1: ≤*2* 10: ≥*195*

		store and reconvert the energy in a usable form.	
Discharge duration	Quant.	Time of discharge of a technology at full rated capacity.	1: *seconds*, 4: *minutes* 7: *hours*, 10: *months*
Response time	Quant.	The time it takes for a system to provide energy at its full rated power.	1: *hours*, 5: *minutes*, 8: *seconds*, 10: *milliseconds*
Capacity (MW)	Quant.	Maximum power output.	1: *≤0.1*, 10: *≥10,000* Log scale
Efficiency (%)	Quant.	Percentage of recovered energy divided by the energy stored and the energy used or lost in the storage process.	1: *≤20*, 3: *21–30*, 4: *31–40*, 5: *41–50*, 6: *51–60*, 7: *61–70*, 8: *71–80*, 9: *81–90*, 10: *91–100*
Safety	Qual.	Measure of the safety of deploying an energy storage solution.	1: *poor*, 4: *medium*, 6: *sufficient*, 10: *no impact*
Environmental impact	Qual.	Environmental impact related to the procurement, installation, operation and decommissioning of the solution.	1: *high*, 4: *medium*, 6: *sufficient*, 10: *no impact*
Maintenance requirement	Qual.	Maintenance needs of a technology over its lifetime.	1: *more than once per year*, 3: *yearly*, 5: *every three years*, 8: *every five years*, 10: *no maintenance*
Integrability	Qual.	Feasibility of the technology to be integrated in the operational environment.	1: *full redesign required*, 6: *some redesign required*, 10: *no or minimal redesign required*
TRL	Qual.	The Technology Readiness Level.	1: *TRL 1*, 10: *TRL 9*

2.3. Definition of Energy Storage Technologies

A thorough literature review was performed to identify energy storage solutions that could, in principle, be used to electrify offshore assets. Screening state-of-the-art energy storage technologies allows devising promising technological options for further consideration. Each technology was measured against the above KPIs. The results of the technology performance quantification are provided in the Analysis section.

2.4. Analysis of Potential Use of Storage Technologies for Various Operation Scenarios

A particular challenge is related to the fact that short-term storage technologies present a very high maturity level, while others, especially the ones covering long-term storage, do not. A scaled approach was adopted to avert this challenge, initially favouring high TRL technologies and further focussing on lower TRL opportunities. The present work assessed two scenarios, one considering 40% renewable penetration by 2030 and another targeting 100% by 2050.

The technology evaluation was conducted through a multiple binary decision method. The method quantifies the overall performance of the storage solutions through binary parametric evaluation. The approach (detailed in Appendix A) assigns weight factors to the different KPIs by one-to-one comparison. These individual comparisons yield a material representation of the performances from which the best performing alternatives can be selected based on the highest scores. Such scores will be subjected to the weight assigned to the KPIs; thus, an agreement on these metrics is essential for any technology assessment. A summary of the overarching performance of the energy storage solutions evaluated is presented in Appendix B.

3. Energy Storage Solutions

This section reviews the most promising storage technologies identified in the literature. The study is meant to provide a basis for understanding the technologies' potential for offshore use. A summary of the capabilities of all technologies is reported at the end of this section.

3.1. Batteries

Batteries are the most popular energy storage technology. They are widespread, have a generally high TRL and have been tested in challenging environments, such as aircrafts, vessels and a wide variety of mobile and stationary applications. The energy is stored in a set of multiple cells as electrochemical energy, like illustrated in Figure 2. The cells can be connected in series, in parallel or both to obtain the desired voltage and capacity. A battery energy storage system (BESS) comprises the batteries, the control and power conditioning system (C-PCS), protection against fire or others (i.e., HVAC to assure a good operating environment) and the electronic interfacing between the grid and the battery [8]. In the literature, there are many types of batteries, differentiated by the materials used as electrodes and electrolytes, which determine their specific characteristics, i.e.:

3.1.1. Lead–Acid Batteries

The lead–acid (LA) battery consists of two electrodes (porous lead and lead oxide) submerged in sulfuric acid. Lead–acid batteries are classified as flooded or valve regulated. The flooded LA batteries are less expensive but require more maintenance and ventilation than the valve regulated (VRLA). Despite their poor life cycle and low volumetric energy density of 50–100 Wh/L [9], compared to the other batteries, they have been successfully commercially deployed in several energy storage projects. The main drivers for their extended use are low costs, mature technology and good round-trip efficiency (~82% [9]). In recent years, the addition of carbon in lead–acid batteries has been explored, improving the life cycle. Large systems containing carbon–lead acid are now commercially available. The Ultra batteries, for example, are available at sizes of 0.51 × 0.17 × 0.30 m^3 and a weight of 73 kg for 2 kWh, yielding an energy content footprint of 27 Wh/kg and 39 kWh/m^2 [10,11]. Multiple battery packs can be installed together to provide the amount of energy needed for larger energy storage.

The lead–acid batteries contain sulphuric acid and lead, which are hazardous and restricted materials under the RoHS [12]. The flooded lead–acid batteries need appropriate ventilation to manage the off-gassing (hydrogen, oxygen) or evaporated electrolyte [13] and periodic water maintenance. If the system is in a remote place (i.e., platforms), checking the water loss can add to the OPEX. The use of VRLA lead acid batteries alleviates the risk of acid spillage, the release of acid fumes and water replacement [9]. The operating temperature of the VRLA is around 0–40 °C, meaning they are suitable to work in cold environments. In addition to that, other components do not need regular maintenance.

Various lead–acid-based energy storage systems have been installed worldwide with capacities up to several MWh. A list of the projects, locations and types of batteries is presented by Rand et al. [14]. One example is the Hampton wind farm, where a 900 kWh Ultra battery was installed in 2010 and used to reduce power variability in the wind farms.

3.1.2. Li-Ion Batteries

Li-ion batteries are promising candidates when the response time is essential, especially in short-time scale applications. They are not suitable in applications where they may become fully discharged, as they can become unusable. Li-ion batteries have fast charge and discharge capability, i.e., the time to reach 90% of the rated power is around 200 ms, with a high round-trip efficiency of approximately 95% [9]. The discharge rate, climate and duty cycle play a significant role in the actual efficiency. Specific energies (both mass and volumetric) are much better than for lead–acid ones, as is their life cycle [15]. Li-ion batteries present a high energy density of 200–750 kWh/m^3 [9]. For maritime use, large-scale batteries come in two main formats: steel or aluminium cylindrical or standard rectangular containers, which include the ventilation, control system and the battery (see Ref [16]). These commercial batteries have low operation and maintenance requirements. However, the ventilation system needs to operate continuously; otherwise, flammable gas concentrations can build up. The footprint of the large-scale batteries is in the order of standard shipping containers, depending on the energy capacity required.

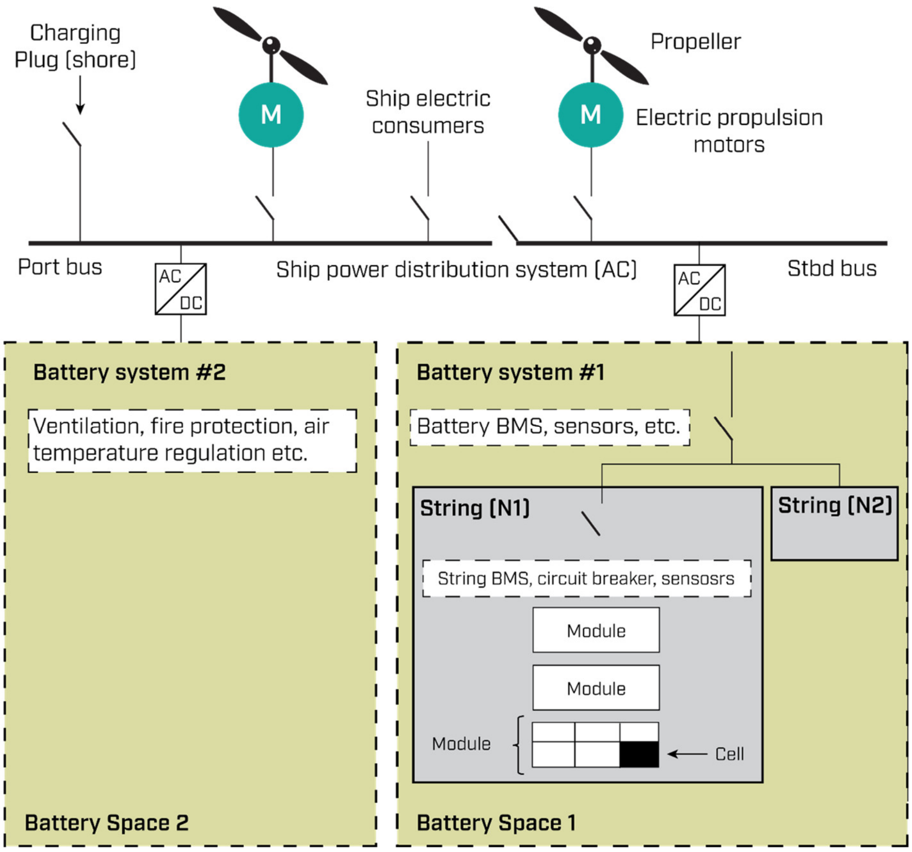

Figure 2. Generic maritime battery system (Reprinted/adapted with permission from [16]. Copyright 2022, DNV AS).

Many rules/regulations are relevant for offshore installation, including those from the Norwegian Maritime Authority, the U.K. Maritime and Coastguard Agency, DNV and others. For example, the battery systems need to be tested against off-gas risk propagation and explosion. DNV presents a table with guidelines and regulations for battery installation offshore [16]. The cost of installing li-ion batteries is higher than other types of batteries (refer to Appendix C for representative cost figures of this and all other technologies).

Lithium cobalt oxide (LCO) has a relatively high energy density, short life cycle and lower power rate. Cobalt oxide presents safety concerns due to the oxygen released at high temperatures, producing self-heating, resulting in thermal runaway. Lithium manganese oxide (LiMO) has a low energy density, but larger the safety benefits due to high thermal stability. Lithium nickel manganese cobalt oxide (NCM or NMC) is one of the most recent developments, and it is currently the market leader for large-scale applications. The relative composition of the three metals plays a role in the battery's total energy density and safety. Nickel and cobalt provide high specific energy, and manganese stabilises the system. Lithium iron phosphate (LFO) has a low energy density. This battery type does not need an oxygen source at the cathode, thus posing a potentially reduced risk of thermal runaway incidents. Cobalt and Lithium are metals characterised by sustainability and environmental issues. In addition, they have weak recovery and recycling schemes [9,16,17] (refer to Appendix C for safety, environmental and integrability notes of batteries and all other technologies).

3.1.3. Ni–Cd Batteries

Ni–Cd batteries are direct competitors of lead–acid batteries; they are well established in the market and have similar technical characteristics. Ni–Cd has superior cycling abilities (more than 3500 cycles [18]), higher energy density and very low maintenance requirements.

Other nickel-based batteries are the nickel–metal hydride (NiMH) and nickel–zinc (Ni–Zn) batteries. NiMH batteries are a feasible alternative to Ni–Cd batteries due to their improved performance and environmental advantage. Compared to lead–acid and Ni–Cd batteries, NiMH batteries are environmentally friendly. NiMH batteries lack toxic substances, such as cadmium, lead or mercury. The energy density of NiMH cells is 25–30% better than high-performance Ni–Cd cells [19]. Although NiMH batteries have superior specific energy when compared to lead–acid and Ni–Cd batteries, NiMH batteries suffer from severe self-discharge, making them inefficient for long-term energy storage. Their major drawback is their toxicity. Cadmium and Nickel are toxic heavy metals, which can cause a health risk for humans. Cadmium is a restricted element under the RoHS [12]. Another disadvantage is that they cost over 10 times more than the Lead–Acid batteries (see Appendix C).

3.1.4. NaS Batteries

NaS batteries are a relatively new technology, with some of the most promising options for high power energy storage applications. They have high energy density and efficiency, 140–300 kWh/m^3 and around 85%, respectively [9]. NaS batteries do not self-discharge, require low maintenance and are 99% recyclable. NaS batteries show an attractive energy density (four times that of lead–acid batteries [9]), a long cycle capability (2500 cycles upon 90% depth of discharge) and a millisecond response for full charging and discharging operations [19]. The main concern with this type of battery is the exothermic reaction, which can reach temperatures of around 350°C. At such temperatures, sulphur and sodium compounds are highly corrosive; hence, containers and seals must be resistant under these conditions. Research on low-temperature Na-S batteries is underway to mitigate the safety concerns; however, there is not yet a good candidate [20].

3.2. Supercapacitors (SCESS)

Like batteries, supercapacitors are based on electrochemical cells containing two conductor electrodes, an electrolyte and a porous membrane, whereby the ions pass. SCEES store energy by attracting solvated ions to a conducting surface using electric fields. Supercapacitors have a high energy storage capacity, helping bridge the disparity in the performance between fuel cells and batteries. SCEES technologies are used for systems where a fast response is needed due to their ability to discharge the stored energy within milliseconds. SCESS have higher power capability than most batteries (up to a tenfold) and can operate in a wide range of temperatures. The energy density of supercapacitors can reach up to 1 kWh/kg [21]. However, even though the reported coulombic efficiencies reach up to 99%, they could lose, due to leakage, 10–20% of their stored energy over a 24 h period [15]. There are readily available supercapacitors for short charge and short discharge time; however, for long discharge times, the technology is at a lower level—TRL 3 [22].

The size of the supercapacitors is dependent on the ratio between the required energy and the energy density. To have an idea of the scale, Maxwell Technologies, a global market leader of supercapacitors, has standardised the diameter of the cell to 60 mm with the height adjusted to achieve the desired capacitance. The maximum module capacities are 5.8–500 farads and cell capacities of up to 3400 farads [23]. Relevant for industrial use, the largest supercapacitor built worldwide is ten times the capacity of the Maxwell cells referred to above, with a capacity of 30,000 farads [24].

3.3. Flywheels Energy Storage (FEES)

A flywheel is an electromechanical system that stores kinetic energy in a revolving shaft. A mass rotates on two magnetic bearings that decrease friction at high speed, coupled with an electric machine. The entire structure is placed in a vacuum to reduce wind shear. Details of its design are thoroughly provided in the literature [8,15,25–28]. FESS has high efficiency (up to 95% at rated power), yet relatively high standing losses. The self-discharge rates for complete flywheel systems are about 20% of the stored capacity per day [15], hence restricting it to short-term storage, load-levelling and load-shifting applications. FEES also has high power and relatively high energy density (up to 400 Wh/kg), yielding a space/energy density ratio of 0.2 m^2/kWh [15,29]. Available off-the-shelf FEES systems have energy capacities of up to 20 MW. The largest one can deliver 10 s of ride-through at a 1.65 MW load and proportionately a longer ride-through at lesser loads [8] [15].

Flywheels have been used in numerous applications, including powering turbomachinery and mechanical batteries in diverse sectors [30]. They have been used in mine locomotives where explosion risk is present. The primary risks associated with energy storage in flywheel systems arise from a rotor failure leading to explosions and/or disintegration. Risks can be reduced by operating the flywheel at several times below its failure speed, but this operational strategy would substantially reduce its energy density.

3.4. Hydro-Pneumatic Energy Storage (HPES)

The solution is primarily intended for short- to medium-term energy storage. The technology is based on a hydro-pneumatic liquid piston concept, whereby electricity is stored by using it to pump seawater into a closed chamber and compress a fixed volume of pre-charged air. The energy can then be recovered by allowing the compressed air to push the water back out through a hydraulic turbine generator.

This technology is in a prototype phase, TRL 4–6. A full scale could be composed of four floating cylinders of 6 m diameter each. The full scale will be able to store energy up to 5 MWh with a round-trip efficiency of around 75% [31]. The technology uses pressurised seawater and compressed air, and none of the sub-components or materials are considered hazardous or flammable [10]. The HPES is a floating structure that can stand alone beside the platform or be coupled with wind turbines, as shown in Figure 3.

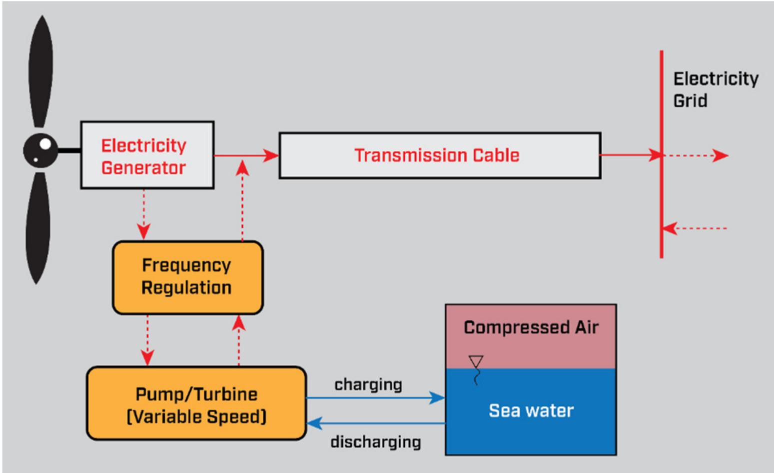

Figure 3. Operating principle of a wind-turbine-integrated hydro-pneumatic energy storage concept. (Modified from Sant et al. [32]).

3.5. Hydrogen

Hydrogen can be obtained in various ways; in offshore platforms, the two obvious means are gas reforming (blue hydrogen) and water electrolysis. The latter is of particular interest for decarbonisation schemes if fed from RES. Hydrogen storage can occur in multiple fashions, i.e., hydrogen pressurisation, hydrogen adsorption in metal hydrides and the liquefaction of hydrogen (the latter two being in a stage of development) [19].

Pressurised hydrogen with an energy density of approximately 767 kWh/m^3 [33] can be stored as gas in metal tanks (or other composite materials, such as carbon fibre or polymer) at pressures up to 700 bar (see Table 2) or in metal hydrides. Storing hydrogen in metal hydrides is suitable for storage periods longer than 3 h. In contrast, metal tanks may be better suited for large volume applications for storage of more than 30 h, including hydrogen in a liquid phase at 2224 kWh/m^3 [34].

Gaseous hydrogen is about 8 times less dense than methane, and in a liquid state, it is 6 times less dense than liquid methane and 55 times less dense than gasoline. Thus, weight shall not be a restriction for use on platform systems; yet, the storage space requirements can be prohibitive. The project Deep Purple [35] has evaluated the possibility of moving hydrogen production to wind farms and storing hydrogen in metal tanks on the seabed. Another argument for hydrogen storage outside the platform premises concerns safety, especially when handling liquid hydrogen. Liquid hydrogen requires complex, thermally insulated containers and special handling common to all cryogenic substances. Further, air-contaminated hydrogen (from the environment or traces from manufacturing processes) forms an unstable, highly explosive mixture.

Alternatively, large storage capacities to overcome seasonal variations when produced from renewables can be obtained in underground structures, e.g., salt caverns. The option of storing hydrogen in depleted gas fields could be highly attractive for the oil and gas industry. Such appeal owes to the proximity to reservoirs (and proven tightness of such reservoirs to hydrocarbon gases over geological time periods) and the already existing equipped installation for injection and withdrawal of gas and processing. The TRL of underground hydrogen storage in depleted reservoirs is expected to reach TRL 5 by the end of the HyStories project [36].

The storage of liquid and compressed hydrogen in tanks showed efficiencies of up to 80% [37] and 60% [37], respectively. Underground storage efficiency is estimated between 28 and 78% [38]. Additionally, losses due to production, compression/liquefaction, storage and expansion should be considered. Storage in metal hydrides and depleted underground reservoirs must also account for retrieval efficiency. In metal hydrides, the adsorption of hydrogen molecules is typically associated with large binding energies, which requires elevated pressures. Thus, reverting the adsorption process to release the stored hydrogen molecules entitles pressure release and application of heat—two requirements that are not particularly desirable. Disadsorption of hydrogen from some metal hydrides can occur near ambient temperatures at the expense of very low gravimetric hydrogen storage capacities and release percentage of 80% to 60% [39,40].

The costs of the hydrogen storage systems reported in the literature vary significantly. A techno-economic or cost–benefit analysis of electricity storage systems requires consistent, updated cost data and a holistic cost analysis framework. For the sake of cohesiveness, costs independent of the storage technology are taken from the life cycle assessment (LCA) in Ref [25]. These elements comprise the power conversion system (PCS), including the balance of plant (BOP—engineering, system integration, protective devices, construction management, monitoring and control systems, shipment and installation), and the operation and maintenance costs, as detailed in Table A8. The costs of liquid hydrogen systems comprise the liquefaction process and cryogenic storage in addition to production. Recompression energy is not considered because it is assumed that hydrogen will be used under ambient conditions. Specific liquefaction costs are estimated at EUR 1.72/kg LH_2 for a post-demonstration installation, as per the Idealhy project results [41]. The storage of liquified hydrogen in integrated refrigeration and storage (IRaS) tanks, which allows control of the fluid inside the tank and reduces losses, is estimated at USD 149/kg [42]. The alloy material is the main cost of H_2 gas storage in metal hydrides. The expenses of low-temperature hydrates are reported to represent between 50% and 93% of a storage system comprising a heat transfer system and pressure vessel with total costs of USD 32.4/kWh and USD 200/kWh [43]. The cost of storing compressed hydrogen in tanks is estimated at USD 13.1/kWh, based on the costs summarised in Ref [44] gathered from several recent reports. The economics of other components (such as the converter, electrolyser and reconversion equipment) reported in Ref [44] agree with the baseline costs from the LCA in Ref [25], thus ensuring the overall system costs are consistent.

Alternative storage solutions for gaseous hydrogen in offshore locations comprise underground storage in reservoirs, pipelines and other offshore structures, e.g., wind towers and platform jackets. The cost of storage heavily depends on the use of the available infrastructure. Generally, it is estimated that the cost of aboveground storage would be around EUR 128–132/kWh, while storage in underground caverns ranges from EUR 0.2 to 11/kWh [45]. The preparation and processing needs vary among the underground solutions, with corresponding effects on the associated costs. In this sense, storage in depleted reservoirs does not require cavern mining; hence, decreased costs of approximately 24% are expected [46]. Hydrogen storage in wind towers at 11 bar is estimated to cost USD 120/kg (USD 3.6/kWh) [46]. It is noteworthy that the cost of hydrogen storage may decrease in the years to come, particularly in large storage applications.

The footprint densities of the different hydrogen solutions have the hydrogen production process in common. Figure 4 shows a proposed configuration, where the hydrogen storage may or may not be on the platform, depending on each solution. The footprint of the electrolyser and rectifier was computed based on state-of-the-art technology. The largest installed proton exchange membrane (PEM) electrolyser accounts for 30.57 m^2 for a 5 MW unit [47]. Regarding the water supply, it is estimated that 9 kg H_2O are needed to produce 1 kg H_2 [48]. Further, reverse osmosis systems have a recovery rate of 50% to 70%; hence, the pumping system shall be sized to supply about double the amount of water needed for the electrolysis process. Considering a 1000 gpm pump of 60 inch × 87 inch (3.37 m^2) [49], the footprint density associated with water pumping is approximately 251 MWh/m^2. For a reverse osmosis system of about the same dimensions as the pump (2 units of 30 inch × 45 inch each −3.48 m^2 [50]), the footprint density is estimated at 1.6 MWh/m^2.

For hydrogen compression, the dimensions of a non-lubricated piston compressor for hydrogen service were considered [51], yielding a footprint density of 81.4 MWh/m^2. Further electrification via a hydrogen gas turbine, as used in the Enel's hydrogen demonstration at Fusina [52], yields a footprint density of 0.36 MW/m^2.

As per the footprint of the different hydrogen storage solutions, for the sake of consistency, a Length/Diameter ratio of 5 was considered [53], assuming compressed gas stored at 300 barg and 20 °C yields a footprint density of 8.5 MWh/m². The storage of hydrogen in metal hydrides occupies up to 18 times smaller volumes than the equivalent gas storage in vessel tanks (at 40 barg and 20 °C) [54], yielding a footprint density of 1.6 MWh/m². For liquid hydrogen at 2 barg and −250 °C, the same container dimensions yield a footprint density of 27.5 MWh/m². However, adding a liquefaction plant to the platform premises increases the technology footprint.

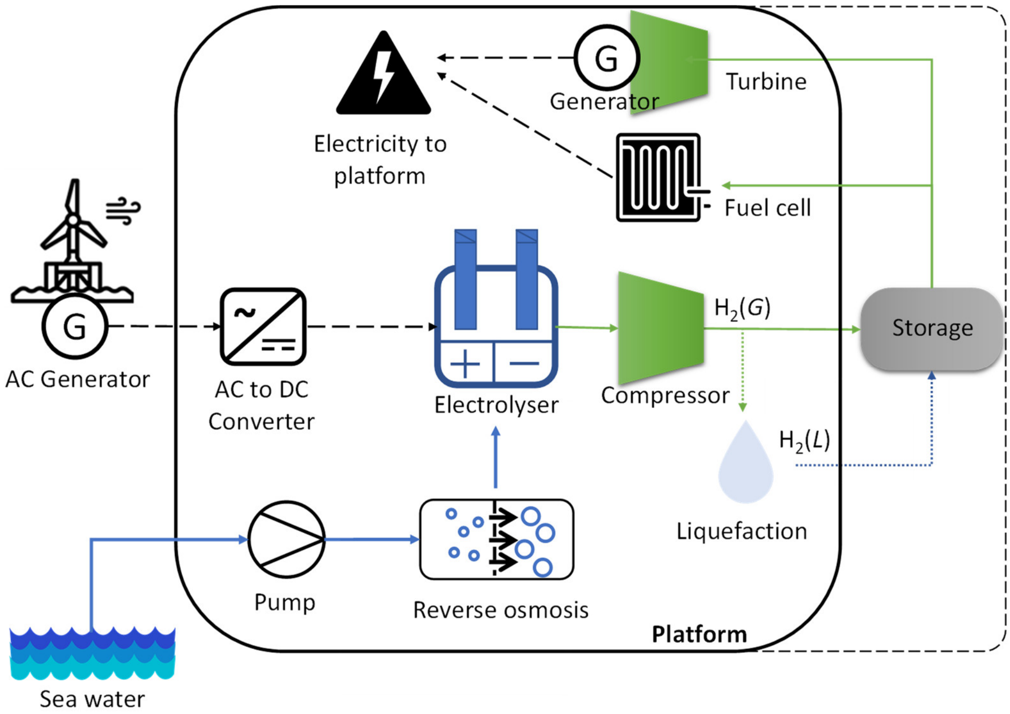

Figure 4. Schematic of offshore hydrogen production from wind.

3.6. Ammonia

Ammonia has been identified as a sustainable fuel for mobile and remote applications because it is easier to transport and store than hydrogen (see Table 2). Ammonia can be obtained by a catalytic reaction from hydrogen and nitrogen. Figure 5 illustrates the value chain of ammonia production from hydrogen. The reaction is typically carried out over an iron catalyst at temperatures around 400–600 °C and pressure ranging from 200 to 400 barg.

The nitrogen is extracted from the air, and the hydrogen is obtained by electrolysis, as discussed above. Ammonia is produced by the Haber–Bosch (HB) synthesis. Another approach developed by Haldor Topsøe is a combination of the solid oxide electrolysis cell (SOEC) and the HB process. In this approach, the SOEC separates the hydrogen from water and nitrogen from the air/steam mixture, so an air separation unit is not required [55]. Ammonia has an energy density of 6 kWh/kg (comparable to natural gas), and it can be easily rendered liquid by compression to 8 barg at atmospheric temperature. Ammonia produced from renewable sources can be synthesised with an entirely carbon-free process [56]. However, ammonia indirectly impacts ozone due to NOx production when combusted.

Table 2. Typical storage conditions of ammonia and hydrogen.

Carrier	Temperature	Pressure
Hydrogen	Gas: ambient temperature Liquid: −252 °C	Gas: 350–700 barg Liquid: ambient pressure
Ammonia [57]	Refrigerated: −33 °C to −50 °C Semi-refrigerated: −10 °C Pressurised: <45 °C	Refrigerated: ambient Semi-refrigerated: 4–8 barg Pressurised: 17–18 barg

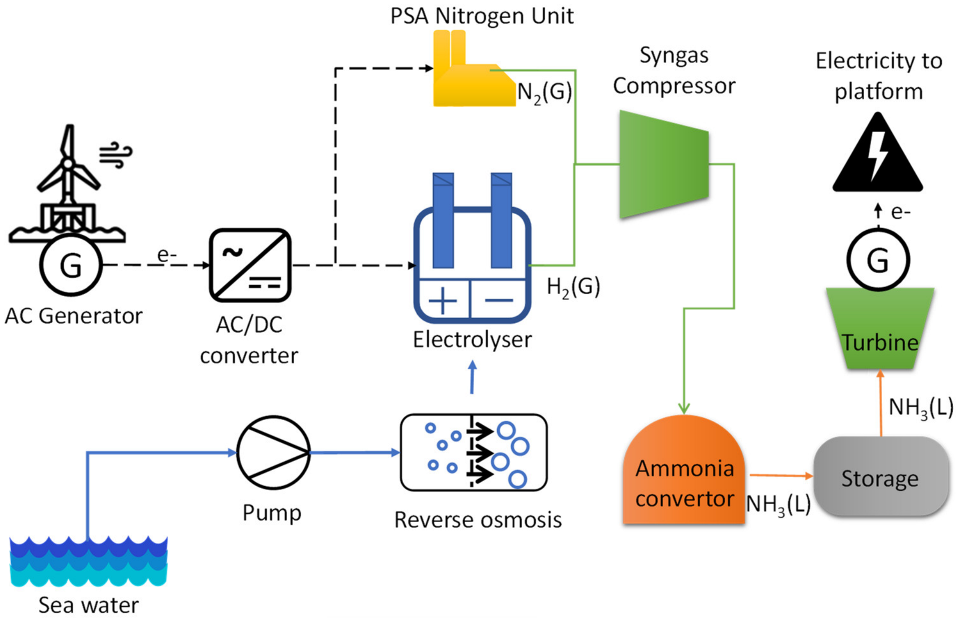

Figure 5. Ammonia value chain, including the main components in its production.

The highest efficiency of green ammonia production is around 74%, which includes all the processes involved in converting electricity to ammonia with optimal integration of steam cycles [58]. Further, ammonia conversion yields a thermal efficiency of 30–40% [59]. Regarding the regulations and environmental risk, ammonia is a toxic chemical with severe consequences on health. The release of ammonia into the sea impacts the environment because it is also harmful to aquatic life. The combustion of ammonia may generate NOx and N_2O, powerful greenhouse gases. According to Ref [60], effective safety regulations for using ammonia as fuel on board ships are currently not in place, which is probably the case for offshore platforms.

According to DNV-GL Maritime [55], the capital cost for ammonia production is around USD 2200 to 3500 per tonne annual production capacity, depending on the scale of the equipment. The major contributors are ammonia synthesis and the electrolyser (~50%). The capital cost for a refrigerated storage facility (−33 °C and 1 barg) is around USD 700 per tonne of ammonia [55].

The energy content footprint of ammonia has been calculated similarly to the hydrogen case. The footprint density from electrolysers, rectifiers, compressor, reverse osmosis, water pump and turbine were taken from the hydrogen subsection. For the ammonia, the costs of PSA unit, ammonia convertor and storage unit were added to the components previously mentioned. For the PSA unit, a space of 2.25 m^2 is needed for a unit of 5 Nm^3/h, yielding a footprint density of 314 MW/m^2. For the ammonia convertor, we consider that the footprint density is similar to both the electrolyser and rectifier together. The storage cylinder vessel occupies 0.05 m^2 for storing 50 L of ammonia at 8 barg and 20 °C [61], yielding a footprint density of 3.5 MW/m^2.

3.7. Compressed Air Energy Storage (CAES)

In CAES systems, the air is compressed and stored, typically underground, using off-peak electricity [62]. When energy is needed, the compressed air is retrieved, heated and expanded through a turbine, converting most of the potential energy of the compressed air into rotational kinetic energy (see Figure 6). CAES can also be used in combination with conventional gas turbines by utilising the compressed air directly in the combustor of the gas turbine, increasing the turbine's energy output.

CAES has an energy density of 3–140 kWh/kg [63,64] and a surface footprint comparable with a gas-fired power station of equivalent size, granting a space/energy density ratio of 0.01 m^2/kWh. However, the most significant space demand is associated with the (underground) storage, which is equivalent to approximately 1 km^2 per plant [65]. The technology provides quick ramp rates and start-up ranging between 9 min emergency start to 12 min in normal operation; yet, it is relatively slow in discharging the stored power capacity (hours-to-day range) [66].

The round-trip efficiency of CAES can be increased from 25 to 45% [8] for the conventional configuration to 70% [64,65] via adiabatic compression, designated A-CAES. A-CAES requires additional heat exchangers and a thermal fluid to store the compression heat. Suppose on platforms, not all turbines can be substituted. In that case, the space required (especially by the additional equipment—heat exchangers, compressors, turbine) could be a limiting factor, given the strict constraints on offshore applications [67].

The published storage costs depend on the site, scale of the plant and storage type. Underground air storage for sizes with 8 h discharge time has been estimated at EUR 97–120/kWh [25]. The average cost of the PCS is in the range of EUR 845/kW, while the storage costs vary between EUR 40/kWh for aboveground and EUR 110/kWh for underground storage, on average [25]. In addition to the CAPEX of such CAES systems, one must consider the fixed operation and maintenance costs of EUR 3.9/kW-yr [25].

Despite the few large-capacity CAES plants in the world (above 100 MW), with high reliability to mitigate wind variability for wind levelling and energy management purposes, CAES has had limited market penetration. As reported by the 2002 EPRI study [68], one probable reason is the need for underground geological storage, which is likely perceived as a risk by utilities. However, this should not be an issue to the oil and gas sector, with vast experience storing hydrocarbon-based fuels in underground reservoirs. On the other hand, A-CAES systems are in the demonstration process and are not yet commercially available. Conventional CAES systems store the compressed air in underground salt domes and open caverns. For offshore applications, compressed air storage in porous media (PM-CAES) could present higher potential due to the abundance of sites [68].

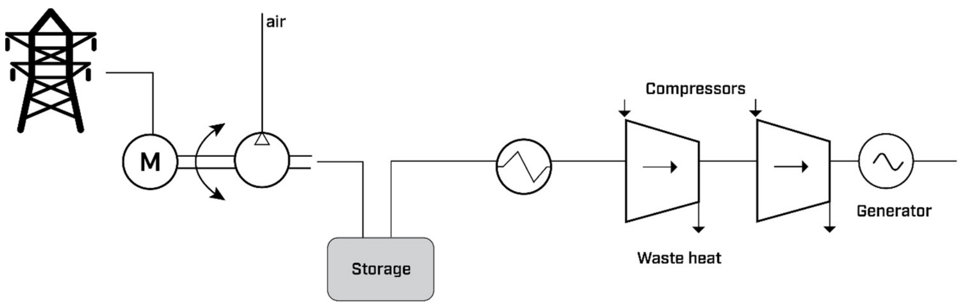

Figure 6. Compressed air energy storage.

The technical characteristics of each energy storage technology are depicted below in separate tables. Table 3 summarises the capabilities for the quantitative KPIs, namely efficiency, response time, discharge time, capacity, mass energy density and energy content per footprint. Table 4 condenses those of a more qualitative nature. The data are based on the review of the references in the respective tables, the computations detailed above and the details in Appendix C.

Table 3. Technical characteristics of energy storage technologies based on public literature.

Technologies	Round-Trip Efficiency (%)	Response Time	Discharge Time	Capacity (MW)	Mass Energy Density (Wh/kg)	Energy Content per Footprint (kWh/m^2)	References
Lead–acid	80–82	msec–sec	sec–hours	0–40	30–50	23	[8,9,19,64,69]
Li-ion	92–96	msec–sec	min–hours	0–100	100–250	194	[9,19,69]
Ni–Cd	60–85	msec–sec	sec–hours	0–40	40–75	17	[8,19,69,70]
NaS	75–90	msec	sec–hours	0.05–34	150–240	140	[8,9,19,69,70]
Ammonia	>22	min	hours	0.1–1000	5000	50	[58,59,71]
CAES	45	min	hours	0.003–300	3.2–140	100	[8,63,64,72]
HPES	96	min	hours	2	50	25	[31,73]
SCESS	>80	msec–sec	sec–min	2	1100		[15,74]
FEES	78–95	msec–min	sec–min	0.1–20	5–400	5	[8,63]
H_2 MH	15–25	min–hours	hours	0.3–50	300–964	91	[8,40,75–77]
H_2 gas	25–40	min–hours	hours	30	33,000	95	[37,75–78]
H_2 Liq	12–25	min–hours	hours	30	31,300	48	[76–78]
H_2 Underground	25–40	min–hours	months	10 000	33,300	96	[38,76–78]

Table 4. Qualitative performance of energy storage technologies based on the literature in Table A8.

Technologies	Safety	Environmental Impact	Maintenance	Integrability	TRL
Lead–acid	●	◐	●	●	●
Li-ion	●	◐	●	●	●
Ni–Cd	●	◐	●	●	●
NaS	●	●	●	●	●
Ammonia	◐	◐	●	◐	◐
CAES	●	●	◐	◐	●
HPES	●	●	●	●	◐
SCESS	●	○	●	◐	○
FEES	●	●	◐	●	●
H_2 MH	◐	●	●	◐	●
H_2 gas	◐	●	●	◐	●
H_2 Liq	◐	●	◐	○	●
H_2 Underground	●	●	●	◐	○

● *High performance*
◐ *Medium performance*
○ *Low performance*

4. Analysis

Two scenarios were evaluated to shed light on the benefits of the different solutions to store energy in offshore facilities. Scenario A accounts for offshore assets powered with renewables to cover 40% of the energy load, considering an average energy requirement of offshore platforms of at least 30 MW. Scenario B considers a 100% renewable energy supply. This two-step approach enables identifying the most promising technological developments, both for the short and long term. Specifically, the short-term Scenario A limits the possibility of introducing disruptive innovations, favouring solutions that are easy to deploy and integrate within a short time frame. In contrast, a longer time perspective (Scenario B) introduces the opportunity of deploying technologies that are not yet commercially available but present potential long-term benefits. To compare the technology for both scenarios, the KPI values of the technologies were standardised. For that, the KPI scales in Table 1 and the current state of the art of technologies in Tables 3 and 4 were combined. The technical performance of the various storage solutions was scored for every KPI. The results are shown in Table 5. Further discussion on the scenarios follows below.

Table 5. Technology performance.

	KPI	Batteries				NH_3	CAES	HPES	SCESS	FEES	Hydrogen Storage			
		Lead–acid	Li-ion	Ni–Cd	NaS						MH	Gas	Liq	Undergr
A	Mass energy density	1	1.1	1	1.1	2.5	1	1	1.3	1.1	1.3	10	10	10
B	Energy content per footprint	2	10	1.7	7.5	3.2	5.6	2.1	3	1.1	5.2	5.4	3.2	5.4
C	Discharge duration	4	2.5	4	4	10	10	6	5	5	7	7	7	10
D	Response time	10	10	10	10	5	5	5	10	10	5	4	4	3
E	Capacity	6	6	6	6	8	4.7	3	4	5	6	5	5	10
F	Efficiency	9	10	9	9	3	7	10	8	10	3	4	3	4
G	Safety	8	8	8	7	4	8	9	8	9	6	5	4	7
H	Environmental impact	4	4	4	9	4	10	10	3	10	10	10	9	8
I	Maintenance	10	10	10	8	8	5	8	10	5	8	7	5	10
J	Integrability	9	9	9	8	5	6	7	6	7	5	4	2	6
K	TRL	9	9	8	8	6	9	4	3	9	7	9	8	3

4.1. Scenario A (40% Powered by Renewable Energy)

The analyses of the storage solutions for both scenarios were performed via the multiple binary decision (MBD) method, detailed in Appendix A. The KPIs were contrasted with each other on a one-to-one basis. Such method yields a KPI ranking (see Figure 7), which allows further assessment of the technologies with greater promise to fulfil the target objective based on the premises of the scenario under study.

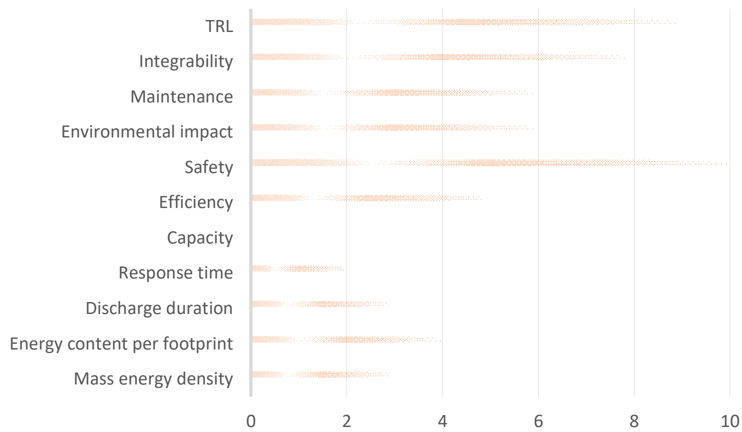

Figure 7. KPIs' comparative ranking for Scenario A.

The overarching premises considered for the KPIs comparison for the present scenario comprise:

1. Energy content per footprint and maintenance are highly relevant, as they reflect the use of the technologies in challenging environments, such as offshore facilities.
2. Discharge duration and response time are less relevant for *Scenario A*, where only 40% penetration is foreseen. Hence, gas turbines will support the energy system if high discharge time and low response time are needed.
3. Given the partial penetration rate, limited to 40%, the capacity is seemingly less relevant than other performance indicators.
4. Technology readiness and integrability are essential for the viability of *Scenario A*, which lacks the time for significant technology advancements and scale optimisation.

5. Safety and environmental impact were highly valued, in agreement with the interest of the consulted stakeholders as per industrial workshops undertaken in the context of the OFFLEX project [79].

Subsequently, all technologies were contrasted with each other based on the technology performances per Table 5, using the MBD method in Appendix A. Figure 8 summarises the technologies' overall performance.

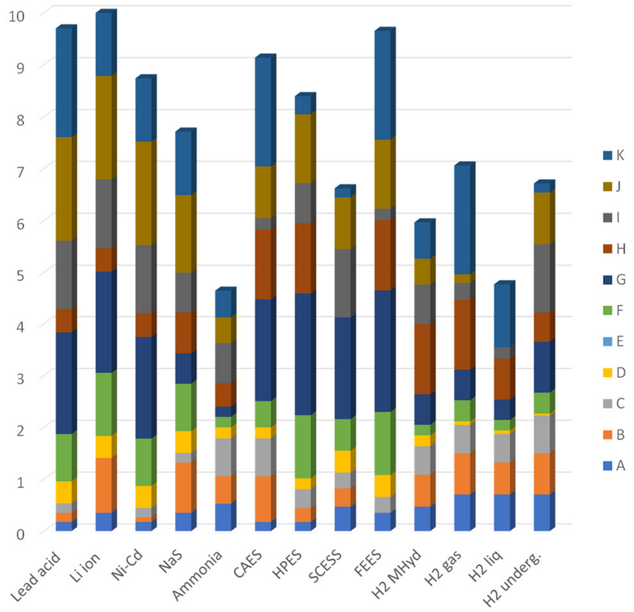

Figure 8. Performance of storage solutions per KPIs—Scenario A-2030. A–K are the KPIs. (A) Mass energy density, (B) Energy content per footprint, (C) Discharge duration, (D) Response time, (E) Capacity, (F) Efficiency, (G) Safety, (H) Environmental impact, (I) Maintenance, (J) Integrability and (K) TRL.

It is evident that CAES, Flywheel and Lead–acid and Li-ion batteries show the most significant promise to meet the challenges of the scenario under evaluation. Of these, Li-on batteries have the additional advantages of providing low maintenance, high integrability and high energy density per footprint (see Figure 9), relevant for offshore platforms where space is a constraint. Large-scale batteries in containers can be installed on offshore platforms without additional modifications. Due to the flexibility of Li-ion batteries, they can also be deployed together with wind farms. Yet, the environmental impact is a drawback to consider, and a low availability of Lithium and Cobalt is expected in the future. Flywheels are environmentally more attractive. Yet, the batteries outperform the flywheels in maintenance, integrability and footprint. CAES is an immediate solution for seasonal storage, with capacities large enough to provide the entire load requirements of an offshore platform. The technology is well established and based on conventional gas turbine technology, heat exchangers and well underground storage/retrieval, largely customary in the oil and gas industry. However, the installation of CAES systems requires some re-design.

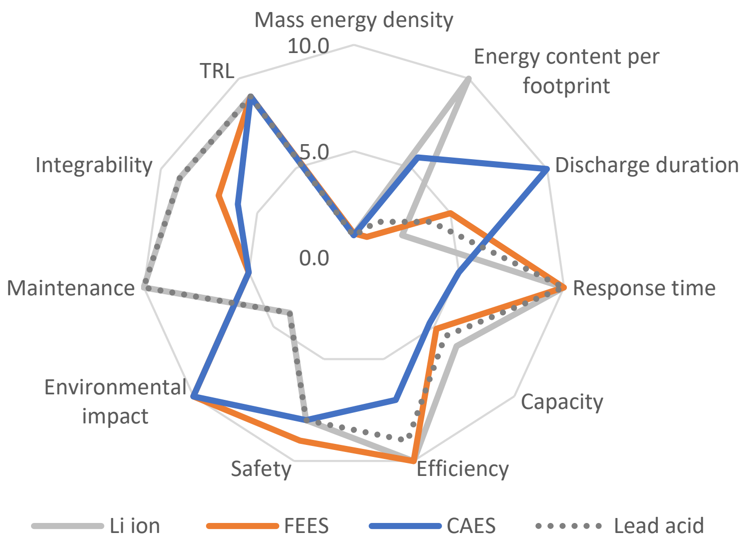

Figure 9. Spider chart of the most promising technologies for Scenario A-2030 and how they perform in each KPI. The data are available in Table 2.

Regardless of the chosen solution, storage systems must be integrated in the safety systems of the platform (e.g., deluge, emergency pathways). Additionally, thorough risk assessments shall be undertaken prior to technology selection for individual deployment cases. The environmental impact, safety concerns and maintenance requirements presented in Table 4 allow an initial high-level risk assessment. Table 6 summarises the principal risks and mitigation measures for the above-highlighted technologies. The probability (*P*) of unwanted incidents and consequences (*C*) to health, the environment and/or costs if the risks materialise, are provided. *P* and *C* are estimated on a scale, where 1 is the lowest level and 3 is the highest.

Table 6. High-level risk assessment for implementation of technologies in Scenario A.

Technology Risk	*P*	*C*	ESS	Available Risk Mitigation Measures
Battery failures leading to gas release, fire and explosion	1	3	Li-ion	Multiple safeguards and additional on-site mitigating factors have allowed events like this to be in the low-risk zone (likelihood between once in 100,000 years to once in 1,000,000 years) [80].
Exposure to hazardous material leading to poisoning and death	1	2	Lead–acid	Use maintenance-free sealed battery with no removable caps and leak-proof containers. Keep batteries in a cool, well-ventilated area away from ignition sources.
Low recycling	3	1	Li-ion Lead–acid	Several projects are looking for recycling paths for some batteries. Yet, the use of hazardous materials and the diversity in the chemistry of these batteries pose a challenge.
Enclosure failure	1	2	FEES CAES	Safety regulations make this a rare occurrence at the cost of higher weight and additional safety features, such as pressure relief valves.
Poor performance in offshore environment	2	1	All	Sealed, frictionless bearings with no lubrication and little maintenance are preferred for flywheel systems offshore.

	Air storage in depleted reservoirs has not been tried offshore. In the short-term, air storage in tanks would be more suitable for offshore locations. Such approach avoids environmental concerns regarding excavation and the structural stability of the membrane. Thermal management systems are required to avoid poor performance at low or high temperatures of Lead–acid batteries.

4.2. Scenario B (100% Powered by Renewable Energy)

When targeting 100% renewable penetration, the energy system in the platform needs to be supported by a hybrid energy storage solution to give complete operability of the installation, i.e., constant and reliable power supply. Hence, technologies for large-scale and seasonal storage, essential to achieving total decarbonisation of the offshore energy sector, will be needed. Technologies must also be able to cover the peak demands. In this section, we benchmark the energy storage solutions. The method uses the KPI to assess the technologies focusing on sustainable solutions.

Similar to the above, the relative relevance of each KPI was assessed by the MBD method. The KPIs were contrasted, yielding the rank in Figure 10. For the present scenario, the following considerations were taken:

1. Safety and environmental impact are very relevant to focusing on sustainable technologies.
2. The discharge duration is of great relevance, as it reflects the feasibility of long-term storage (seasonal).
3. Without the use of turbines, the response time becomes highly relevant in the present scenario.
4. Capacity is of the utmost importance in Scenario B, as the totality of the energy needs is to be covered by the energy stored.
5. Technology readiness and integrability are less relevant than in Scenario A. The time gap between both scenarios is assumed to provide sufficient room for technology advancements and scale optimisation.

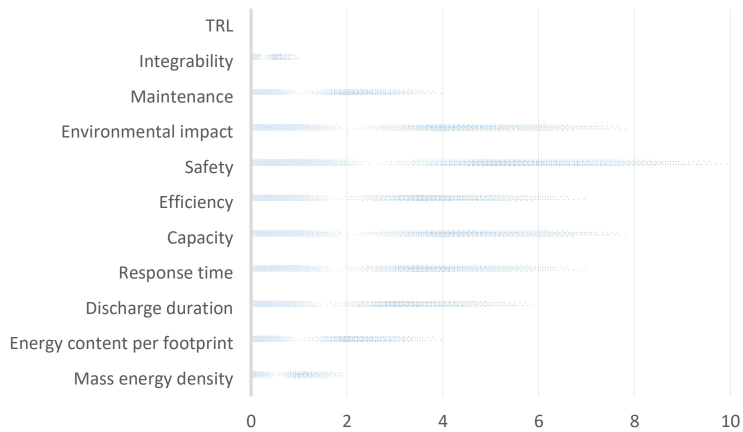

Figure 10. KPIs' comparative ranking for scenario B.

Figure 11 shows the different storage solutions in a scenario in which the KPIs have different weights. The results therein do not intend to be a forecast, as they are drawn from the current technological development state of each storage solution. They represent an overview that carries significant uncertainties.

Nevertheless, by comparing Figure 11 with the results from Scenario A, it is noticeable that energy carriers such as Hydrogen and Ammonia show enhanced features. This responds to TRL and integrability evolving over time. The large capacity and discharge duration of ammonia and hydrogen (underground) solutions are promising for seasonal storage (see Figure 12). Nominally, both technologies require large footprints due to the components needed for production, pressurisation or liquefaction, storage and electricity conversion. However, alternative configurations can be adopted as in Ref [35], where the production takes place within the wind turbines' structure, and storage tanks are installed on the seabed. Such approaches reduce the space needed on the platform. According to our analysis, underground hydrogen storage presents higher capacity integrability compared to the other hydrogen options and ammonia.

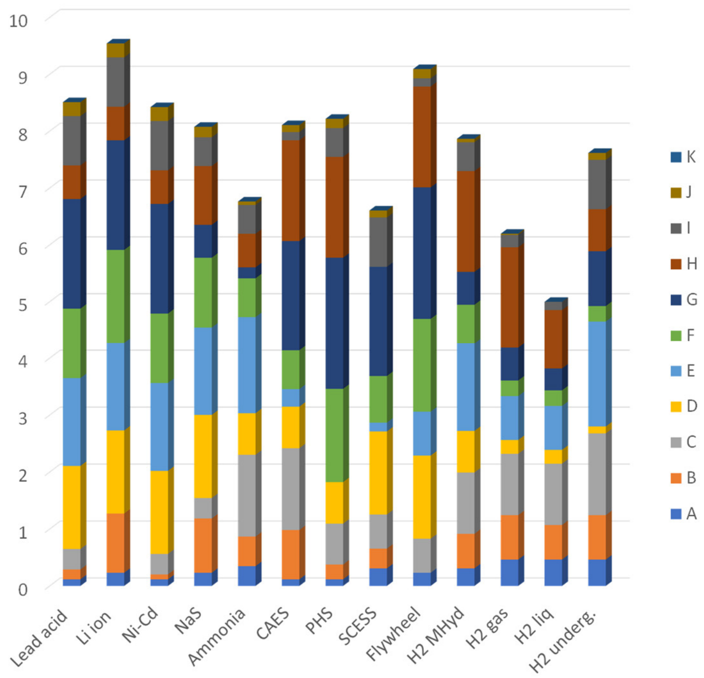

Figure 11. Performance of storage solutions per KPIs—Scenario B-2050. A–K are the KPIs. (A) Mass energy density, (B) Energy content per footprint, (C) Discharge duration, (D) Response time, (E) Capacity, (F) Efficiency, (G) Safety, (H) Environmental impact, (I) Maintenance, (J) Integrability and (K) TRL.

The integrability of ammonia storage systems is also expected to improve in the medium term. Extensive work is being carried out, and ammonia has been designated as a marine fuel for the future [81]. For offshore assets, ammonia can be particularly attractive, since it can be exported or imported easily if needed. Additionally, because the storage requirements are similar to propane (vapour pressure $p_{vap,20C} = 8$ barg [57]), transport ships designed for propane can be used for ammonia. The toxicity and environmental concerns remain significant for ammonia, subject to ongoing research [82].

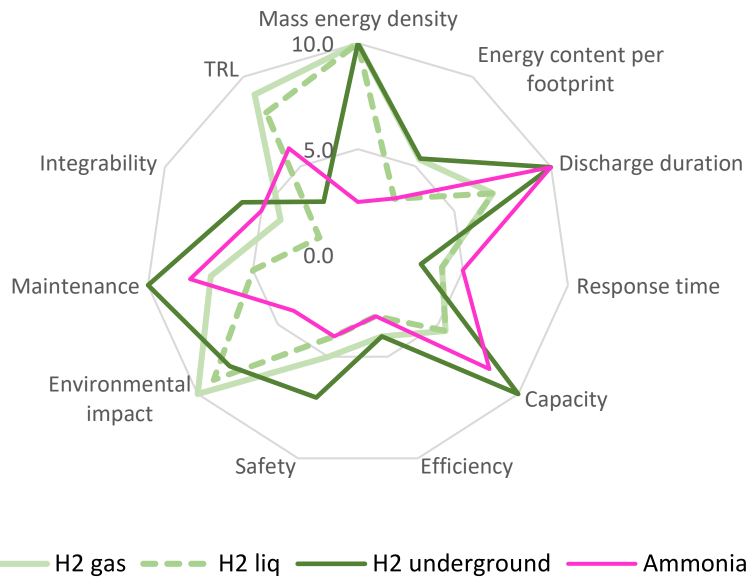

Figure 12. Spider chart of energy carriers, hydrogen and ammonia, and how they perform in each KPI. The data are available in Table 2.

Figure 13 illustrates the performance of a hybrid battery–hydrogen ESS. Theoretically, such a system could build on the potentiality of the individual technologies to circumvent the demand for energy storage solutions offshore. Such a system would, in principle, rely on batteries for short-term, rapid load supply and on hydrogen for seasonal variations. This exercise illustrates the need to use complementary technologies to satisfy the energy demand, ensure reliable energy supply and grant feasible implementation. However, a thorough evaluation of short- and long-term variations in electric power and heat load of characteristic platforms is required at an individual platform level. Such evaluation shall take into consideration the availability of renewables and risk factors.

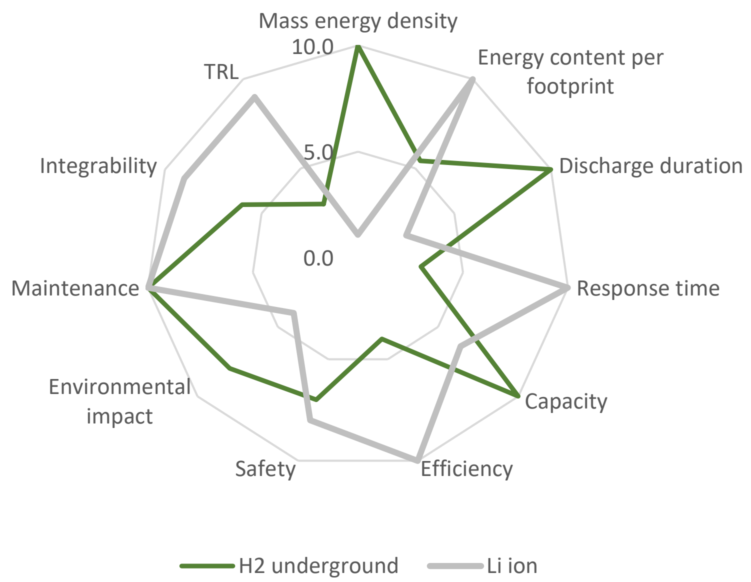

Figure 13. Spider chart of a hybrid battery–hydrogen system performance for each KPI. The data are available in Table 2.

5. Conclusions

The technical capabilities, of eleven energy storage solutions, including four types of batteries and four types of hydrogen storage technologies, were screened and assessed. The focus was on offshore use, based on eleven key performance indicators, namely, mass energy density, energy content per footprint, discharge duration, response time, storage capacity, efficiency, safety, environmental impact, maintenance requirement, ease of integrability and TRL.

The analysis of the storage solutions for offshore platforms shows that Li-ion batteries and CAES hold the most promise to meet partial energy demands in the near future. The readiness level and integrability of both technologies are instrumental for RES deployment offshore in the short term. For more distant future use, the similarity among numerous technologies precludes any value judgment. However, a hybrid storage system could prove helpful to overcome the current low maturity level of technologies with a potential to meet the entirety of the load requirements of offshore platform, given seasonal fluctuations.

This study mainly addressed technologies that could have a valid application potential based on the challenges of offshore environments and specificity of the operations therein. The application of the various screened solutions requires more work and dedicated platform-specific assessment, as none have been extensively tested offshore. Thorough CAPEX, OPEX, risk assessments and life cycle assessments also require further attention. Variations among the proposed technologies can significantly influence their applicability.

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Appendix A. Multiple Binary Decision Method

The analysis of the storage solutions for the short- and long-term scenarios was performed via the multiple binary decision (MBD) method, detailed in Ref [83].

The MBD method was employed to assess what KPIs were more relevant for each scenario. One-on-one KPIs comparisons yield weighting factors to further assess, among different storage solutions, the technologies with greater promise according to the scores obtained. The procedure is detailed below:

1. Each KPI is compared to one another based on the specificity of the scenario, that is, (A) 40% renewable energy by 2030 and (B) 100% renewable by 2050. As a result, two matrices, and hence, KPIs' ranks, will be obtained, one for each scenario.
2. For every row pertinent to a KPI, the said KPI is contrasted with every other KPI. If the KPI under evaluation is more relevant, the interjecting matrix element is assigned the value of "1". Otherwise, if such KPI is less relevant, the matrix element is rendered "0". The KPIs comparison yields a binary triangular matrix, where the upper triangle is opposite to the lower one.

3. If two KPIs are equally relevant, the interjecting matrix elements on both pertinent rows are assigned a value of "1". In such a case, the resulting upper and lower triangles will not be exact opposites.
4. Following the above steps, each parameter is compared to the remaining parameters. The KPI matrices obtained for every scenario are shown in Tables A1 and A2.

Table A1. KPI comparison matrix (Scenario A).

KPIs		A	B	C	D	E	F	G	H	I	J	K
Mass energy density	A		0	1	1	1	0	0	0	0	0	0
Energy per footprint	B	1		1	1	1	0	0	0	0	0	0
Discharge duration	C	0	0		1	1	0	0	1	0	0	0
Response time	D	0	0	0		1	1	0	0	0	0	0
Capacity	E	0	0	0	0		0	0	0	0	0	0
Efficiency	F	1	1	1	0	1		0	0	1	0	0
Safety	G	1	1	1	1	1	1		1	1	1	1
Environmental impact	H	1	1	0	1	1	1	0		1	0	0
Maintenance	I	1	1	1	1	1	1	0	0		0	0
Integrability	J	1	1	1	1	1	1	0	1	1		0
TRL	K	1	1	1	1	1	1	0	1	1	1	

Table A2. KPI comparison matrix (Scenario B).

KPIs		A	B	C	D	E	F	G	H	I	J	K
Mass energy density	A		0	0	0	0	0	0	0	0	1	1
Energy per footprint	B	1		0	0	0	0	0	0	1	1	1
Discharge duration	C	1	1		0	0	1	0	0	1	1	1
Response time	D	1	1	1		1	0	0	0	1	1	1
Capacity	E	1	1	1	1		1	0	0	1	1	1
Efficiency	F	1	1	0	1	0		0	1	1	1	1
Safety	G	1	1	1	1	1	1		1	1	1	1
Environmental impact	H	1	1	1	1	1	0	0		1	1	1
Maintenance	I	1	0	0	0	0	1	0	0		1	1
Integrability	J	0	0	0	0	0	0	0	0	0		1
TRL	K	0	0	0	0	0	0	0	0	0	0	

5. Once the one-to-one comparison is completed, and the indicative "ones" and "zeros" are obtained, the parameter weighting factors (W_{KPI_i}) are computed by applying the following equation:

$$W_{KPI\_i} = \frac{SW_{KPI\_i}}{ST_{KPI}} \times 100 \quad \text{(A1)}$$

where SW_{KPI_i} represents the parameter i weight from the sum of all elements in their respective row. ST_{KPI} is the total sum of the parameters scores. The weighting distribution for Tables A1 and A2 follows in Tables A3 and A4, respectively.

Table A3. KPI comparison matrix with weights (Scenario A).

	A	B	C	D	E	F	G	H	I	J	K	SW_{KPI_i}	W_{KPI_i}
A		0	1	1	1	0	0	0	0	0	0	3.0	5.4%
B	1		1	1	1	0	0	0	0	0	0	4.0	7.1%
C	0	0		1	1	0	0	1	0	0	0	3.0	5.4%
D	0	0	0		1	1	0	0	0	0	0	2.0	3.6%
E	0	0	0	0		0	0	0	0	0	0	0.0	0.0%

	A	B	C	D	E	F	G	H	I	J	K			
F	1	1	1	0	1		0	0	1	0	0		5.0	8.9%
G	1	1	1	1	1	1		1	1	1	1		10.0	17.9%
H	1	1	0	1	1	1	0		1	0	0		6.0	10.7%
I	1	1	1	1	1	1	0	0		0	0		6.0	10.7%
J	1	1	1	1	1	1	0	1	1		0		8.0	14.3%
K	1	1	1	1	1	1	0	1	1	1			9.0	16.1%
												ST_{KPI}	56	

Table A4. KPI comparison matrix with weights (Scenario B).

	A	B	C	D	E	F	G	H	I	J	K		SW_{KPI_i}	W_{KPI_i}
A		0	0	0	0	0	0	0	0	1	1		2	3.5%
B	1		0	0	0	0	0	0	1	1	1		4	7.0%
C	1	1		0	0	1	0	0	1	1	1		6	10.5%
D	1	1	1		1	0	0	0	1	1	1		7	12.3%
E	1	1	1	1		1	0	0	1	1	1		8	14.0%
F	1	1	0	1	0		0	1	1	1	1		7	12.3%
G	1	1	1	1	1	1		1	1	1	1		10	17.5%
H	1	1	1	1	1	0	0		1	1	1		8	14.0%
I	1	0	0	0	0	1	0	0		1	1		4	7.0%
J	0	0	0	0	0	0	0	0	0		1		1	1.8%
K	0	0	0	0	0	0	0	0	0	0			0	0.0%
												ST_{KPI}	57	

6. Once the parameters' weighting factors are obtained, the storage solutions are evaluated. All alternatives are contrasted with each other in reference to an alternately defined KPI. The technology with the best performance (according to the evaluation in Table 2) obtains a "1", otherwise a "0". If both technologies score the same, they are both assigned a "1" (indicated in yellow cells below).
7. Similar to the parameter weighting factors, the technology weighting factors per KPI (W_{T_i}) are computed by applying the following equation:

$$W_{T\_i} = \frac{SW_{T\_i}}{ST_T} \times 100 \tag{A2}$$

where SW_{T_i} represents the technology i weight from the sum of all elements in their respective row. ST_T is the total sum of the scores of the solutions.

8. The result is one matrix per every KPI, with the corresponding weights. Table A5 illustrates the procedure for parameter A: mass energy density.

Table A5. Technology comparison matrix for parameter A—mass energy density with weights.

Technology		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	SW_{T_i}	W_{T_i}
Lead–acid	I		0	1	0	0	1	1	0	0	0	0	0	0	3	3.30%
Li-ion	II	1		1	1	0	1	1	0	1	0	0	0	0	6	6.59%
Ni–Cd	III	1	0		0	0	1	1	0	0	0	0	0	0	3	3.30%
NaS	IV	1	1	1		0	1	1	0	1	0	0	0	0	6	6.59%
Ammonia	V	1	1	1	1		1	1	1	1	1	0	0	0	9	9.89%
CAES	VI	1	0	1	0	0		1	0	0	0	0	0	0	3	3.30%
HPES	VII	1	0	1	0	0	1		0	0	0	0	0	0	3	3.30%
SCESS	VIII	1	1	1	1	0	1	1		1	1	0	0	0	8	8.79%
FESS	IX	1	1	1	1	0	1	1	0		0	0	0	0	6	6.59%
H_2 MH	X	1	1	1	1	0	1	1	1	1		0	0	0	8	8.79%
H_2 gas	XI	1	1	1	1	1	1	1	1	1	1		1	1	12	13.19%

H_2 Liq	XII	1	1	1	1	1	1	1	1	1	1	1		1	12	13.19%
H_2 Underg.	XIII	1	1	1	1	1	1	1	1	1	1	1	1		12	13.19%
														ST_T	91	

9. The scores obtained for all KPIs (illustrated in Table A5) are then weighted by the specific weight per parameter within the parameters comparison matrix (refer to Tables A3 and A4). To exemplify this, take the technology I—Lead–acid battery—weight for parameter A (3.3%), parameter A weights for scenario A 5.4% according to Table A3; thereafter, the solution I score within the general matrix of Scenario A is computed as follows:

$$\frac{(3.3\times 5.4)}{100} = 0.18\text{ points} \tag{A3}$$

The scores obtained from Equation (A3) are later tabulated and added together to obtain the general score for every technology (See Tables A6 and A7). The graphical representations of these general matrices are in Figures 8 and 11.

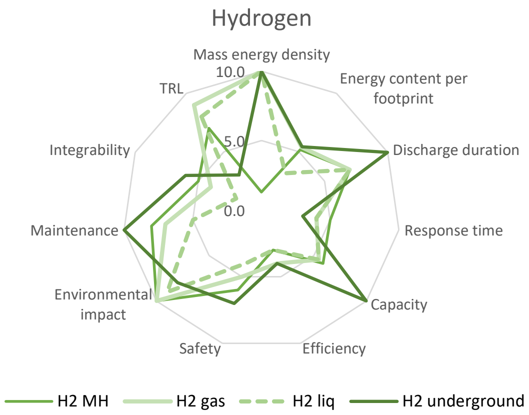
Table A6. General matrix of technology comparison for Scenario A.

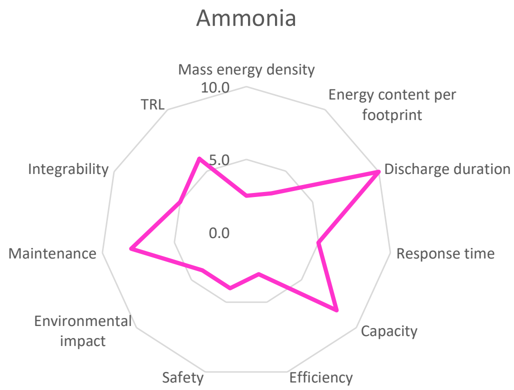
		Weight	Lead–Acid	Li-Ion	Ni–Cd	NaS	NH_3	CAES	HPES	SCESS	FESS	H_2 MH	H_2 Gas	H_2 Liq	H_2 Underg.
Mass energy density	A	5.4	0.2	0.4	0.2	0.4	0.5	0.2	0.2	0.5	0.4	0.5	0.7	0.7	0.7
Energy per footprint	B	7.1	0.2	1.1	0.1	1.0	0.5	0.9	0.3	0.4	0.0	0.6	0.8	0.6	0.8
Discharge duration	C	5.4	0.2	0.0	0.2	0.2	0.7	0.7	0.4	0.3	0.3	0.5	0.5	0.5	0.7
Response time	D	3.6	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.2	0.1	0.1	0.0
Capacity	E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Efficiency	F	8.9	0.9	1.2	0.9	0.9	0.2	0.5	1.2	0.6	1.2	0.2	0.4	0.2	0.4
Safety	G	17.9	2.0	2.0	2.0	0.6	0.2	2.0	2.4	2.0	2.4	0.6	0.6	0.4	1.0
Environmental impact	H	10.7	0.5	0.5	0.5	0.8	0.5	1.4	1.4	0.0	1.4	1.4	1.4	0.8	0.6
Maintenance	I	10.7	1.3	1.3	1.3	0.8	0.8	0.2	0.8	1.3	0.2	0.8	0.3	0.2	1.3
Integrability	J	14.3	2.0	2.0	2.0	1.5	0.5	1.0	1.3	1.0	1.3	0.5	0.2	0.0	1.0
TRL	K	16.1	2.1	2.1	1.2	1.2	0.5	2.1	0.3	0.2	2.1	0.7	2.1	1.2	0.2
Score		100	10	11	9	8	5	9	8	7	10	6	7	5	7

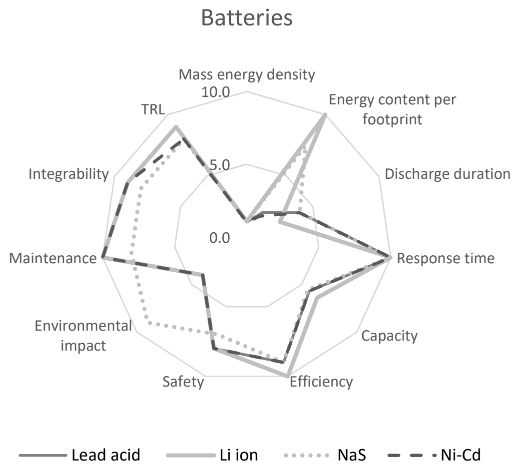
Table A7. General matrix of technology comparison for Scenario B.

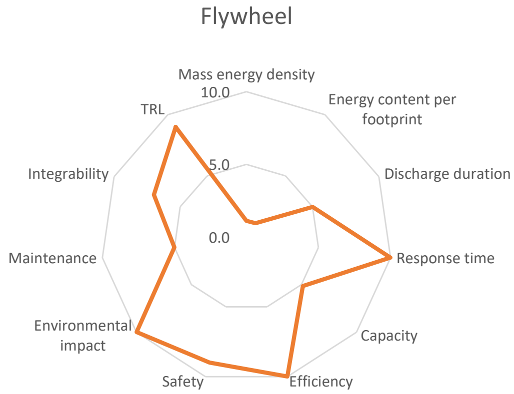
		Weight	Lead–Acid	Li-Ion	Ni–Cd	NaS	NH_3	CAES	HPES	SCESS	FESS	H_2 MH	H_2 Gas	H_2 Liq	H_2 Underg.
Mass energy density	A	3.5	0.1	0.2	0.1	0.2	0.3	0.1	0.1	0.3	0.2	0.3	0.5	0.5	0.5
Energy per footprint	B	7.0	0.2	1.0	0.1	1.0	0.5	0.9	0.3	0.3	0.0	0.6	0.8	0.6	0.8
Discharge duration	C	10.5	0.4	0.0	0.4	0.4	1.4	1.4	0.7	0.6	0.6	1.1	1.1	1.1	1.4
Response time	D	12.3	1.5	1.5	1.5	1.5	0.7	0.7	0.7	1.5	1.5	0.7	0.2	0.2	0.1
Capacity	E	14.0	1.5	1.5	1.5	1.5	1.7	0.3	0.0	0.2	0.8	1.5	0.8	0.8	1.9
Efficiency	F	12.3	1.3	1.7	1.3	1.3	0.3	0.7	1.7	0.8	1.7	0.3	0.6	0.3	0.6
Safety	G	17.5	1.9	1.9	1.9	0.6	0.2	1.9	2.3	1.9	2.3	0.6	0.6	0.4	1.0
Environmental impact	H	14.0	0.6	0.6	0.6	1.0	0.6	1.8	1.8	0.0	1.8	1.8	1.8	1.0	0.7
Maintenance	I	7.0	0.9	0.9	0.9	0.5	0.5	0.1	0.5	0.9	0.1	0.5	0.2	0.1	0.9
Integrability	J	1.8	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.0	0.0	0.1
TRL	K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Score		100	9	10	8	8	6	8	8	7	9	7	6	5	8

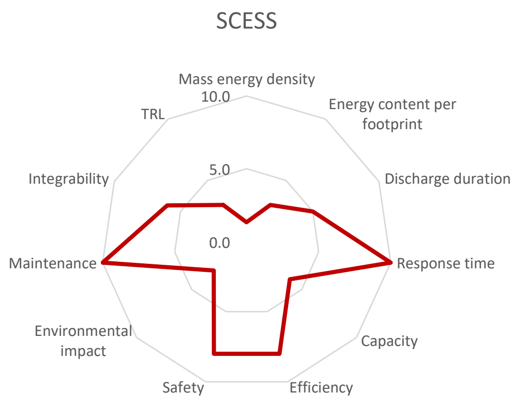
Appendix B. Overall Performance of Storage Solutions

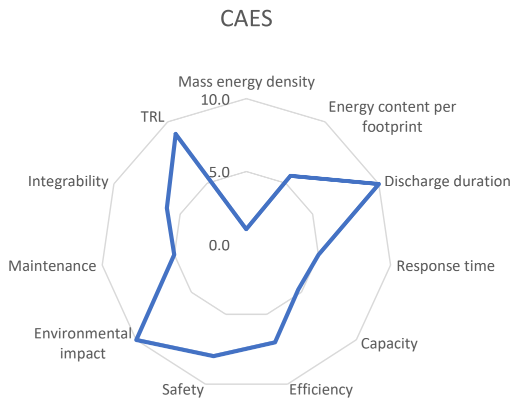












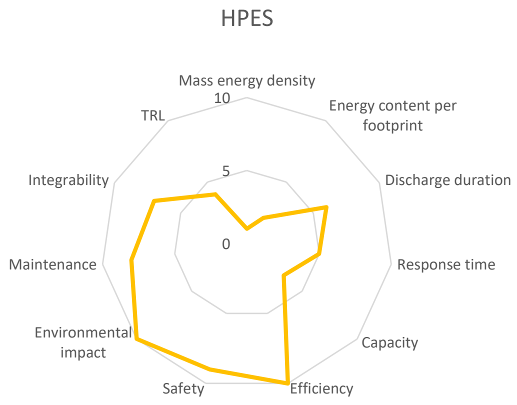


Figure A1. Spider charts of Energy Storage Systems for each KPI.

Appendix C. Complementary Information of the Energy Storage Technologies

Table A8. Information on safety, environmental impact, integrability and costs of energy storage technologies.

Technologies	(1) Safety Indicators, (2) Environmental Impact, (3) Maintenance Requirement	Integrability	Costs	Ref.
CAES	(1) The main concern with CAES is related to compressed air storage in vessels, i.e., catastrophic rupture of container. Yet, the safety regulations make this a rare occurrence at the cost of higher weight and additional safety features, such as pressure relief valves. (2) The highest negative environmental impact of CAES is related to underground storage in caverns, i.e., excavation process, materials and components used for construction and the structural stability for the membrane. If tanks were to be used for storage, the main impact would derive from abiotic depletion from raw materials used in the manufacturing of the vessels. (3) The maintenance requirements are the same as a simple cycle combustion engine (~USD 0.30/MWh generated).	Integrability of CAES should not be an issue in offshore platforms. The technology is based on conventional gas turbine technology, heat exchangers and underground storage/retrieval, largely customary in the oil and gas industry.	Power conversion system: EUR 696–928/kW Storage component: EUR 97–120/kWh O&M: EUR 3.9/kWh-yr [25]	[25,66,84]
H_2 stored in metal hydride	(1) Metal hydrides provide good safety features when compared to other hydrogen storage solutions, as they do not explode and may be rendered self-extinguishing. However, an important safety concern is the release temperatures of some metal hydrides, which can reach high temperatures (>500 °C), which can be prohibitive in the vicinity of certain processes and or hazardous areas. (2) It is seen as lacking negative environmental impact; however, the availability of the raw material for large-scale application involving lanthanum poses an environmental factor for consideration. (3) Metal hydrides can operate for decades without major losses. Commercially available systems claim 99% capacity after 3500 cycles. Yet, the charging and discharging of metal hydrides causes stress in the material, yielding tiny defects that eventually degrade the material's ability to store hydrogen. However, dedicated research is underway to improve the long-term efficiency, including particle size, controlled use of material defects, moisture and oxygen monitoring, thermal control, etc.	All of the key components for hydrogen production are readily available to the industry. Electrolysers are becoming more efficient as the technology further matures. The location of the storage solution withing the platform shall be carefully considered due to the high temperatures achieved during retrieval.	Power conversion system: Electrolysis and small to medium turbine (including balance of plant): EUR 1359–2673/KW Storage in hydrides: Low thermal hydrides: USD 14–200/kWh High-thermal hydrides: USD 10–20/kWh. O&M: EUR 25–45/kW-yr	[25,39,43,85–88]
H_2 compressed in tank	(1) Hydrogen has a low molecular size. In the event of a vessel failure, hydrogen will leak through the cracks, triggering an increase in the temperature due to the negative value of the Joule–Thompson coefficient. Once leaked, hydrogen forms an explosive mixture, given its wide range of flammable concentrations in the air and lower ignition energy than, e.g., natural gas. Special flame detectors are required. (2) The environmental impact of hydrogen is related to possible leakage. Hydrogen can be considered as an indirect greenhouse gas with the potential to increase global warming. This is because hydrogen reacts in the atmosphere with tropospheric OH radicals, disrupting the distribution of methane and ozone. However, the potential effects on climate from hydrogen-based energy systems would be over 10 times lower than those from fossil-fuel-based energy systems.	Reuse of platforms previously used for the oil and gas industry to accommodate the green hydrogen production is seen as a potential solution for decreased investment costs of energy production from wind turbines, especially as the electrolysers technology advances and costs decrease.	For costs of power conversion system and operation and maintenance, see metal hydrides above. Storage in tanks: USD 438/Kg [45]: ~ USD 13.1/kWh	[44,89–91]

	(3) Storage vessels should be subjected to non-destructive examination at planned intervals and be recertified periodically with regard to their safety and reliability. Cyclic service is of particular concern due to the potential failure due to fatigue and hydrogen embrittlement. Pressure vessels must follow standards, as well as the manufacturer's and best practice recommendations and consider the particularities of the location.			
H_2 liquefied in tank	The considerations described for compressed hydrogen systems are applicable to liquid systems. In addition: (1) Extremely low temperatures of liquid hydrogen yield air condensation on exposed surfaces, such as vessels and piping. Nitrogen, which has a lower boiling point than oxygen, will evaporate first, leaving oxygen-enriched condensation on the surface. All areas of potential condensation should be free of hydrocarbons (oils, grease, etc), and the insulation material shall be non-combustible to prevent possible ignition. Further, material integrity for low temperature operation should be thoroughly considered; the vessel and the connecting piping must have sufficient flexibility to prevent fatigue failures caused by thermal contraction. (2) For environmental impact, see notes on H_2 tanks above. (3) Even if hydrogen is not being drawn from the tank, the evaporation of liquid H_2 will take place at a rate of up to 1% per day. Hence, periodical pressure relief shall be accounted for as a normal part of operation.	The use of liquefaction plants within operating oil and gas platforms poses integrability issues that must be thoroughly addressed, such as the space availability and safety concerns.	For costs of power conversion system, see metal hydrides above. Liquefaction costs (including operation and maintenance based on the IDEALHY project): USD 58/kWh Storage: USD 149/kg ~ USD 4.8/kWh.	[41,42,91–94]
H_2 storage underground	(1,2) The main safety and environmental issues of underground storage of hydrogen are related to the unlikely events of unhindered escape of the stored gas in case of a blow-out and leakage through faults or other leakage paths. The former could be prevented by an automatically closing subsurface safety valve (SSSV); the latter has a lower incidence in depleted gas and oil fields, where the tightness is initially known and thoroughly tested. However, knowledge gaps exist regarding the geochemical, mineralogical and microbiological reactions, as well as geomechanical effects in geological stores in the presence of hydrogen. (3) During the operation of depleted oil fields, residual oil may periodically be produced and increase the operation and maintenance efforts of the storage.	Storing hydrogen in depleted gas fields would leverage promising features, such as proximity to reservoirs, proven tightness to gases over geological time periods and the already existing facilities for injection and withdrawal of hydrogen from the reservoir.	For costs of power conversion system and operation and maintenance, see metal hydrides above. Storage in underground caverns: EUR 0.2–11.6/kWh	[45,95]
Lead–acid -Flooded LA	(1) Poor performance at low or high temperatures, so they need a thermal management system. They also need appropriate ventilation to manage the off-gassing (hydrogen) or evaporated electrolyte. (2) They contain sulphuric acid, and they depend on hazardous and restricted materials. Lead is a restricted element under the RoHS. (3) Ample manufacturing and operational experience. It needs periodic water replacement.	Batteries for offshore applications are usually offered in container modules. Such modules include the batteries, dual connection shore, AC/DC drives, cooling, ventilation and fire protection. The container can be installed on the platform, or it can be coupled to the wind turbines. For installing the batteries offshore, there are several guidelines and regulations from the Norwegian maritime authority and DNV.	USD 150–500/kWh	[9,12,13,16,96].
Lead–acid -VRLA	(1) Non-flooded electrolyte design, which allows for operation in areas without the need for special ventilation. They are more sensitive to higher temperature environment than flooded lead–acid systems. (2) Similar to flooded LA.		USD 106–473/kWh	[9,16]

	(3) Very low maintenance and no water addition required [9].			
Ni–Cd	(1,2) Cd is very toxic and is a restricted element under the RoHS. (3) They survive at high-temperature environments. This battery is used for O&G installations. Easy installation and low maintenance. Resistance to mechanical and electrical abuses.		USD 250–1000/kWh	[8,12,16,70,97]
NaS	(1) Since the batteries operate at high temperatures (300–350 °C), they require a thermal enclosure. These batteries are recommended for use in stationary systems, since in the event of a crash, the ceramic electrolyte can be mechanically damaged, and uncontrollable reactions between the molten sodium and molten sulphur can occur. Special containment is required to manage high-temperature sodium and sulphide compounds, which are highly corrosive. (2) They use non-toxic materials and have a recyclability rate of 99%. (3) Low O&M requirement.		USD 263–735/kWh	[9,16,70]
Li-ion batteries	(1) Safety concerns over thermal runaway incidents for LCO. LFP and NMC reduce the risk of thermal runaways. (2) Currently, the recycling schemes and recovery rate are low. Several projects are looking for recycling paths for these batteries, but the diversity in the chemistry of these batteries poses a challenge. The availability of Lithium and cobalt is a concern, in case of aggressive demand scenarios. (3) Low O&M requirement.		USD 200–1260/kWh	[9,16,17]
FESS—flywheels	(1) Flywheels operate at high circumferential speeds, sometimes even up to 800 m/s. The main safety hazard is related to rotor failure with catastrophic effects. Up to a certain energy content, flywheels can be contained and mounted safely, even in the event of a severe rotor burst. Three design options to decrease the consequences and likelihood of failure are: safe housing to avoid penetration, breach or gas release/intake, bunker the system to avoid penetration or bunker destruction in the radial direction and axial direction, safety margin in rotor design. (2) Low environmental impact, as no greenhouse emission or toxic material is produced during operation. (3) Most flywheel systems use sealed, frictionless bearings and may require no lubrication and little maintenance; yet, replacement is often required, every 5 to 8 years. If the flywheel is coupled to a generator, it will require regular maintenance (coolant and oil changes, filters and batteries).	Integrability shall not be a showstopper. Flywheels have been used in numerous applications, including powering of turbomachinery and mechanical batteries in diverse sectors. Further, the presence of flywheels can enhance the batteries' storage time and, hence, increase their utilisation time [29].	Power conversion system: (including balance of plant) EUR 284–356/KW Operation and maintenance (variable/fixed): EUR 4.8–5.6/kW-yr/ EUR 1.1–2.9/kWh Storage: EUR 1030–18159/kWh [26]	[25,27,30,98,99]
SCESS—Supercapacitor	(1) A short circuit of a fully charged supercapacitor will cause a quick release of the stored energy, which can cause electrical arcing, with consequences to the integrity of the device. However, the generated heat is too low as to pose a real risk of explosion (unlike batteries). (2) Although supercapacitors are not polluting to the environment, their configuration (and new configurations of Lithium-ion batteries) may include carbon nanotubes, which are known toxic compounds for humans and other living beings. However,	Integrability shall not be an issue. Supercapacitors have been used in numerous applications. The supercapacitor space requires a thorough case-by-case assessment and compliance with relevant guidelines. In cases where the supercapacitor system is integrated into the platform power/energy management system, with other subsystems and components, the integration tests of the whole system are to be carried out.	EUR 6800–20,000/kWh	[100–104]

	large-scale environmental impact on a system level over the entire life cycle requires further investigation. (3) Supercapacitors can be charged and discharged millions of times and have a virtually unlimited life cycle. Further, supercapacitors are considered a maintenance-free technology.	Supercapacitor spaces are not to contain any heat sources or high fire risk objects, nor equipment supporting essential services.		
Ammonia fuel	(1) Poison gas and corrosive problems during loading. Although if leakage occurs, the ammonia smell can be detected at small concentrations. (2) Toxic gas for humans and for aquatic life. NOx (GHG) emission from ammonia combustion. (3) Ammonia has a 30 times lower cost per unit of stored energy compared to hydrogen. Ammonia fuel blends for gas turbine power generation is an immature field.	Ammonia is a potential marine fuel. There are several projects assessing the use of ammonia as fuel for ships or for producing it in an artificial island. Therefore, ammonia produced in an oil and gas platform can be very well integrated in a future marine fuel system.	Power conversion system: Electrolysis and fuel cell (including balance of plant) EUR 1630–3884/kW Operation and maintenance: EUR 24–39/kW-yr [26]	[25,55,56,61,105]
Hydro-Pneumatic Energy Storage (HPES)	(1,2) The technology uses pressurised seawater and compressed air. None of the subcomponents or materials are considered hazardous or flammable. (3) There is no information on the maintenance requirement.	The HPES system can stand alone on the sea beside the platform, or it can be coupled with the wind turbines. The deployment depth of the full scale is 100–250 m.	CAPEX: EUR 1800–3000/kWh	[31,32,73]

References

1. Emissions to Air. Available online: https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft (accessed on May 2022).
2. Norwegian Petroleum. Emission to Air, Gas Turbines. Available online: https://www.norskpetroleum.no/en/environment-and-technology/emissions-to-air/ (accessed on 18 May 2022).
3. Watson, S.; Moro, A.; Reis, V.; Baniotopoulos, C.; Barth, S.; Bartoli, G.; Bauer, F.; Boelman, E.; Bosse, D.; Cherubini, A.; et al. Future emerging technologies in the wind power sector: A European perspective. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109270. https://doi.org/10.1016/j.rser.2019.109270.
4. Ringkjøb, H.-K.; Haugan, P.M.; Solbrekke, I.M. A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renew. Sustain. Energy Rev.* **2018**, *96*, 440–459. https://doi.org/10.1016/j.rser.2018.08.002.
5. 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. https://doi.org/10.1016/j.rser.2017.07.062.
6. Paris Agreement, "Paris agreement," 2015. Available online: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf (accessed on).
7. Low-Emission's Research Centre. Available online: https://www.sintef.no/projectweb/lowemission/ (accessed on 18 May 2022).
8. Díaz-González, F.; Sumper, A.; Gomis-Bellmunt, O.; Villafafila-Robles, R. A review of energy storage technologies for wind power applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2154–2171. https://doi.org/10.1016/j.rser.2012.01.029.
9. IRENA. *Electricity Storage and Renewables: Costs and Markets to 2030*; IRENA: Abu Dhabi, United Arab Emirates, 2017.
10. Ultrabattery. Fukukawa Battery. Available online: https://corp.furukawadenchi.co.jp/en/products/indust/ub.html (accessed on 9 November 2021).
11. VRLA Rechargeable Battery MSB-2000. Available online: https://www.battery-direct.com/Datenblaetter/MSB2000.pdf (accessed on 18 May 2021).
12. The European Commission. *Roadmap on Directive 2011/65/EU on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS Directive)*; The European Commission: Brussels, Belgium, 2018.
13. Safety, Operation and Performance of Grid Connected Energy Storage Systems, DNV-GL. 2017. Available online: https://rules.dnv.com/docs/pdf/DNV/rp/2017-09/dnvgl-rp-0043.pdf (accessed on 11 August 2021).
14. Rand, D.A.J.; Moseley, P.T. Chapter 13-Energy Storage with Lead–Acid Batteries. In *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*; Moseley, P.T., Garche, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2015; pp. 201–222.
15. Pickard, W.F.; Shen, A.Q.; Hansing, N.J. Parking the power: Strategies and physical limitations for bulk energy storage in supply–demand matching on a grid whose input power is provided by intermittent sources. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1934–1945. https://doi.org/10.1016/j.rser.2009.03.002.
16. DNV GL. *Handbook for Maritime and Offshore Battery Systems*; DNV-GL: Bærum, Norway, 2016.
17. Zubi, G.; Dufo-López, R.; Carvalho, M.; Pasaoglu, G. The lithium-ion battery: State of the art and future perspectives. *Renew. Sustain. Energy Rev.* **2018**, *89*, 292–308, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2018.03.002.
18. Revankar, S.T. *Chemical Energy Storage*; Academic Press: Cambridge, MA, USA, 2019; pp. 177–227. https://doi.org/10.1016/b978-0-12-813975-2.00006-5.
19. Kousksou, T.; Bruel, P.; Jamil, A.; El Rhafiki, T.; Zeraouli, Y. Energy storage: Applications and challenges. *Sol. Energy Mater. Sol. Cells* **2014**, *120*, 59–80. https://doi.org/10.1016/j.solmat.2013.08.015.
20. Ellis, B.L.; Nazar, L.F. Sodium and sodium-ion energy storage batteries. *Curr. Opin. Solid State Mater. Sci.* **2012**, *16*, 168–177. https://doi.org/10.1016/j.cossms.2012.04.002.
21. Raza, W.; Ali, F.; Raza, N.; Luo, Y.; Kim, K.-H.; Yang, J.; Kumar, S.; Mehmood, A.; Kwon, E.E. Recent advancements in supercapacitor technology. *Nano Energy* **2018**, *52*, 441–473. https://doi.org/10.1016/j.nanoen.2018.08.013.
22. Zyga, L. Can Capacitors in Electrical Circuits Provide Large-Scale Energy Storage? *Phys. Org.* Available online: https://phys.org/news/2014-12-capacitors-electrical-circuits-large-scale-energy.html (accessed on 11 August 2021).
23. Berrueta, A.; Ursa, A.; Martin, I.S.; Eftekhari, A.; Sanchis, P. Supercapacitors: Electrical Characteristics, Modeling, Applications, and Future Trends. *IEEE Access* **2019**, *7*, 50869–50896.
24. Chang, L.; Hu, Y.H. Breakthroughs in Designing Commercial-LevelMass-Loading Graphene Electrodesfor Electrochemical Double-Layer Capacitors. *Matter* **2019**, *1*, 596–620.
25. Zakeri, B.; Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 569–596. https://doi.org/10.1016/j.rser.2014.10.011, ISSN 1364-0321.
26. Anvari-Moghaddam, A.; Dragicevic, T.; Meng, L.; Sun, B.; Guerrero, J.M. Optimal planning and operation management of a ship electrical power system with energy storage system. In Proceedings of the IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 23–26 October 2016; pp. 2095–2099. https://doi.org/10.1109/iecon.2016.7793272.
27. Amiryar, M.E.; Pullen, K.R. A Review of Flywheel Energy Storage System Technologies and Their Applications. *Appl. Sci.* **2017**, *7*, 286. https://doi.org/10.3390/app7030286.
28. Ramli, M.A.; Hiendro, A.; Twaha, S. Economic analysis of PV/diesel hybrid system with flywheel energy storage. *Renew. Energy* **2015**, *78*, 398–405. https://doi.org/10.1016/j.renene.2015.01.026.

29. De Groot, W.; Maloney, T.M.; Vanderaar, M.J. Power, Propulsion, and Communications for Microspacecraft Missions. In *Microsatellites as Research Tools*; Fei-Bin, H., Ed.; No. COSPAR Colloquia Series; Elsevier: Pergamon, Turkey, 1999; Volume 10, pp. 190–199.
30. Cutler, J.C. (Ed.). Flywheels. In *Encyclopedia of Energy*; Elsevier: New York, NY, USA, 2004; pp. 695–704.
31. Buhagiar, D.; Sant, T.; Farrugia, R.N.; Aquilina, L.; Farrugia, D.; Strati, F.M. Small-scale Experimental Testing of a Novel Marine Floating Platform with Integrated Hydro-pneumatic Energy Storage. *J. Energy Storage* **2019**, *24*, 100774. https://doi.org/10.1016/j.est.2019.100774.
32. Sant, T.; Buhagiar, D.; Farrugia, R.N.; Farrugia, D.; Strati, F.M. Cost Evaluation of Two Concepts for the Integration of Hydro-pneumatic Energy Storage in Floating Wind Turbines. *J. Physics Conf. Ser.* **2018**, *1037*, 042019. https://doi.org/10.1088/1742-6596/1037/4/042019.
33. Sheffield, J.; Martin, K.; Folkson, R. Electricity and hydrogen as energy vectors for transportation vehicles. In *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*; Woodhead Publishing: Sawston, UK, 2014; pp. 117–137. https://doi.org/10.1533/9780857097422.1.117.
34. Office of Energy Efficiency & Renewable Energy. An Office of U.S. Department of Energy, USA. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=On%20a%20volume%20basis%2C%20however,based%20on%20lower%20heating%20values (accessed on 26 May 2021).
35. Lindtvedt, J.K. Deep Purple. Available online: https://energyvalley.no/wp-content/uploads/2019/04/Deep-Purple-.pdf (accessed on 31 May 2022).
36. European Comission. HyStorIES-Hydrogen Storage In European Subsurface. Available online: https://cordis.europa.eu/project/id/101007176 (accessed on 20 May 2021).
37. Krishna, R.; Titus, E.; Salimian, M.; Okhay, O.; Rajendran, S.; Rajkumar, A.; Sousa, J.M.G.; Ferreira, A.L.C.; Campos, J.; Gracio, J. *Hydrogen Storage for Energy Application*; IntechOpen: London, UK, 2012. https://doi.org/10.5772/51238.
38. Sainz-Garcia, A.; Abarca, E.; Rubi, V.; Grandia, F. Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. *Int. J. Hydrogen Energy* **2017**, *42*, 16657–16666. https://doi.org/10.1016/j.ijhydene.2017.05.076.
39. Davoodabadi, A.; Mahmoudi, A.; Ghasemi, H. The potential of hydrogen hydrate as a future hydrogen storage medium. *iScience* **2021**, *24*, 101907. https://doi.org/10.1016/j.isci.2020.101907.
40. Di Profio, P.; Arca, S.; Rossi, F.; Filipponi, M. Comparison of hydrogen hydrates with existing hydrogen storage technologies: Energetic and economic evaluations. *Int. J. Hydrogen Energy* **2009**, *34*, 9173–9180. https://doi.org/10.1016/j.ijhydene.2009.09.056.
41. Stolzenburg, K.; Berstad, D.; Decker, L.; Elliott, A.; Haberstroh, C.; Hatto, C.; Walnum, H.T.; Klaus, M.; Mortimer, N.D.; Mubbala, R.; et al. "Efficient Liquefaction of Hydrogen: Results of the IDEALHY Project," in XXth Energie–Symposium, Stralsund/Germany. 2013. Available online: https://www.researchgate.net/publication/335033448_Efficient_Liquefaction_of_Hydrogen_Results_of_the_IDEALHY_Project#fullTextFileContent (accessed on 14 September 2021).
42. CleanTech, NCE Maritime. Norwegian Future Value Chains for Liquid Hydrogen. *Report*. Available online: https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf,2019 (accessed on 14 April 2022).
43. Ward, P.A.; Corgnale, C.; Teprovich, J.A.; Motyka, T.; Hardy, B.; Sheppard, D.; Buckley, C.; Zidan, R. Technical challenges and future direction for high-efficiency metal hydride thermal energy storage systems. *Appl. Phys. A* **2016**, *122*, 462. https://doi.org/10.1007/s00339-016-9909-x.
44. Kharel, S.; Shabani, B. Hydrogen as a Long-Term Large-Scale Energy Storage Solution to Support Renewables. *Energies* **2018**, *11*, 2825. https://doi.org/10.3390/en11102825.
45. Le Duigou, A.; Bader, A.-G.; Lanoix, J.-C.; Nadau, L. Relevance and costs of large scale underground hydrogen storage in France. *Int. J. Hydrogen Energy* **2017**, *42*, 22987–23003. https://doi.org/10.1016/j.ijhydene.2017.06.239.
46. Lord, A.S.; Kobos, P.H.; Borns, D.J. Geologic storage of hydrogen: Scaling up to meet city transportation demands. *Int. J. Hydrogen Energy* **2014**, *39*, 15570–15582. https://doi.org/10.1016/j.ijhydene.2014.07.121.
47. Cummins. HyLYZER Water Electrolyzers. Available online: https://www.cummins.com/sites/default/files/2021-08/cummins-hylyzer-1000-specsheet.pdf (accessed on 21 October 2021).
48. Zyga, L. First Analysis of the Water Requirements of a Hydrogen Economy; Phys.org; 2007. Available online: https://phys.org/news/2007-10-analysis-requirements-hydrogen-economy.html#:~:text=In%20one%20year%2C%2060%20billion,water%20per%20gallon%20of%20gasoline (accessed on 15 February 2022)
49. MWI Pumps. Large-Volume Pumps & Services. 2020. Available online: https://mwipumps.com/wp-content/uploads/Catalog-CIM-MWI-Pumps-9-17-20.pdf (accessed on 9 December 2021).
50. Goodwater Warehouse. Frame Mount Vertical. Available online: https://goodwaterwarehouse.com/cat/FMV-Spec-Sheet.pdf. (accessed on 9 December 2021).
51. Burckhardt Compression. Process Gas Compressors. Available online: https://www.burckhardtcompression.com/wp-content/uploads/2021/09/bc_bro_Process-Gas-Compressor_210917-v2_en.pdf. (accessed on 9 December 2021).
52. General Electric. Hydrogen Fueled Gas Turbines. https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines?gclid=Cj0KCQiAzMGNBhCyARIsANpUkzM2_KCtV_DT2j5WWpk980DLcr1JmhsRNsXP3Ps6klSrgXKrKf57hYE-aAksZEALw_wcB#customers (accessed on 9 December 2021).
53. Decker, L. Liquid Hydrogen Distribution Technology: HYPER Closing Seminar. Available online: https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf (accessed on 21 October 2021)

54. GNK. Hydrogen Storage Based on Metal Powder. Available online: https://www.gknpm.com/en/innovation/hydrogen-technology/hy2green/?__hstc=7113133.747ae4652e7716f57c904bef241a51f0.1579119203615.1579119203615.1579121060533.2&__hssc=7113133.2.1579121060533&__hsfp=502694344&_ga=2.97526879.1908624594.1621945332-1316774408.1621945332 (accessed on 25 May 2021).
55. Reyes-Lua, A.; Bucelli, M. *Reduced-Carbon Operation of Elgin and Franklin O&G Field-Module 2*; LowEmission Research Centre: Trondheim, Norway, 2021.
56. Assessment of Selected Alternative Fuels and Technologies. Group Technology & Research, White Paper. 2020. Available online: https://www.dnv.com/Publications/assessment-of-selected-alternative-fuels-and-technologies-rev-june-2019--116334 (accessed on 18 February 2022).
57. Valera-Medina, A.; Xiao, H.; Owen-Jones, M.; David, W.; Bowen, P. Ammonia for power. *Prog. Energy Combust. Sci.* **2018**, *69*, 63–102. https://doi.org/10.1016/j.pecs.2018.07.001.
58. Zhang, H.; Wang, L.; Van Herle, J.; Maréchal, F.; Desideri, U. Techno-economic comparison of green ammonia production processes. *Appl. Energy* **2019**, *259*, 114135. https://doi.org/10.1016/j.apenergy.2019.114135.
59. Enge, M.; Lunde, A. *Ammonia as Fuel in Maritime Energy Systems*; Høgskulen på Vestlandet: Haugesund, Norway, 2021.
60. Ammonia as a Marina Fuel. *Safety Hankbook*. 2020. Available online: https://grontskipsfartsprogram.no/wp-content/uploads/2022/03/Ammonia-as-Marine-Fuel-Safety-Handbook-Rev-01.pdf (accessed on 15 February 2022)
61. Linde. Ammonia, Datasheet. Available online: https://www.linde-gas.com/en/images/linde-datasheet-01-ammonia-June-2017_tcm17-417364.pdf (accessed on 14 October 2021).
62. Bindra, H.; Revankar, S. *Storage and Hybridization of Nuclear Energy: Techno-Economic Integration of Renewable and Nuclear Energy*; Academic Press: Cambridge, MA, USA, 2018.
63. Beaudin, M.; Zareipour, H.; Schellenberglabe, A.; Rosehart, W. Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy Sustain. Dev.* **2010**, *14*, 302–314. https://doi.org/10.1016/j.esd.2010.09.007.
64. Luo, X.; Wang, J.; Dooner, M.; Clarke, J.; Krupke, C. Overview of Current Development in Compressed Air Energy Storage Technology. *Energy Procedia* **2014**, *62*, 603–611. https://doi.org/10.1016/j.egypro.2014.12.423.
65. Howitt, M. CAES or Batteries? Available online: https://www.storelectric.com/caes-or-batteries/ (accessed on 25 May 2021).
66. CTCN. Compressed Air Energy Storage (CAES). Available online: https://www.ctc-n.org/technologies/compressed-air-energy-storage-caes (accessed on 15 September 2021).
67. Degl'Innocenti, J. *Compressed Air Energy Storage for Clean Offshore Energy Supply*; Department of Energy and Process Engineering, Norwegian University of Science and Technology: Trondheim, Norway, 2018. Available online: http://hdl.handle.net/11250/2560131 (accessed on 12 May 2022).
68. Oldenburg, C.M.; Pan, L. Porous Media Compressed-Air Energy Storage (PM-CAES): Theory and Simulation of the Coupled Wellbore–Reservoir System. *Transp. Porous Media* **2013**, *97*, 201–221. https://doi.org/10.1007/s11242-012-0118-6.
69. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2014.09.081.
70. Fan, X.; Liu, B.; Liu, J.; Ding, J.; Han, X.; Deng, Y.; Lv, X.; Xie, Y.; Chen, B.; Hu, W.; et al. Battery Technologies for Grid-Level Large-Scale Electrical Energy Storage. *Trans. Tianjin Univ.* **2020**, *26*, 92–103. https://doi.org/10.1007/s12209-019-00231-w.
71. Dias, V.; Pochet, M.; Contino, F.; Jeanmart, H. Energy and Economic Costs of Chemical Storage. *Front. Mech. Eng.* **2020**, *6*, 21. https://doi.org/10.3389/fmech.2020.00021.
72. European Union. European Renewable Energy Network Study, Brussels. 2012. Available online: https://www.europarl.europa.eu/document/activities/cont/201202/20120208ATT37544/20120208ATT37544EN.pdf (accessed on 14 October 2021).
73. FLASC. Available online: https://www.offshoreenergystorage.com/ (accessed on 10 September 2021).
74. Mordor Intelligence. Global Supercapacitors Market-Growth, Trends, COVID-19 Impact, and Forecasts (2022–2027). 2021. Available online: https://www.mordorintelligence.com/industry-reports/supercapacitors-market (accessed on 10 September 2021).
75. Gardiner, M. Energy Requirements for Hydrogen Gas Compression and Liquefaction as Related to Vehicle Storage Needs. *DOE Hydrogen and Fuel Cells Program Record*; Volume 9013. 2009. Available online: https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf (accessed on 25 November 2021).
76. Di Christopher, T. *Hydrogen Technology Faces Efficiency Disadvantage in Power Storage Race*; S&P Global Market Intelligence: New York, NY, USA, 2021.
77. NCCS. *Hydrogen-Firing of Gas Turbines*; SINTEF: Trondheim, Norway, 2019.
78. Hydrogen Council. How Hydrogen Empowers the Energy Transition. 2017. Available online: https://cdn.hexagongroup.com/uploads/2019/11/Hydrogen-Council-Vision-Document.pdf (accessed on 26 May 2021).
79. Warner, N.; Carey, V.; Pierce, M. *Quantitative Risk Analysis for Battery Energy Storage Sites*; DNV GL: Bærum, Norway, 2019. Available online: https://www.dnv.com/Publications/quantitative-risk-analysis-for-battery-energy-storage-sites-154811 (accessed on 18 August 2022).
80. SINTEF. *Low Emission/OFFLEX Workshop on Offshore Energy Storage*; SINTEF: Trondheim, Norway, 2021.
81. DNV. Ammonia as a Marine Fuel. Available online: https://www.dnv.com/Publications/ammonia-as-a-marine-fuel-191385 (accessed on 20 May 2021).

82. Costamagna, M.; Barale, J.; Carbone, C.; Luetto, C.; Agostini, A.; Baricco, M.; Rizzi, P. Environmental and economic assessment of hydrogen compression with the metal hydride technology. *Int. J. Hydrogen Energy* **2022**, *47*, 10122–10136. https://doi.org/10.1016/j.ijhydene.2022.01.098.
83. Arellano, Y.; Brito, A.; Trujillo, J.; Cabello, R. Comprehensive Evaluation of Gas-Liquid Cyclonic Separation Technologies. In *Computational and Experimental Fluid Mechanics with Applications to Physics, Engineering and the Environment*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 397–408.
84. RICAS 2020. Feasibility Study and Final Conceptual Design-Deliverable D2.2. 2018. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bf0ca8f0&appId=PPGMS (accessed on 18 January 2021).
85. Conte, M. Hydrogen economy for a sustainable development: State-of-the-art and technological perspectives. *J. Power Sources* **2001**, *100*, 171–187. https://doi.org/10.1016/s0378-7753(01)00893-x.
86. GNK Hydrogen. Metal Hydride Energy Storage. Available online: https://www.gknhydrogen.com/ (accessed on 31 May 2022).
87. Ulvestad, A.; Welland, M.J.; Cha, W.; Liu, Y.; Kim, J.W.; Harder, R.; Maxey, E.; Clark, J.N.; Highland, M.J.; You, H.; et al. Three-dimensional imaging of dislocation dynamics during the hydriding phase transformation. *Nat. Mater.* **2017**, *16*, 565–571. https://doi.org/10.1038/nmat4842.
88. Nguyen, H.Q.; Shabani, B. Review of metal hydride hydrogen storage thermal management for use in the fuel cell systems. *Int. J. Hydrogen Energy* **2021**, *46*, 31699–31726. https://doi.org/10.1016/j.ijhydene.2021.07.057.
89. Utgikar, V.P.; Thiesen, T. Safety of compressed hydrogen fuel tanks: Leakage from stationary vehicles. *Technol. Soc.* **2005**, *27*, 315–320. https://doi.org/10.1016/j.techsoc.2005.04.005.
90. DG Environment News Alert Service. *Global Environmental Impacts of the Hydrogen Economy*; European Commission DG Environment News Alert Service. 2006. Available online: https://ec.europa.eu/environment/integration/research/newsalert/pdf/39na1_en.pdf (accessed on 15 October 2021)
91. Hydrogen Tools. Maintenance Requirements for Vessels. Available online: https://h2tools.org/bestpractices/maintenance-requirements-vessels (accessed on 15 September 2021).
92. Linde. *Hydrogen, Refrigerated Liquid Safety Data Sheet P-4603;* Linde Inc.: Tonawanda, NY, USA, 2021.
93. Kushnir, P. *Hydrogen as an Alternative Fuel*; Army Logistics University: Fort Lee, VA, USA, 2000; Volume 32, No. 3.
94. Bonacina, C.N.; Gaskare, N.B.; Valenti, G. Assessment of offshore liquid hydrogen production from wind power for ship refueling. *Int. J. Hydrogen Energy* **2021**, *47*, 1279–1291. https://doi.org/10.1016/j.ijhydene.2021.10.043.
95. HyUnder. Overview on All Known Underground Storage Technologies for Hydrogen. 2013. Available online: http://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf (accessed on 16 April 2020).
96. Pinnangudi, B.; Kuykendal, M.; Bhadra, S. *Smart Grid Energy Storage*; Academic Press: Cambridge, MA, USA, 2017; pp. 93–135. https://doi.org/10.1016/b978-0-12-805321-8.00004-5.
97. HBL. Nickel Cadmiun Vented Type Batteries. Available online: http://www.hblbatteries.com (accessed on 15 May 2021).
98. vor dem Esche, R. *Safety of Flywheel Storage Systems*; Stornetic: Jülich, Germany, 2016.
99. Schairer, K. Flywheel Maintenance—A Checklist. Available online: https://www.qpsolutions.net/2017/08/flywheel-maintenance-a-checklist/ (accessed on 25 November 2021).
100. EE Power. Capacitor Guide—Chapter 2: Supercapacitor. Available online: https://eepower.com/capacitor-guide/types/supercapacitor/# (accessed on 30 November 2021).
101. Rodriguez-Garcia, G.; Weil, M. *Potential Environmental Impacts of Li-ion Batteries and Supercapacitors: Toxicity of Carbon Nanotubes*; The Ulm Electrochemical Talks (UECT): Ulm, Germany, 2014. Available online: https://www.researchgate.net/publication/264081052_Potential_environmental_impacts_of_Li-ion_batteries_and_supercapacitors_Toxicity_of_carbon_nanotubes.
102. Weil, M.; Dura, H.; Shimon, B.; Baumann, M.; Zimmermann, B.; Ziemann, S.; Lei, C.; Markoulidis, F.; Lekakou, T.; Decker, M. Ecological assessment of nano-enabled supercapacitors for automotive applications. *IOP Conf. Series Mater. Sci. Eng.* **2012**, *40*, 012013. https://doi.org/10.1088/1757-899x/40/1/012013.
103. Stepanov, A.; Galkin, I. Development of Supercapacitor Based Uninterruptible Power Supply. 2007. Available online: http://egdk.ttu.ee/files/kuressaare2007/Kuressaare2007_136Stepanov-Galkin.pdf (accessed on 15 June 2021).
104. *Use of Supercapacitors in the Marine and Offshore Industries*; A. B. o. Shipping: Houston, TX, USA, 2017. Available online: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/288_supercapacitors_2017/Supercapacitors_Guide_e-Dec17.pdf (accessed on 13 February 2022).
105. Papadias, D.D.; Peng, J.-K.; Ahluwalia, R.K. H2@Scale: Outlook of Hydrogen Carriers at Different Scales. 2019, Presentation. Available online: https://www.energy.gov/sites/prod/files/2020/03/f72/fcto-hydrogen-carriers-workshop-2019-anl.pdf (accessed on 15 May 2022).