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Chapter 8

Energy Storage Technology for Decentralised Energy Management: Future Prospects

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Additional information is available at the end of the chapter

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Abstract

The chapter provides a comparison of energy storage technologies in decentralised energy systems for energy management. The various costs, advantages and disadvantages of the storage technologies will be considered. System dynamics modelling will be used to analyse energy management within the decentralised renewable and storage systems. Additionally, the integration of hydrogen storage technology and the use of hydrogen as an energy carrier in a decentralised airport scenario will be highlighted and the arising advantages of a decentralised airport using novel electric planes powered by hydrogen are discussed.

Keywords: decentralised energy storage, energy management, transport, hydrogen, airbus

1. Introduction

Successful management of future energy systems requires not efficient generation and use of energy but also the integration of storage technology to improve energy security, reduce fuel price volatility and allow further penetration of renewable energy by managing energy generation. There are many different types of storage technologies and approaches available with redox flow batteries (RFBs) and hydrogen storage being discussed in further detail including current and future techno-economic impacts of the storage technology. The use of storage technologies is of paramount importance for transitioning to a low-carbon, sustainable and resource efficient economy. The potential integration of energy storage technologies can be complementary within systems for optimal energy management and will also be considered within the study.

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The subject area of this chapter will focus on the energy management of decentralised energy systems using storage technologies. As a result of the transitioning energy sector towards a decarbonised system, a lot of change is occurring within the industry. The development and use of energy storage technologies are one such change that is occurring. Energy storage devices can manage the supply and demand mismatch of renewable energy within decentralised systems. The anticipated hydrogen economy will be of focus as one sustainable energy carrier for storage and therefore energy management. Both compressed and liquid hydrogen will be considered as hydrogen is important as it allows the storage of an energy carrier that can also be used as a cryogen when liquefied which will have implications for the superconducting industry. This additional benefit of hydrogen for will be considered in further detail with the use of liquid hydrogen for a decentralised future innovative airport scenario highlighted.

The preliminary chapter map is presented in **Figure 1**. The growth of renewable energy will be first discussed. Although the continued integration of renewable energy increases indigenous energy generated and therefore reduces import dependence. It is important to note with increased intermittent energy generation introduced an increased amount of back-up fossil fuel energy or adequate amounts of storage capacity is required. Storage technology with focus on hydrogen and redox flow batteries will then be considered. Finally, the case for the decentralised hydrogen production, storage, liquefaction and use on electric airplanes will be presented.

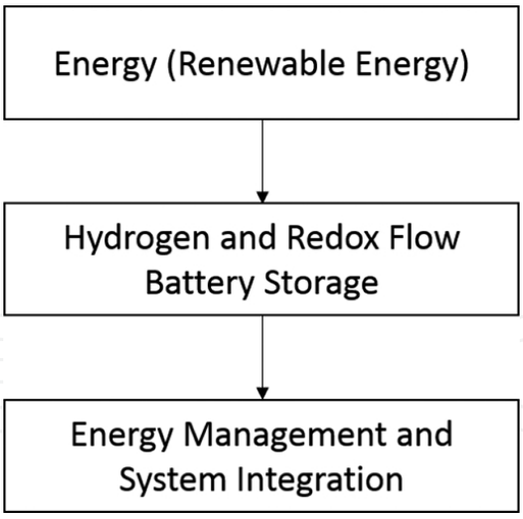


Figure 1. Preliminary chapter map.

The key result will present decentralised hydrogen and redox flow batteries for storage that can be used for energy management. The study will provide a basis for reference when considering the current and future prospects of energy storage in decentralised energy systems that can aid with the management of renewable energy. Further advantages and disadvantages of the technologies will be considered also including additional benefits arising from storage

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focusing on the storage of hydrogen as an energy carrier for novel electrically powered, superconducting airplanes.

2. Renewable energy and energy storage

2.1. Growth of renewable energy

The world is transitioning to a decarbonised economy, less than 300 years after the emergence of the industrial revolution. There is widespread acceptance for this transition due to accelerating climate change, increasing population and increasing demand for finite resources. A shift towards the use of novel, low carbon alternative fuels and technology is imminent. As from **Table 1**, it can be deduced an overall electricity demand is increasing; however, more of this electricity is being met by renewables. Additionally, renewable energy is also important for the heat and transport sectors and it is estimated that ~11% of energy consumption is from renewable energy sources and this is expected to rise to 15% by 2040 [1]. With the continued penetration of renewable energy storage technology can be a potential solution to manage curtailment within the system caused by supply and demand mismatch.

	2000 (%)	**2012 (%)**
Nuclear	16.68	10.86
Fossil Fuels	63.57	67.17
Hydroelectricity	17.86	16.89
Geothermal	0.351	0.315
Solar	0.007	0.444
Tide and Wave	0.004	0.002
Wind	0.21	2.41
Biomass and Waste	1.12	1.78
Pumped Hydroelectric Storage	0.18	0.12
Total Electricity (billion kWh)	14681.87	21582.97

Table 1. Global electricity generation expressed as a percentage of total electricity generation [2].

2.2. Energy storage

Storage systems like pumped hydroelectric energy storage (PHES) have been in used since 1929 for energy management [3]. Although it is clear that energy storage is an established concept, storage technologies are currently not a widespread solution. Energy storage technologies have different characteristics including applications, suitable power capacities, energy storage capacities, efficiencies, costs and response time. A discussion on the integration of energy storage technologies to complement other storage technologies will be included. The main function of the discussion of storage systems is to identify their role in energy manage-

ment of decentralised energy generation systems integrated with renewable technology. Furthermore, storage technology is important within energy systems as it can serve many different functions that will be further discussed in the case of hydrogen. There are a wide range of storage technology that are available today; however, many are not currently at the commercial stage or suffer from high economic costs. Currently, pumped hydroelectric energy storage represents 98.3% of total installed storage capacity for the grid (127 GW) and less than 10 MW of capacity is from redox flow batteries, **Figure 2** [4, 5]. The use of alternative energy storage technologies to pumped hydro-electric storage can allow the continued successful integration of renewable energy into the grid. Renewable energy allows countries to develop an indigenous energy supply as resources are available worldwide.

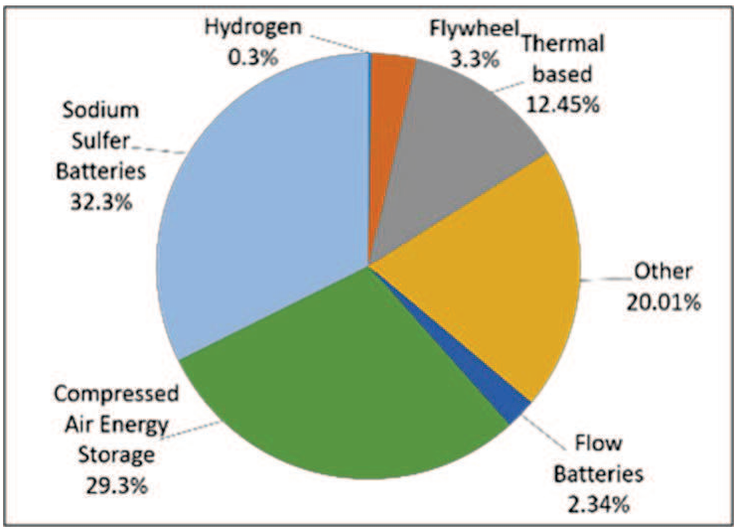


Figure 2. Non-pumped hydroelectric storage installed capacity accounting for 1% of worldwide storage capacity, with hydrogen and flow batteries included [4].

As the energy industry is undergoing a transition to a decarbonised energy system, energy storage is becoming a realistic option to aid this transition. Hydrogen storage and redox flow batteries are further discussed in the next section.

In an energy view depicted in **Figure 3**, the use of storage including hydrogen storage, pumped hydroelectric storage and stationary battery storage is considered. However, the use of the stored energy is considered only for electricity and meeting electric needs in a centralised manner. This chapter wants to provide an insight into the management of distributed energy systems that can focus more on the overall picture rather than just electricity. The use of renewable energy within the energy system has mainly focused on the electricity sector. Currently, in the European Union, 25.5% of electricity demand is met by renewables, 16.5% for heat and cooling and 5.4% for transport [6]. The focus for the use of renewable energy for transport will increase as a result of energy polices and energy security particularly in the transport sector. The source of final energy consumption is becoming more important, and the need for more complex energy systems that integrate the electricity, heat and transport sectors is required to ensure the optimal management and use of resources. Hydrogen is a flexible

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energy carrier as a result its potential use in the sectors as mentioned and alternatively as a storage and cryogenic medium.

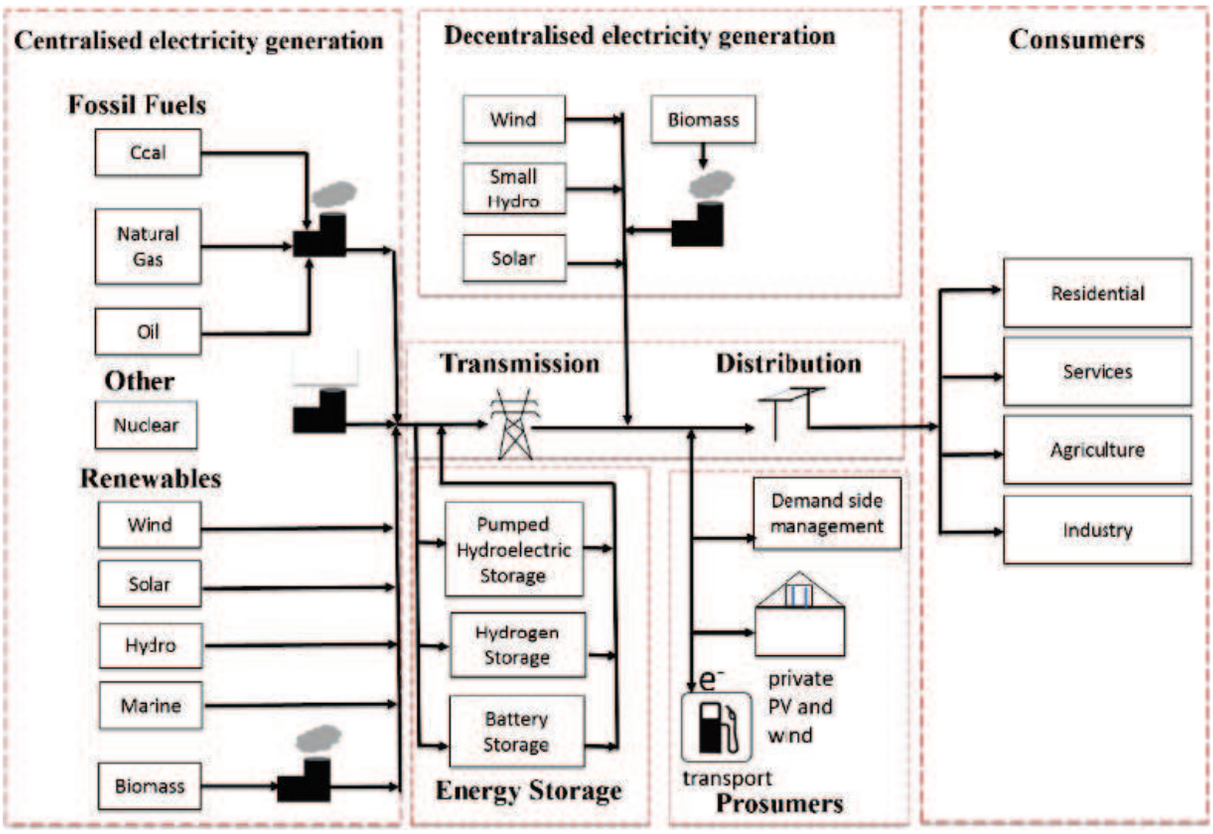


Figure 3. Current energy systems highlighting the dependence on centralised energy generation.

3. Hydrogen and redox flow batteries storage technologies

3.1. Hydrogen storage for energy management

Hydrogen is one sustainable alternative fuel and cryogen for future energy and resource requirements that can be stored in both gaseous and liquid form. Hydrogen's use as an energy carrier is well known; however, it has failed to successfully penetrate energy markets on a large scale. With focus on the transition from conventional energy generation methods and fuels, the 'hydrogen economy' can now emerge and be a key enabler to securing a sustainable, decarbonised energy future [7–9].

For hydrogen to be considered, a low-carbon fuel renewable electrolysis and zero-low carbon methods of hydrogen production using natural gas such as the microwave plasma processing of natural gas and thermal cracking of methane can be considered for a decentralised solution. The cost of hydrogen from wind electrolysis depends on the wind electricity generation price in a particular region, but it can typically vary from 3.58 to 5.86 $/kg with other sources

estimating higher costs of 6–7 $/kg [10]. PV electrolysis is more expensive than wind electrolysis with expected current values of 28.19 $/kg and future values of 6.18 $/kg due to expected rapid cost decrease of PV energy [10, 11]. Among different processing methods, microwave plasma processing of natural gas is a 'low-emission' (zero CO_2) production method. The technology has a high efficiency with an estimated hydrogen production cost of 1.5 $/kg, noticeably lower than the renewable electrolysis process, and is dependent on natural gas prices. Alternatively, the steam methane reforming method of hydrogen production the most common way to produce hydrogen today integrated with carbon capture and storage can be considered [12]. Low-carbon hydrogen generation is anticipated due to the aforementioned increase in penetration of renewable energy and also for providing an additional low-carbon fuel for the transport sector. Therefore, suitable methods for bulk energy storage and on-board storage for hydrogen transport must be available [13]. Four different methods of hydrogen storage are currently being considered; high pressure compressed hydrogen, liquid hydrogen in insulated tanks, solid-state hydride storage and porous solid adsorption of molecular hydrogen [14, 15]. Storage of compressed hydrogen requires high pressures (200–700 bar) and liquid hydrogen requires low temperatures (20.39 K) [16]. Another possibility for storing hydrogen is by the formation of metal hydrides. High volumetric capacities can be reached with metal hydrides, but energy is required for heating for hydrogen release. Finally, adsorption in porous material is an alternative hydrogen storage method that research has grown significantly.

Carbon fibre-reinforced composite tanks for 350 bar and 700 bar compressed hydrogen are under development and are already used for hydrogen storage for stationary applications and hydrogen-powered vehicles. The cost of high-pressure compressed hydrogen gas tanks depends on the pressure needed and the amount of the carbon fibre that must be used for structural reinforcement for the storage tanks. Liquid hydrogen is an alternative hydrogen storage method. A hybrid liquid hydrogen storage and superconducting magnetic energy storage (SMES) system can provide a robust energy system for back-up power. Alternatively, it can be considered for storage at refuelling stations for transport [14]. Liquid hydrogen tanks can, in principle, store more hydrogen in a given volume than compressed gas tanks, since the density of liquid hydrogen is 70 kg/m^3 compared to compressed hydrogen that has a density of 39 kg/m^3 at 700 bar, **Figure 4** [13].

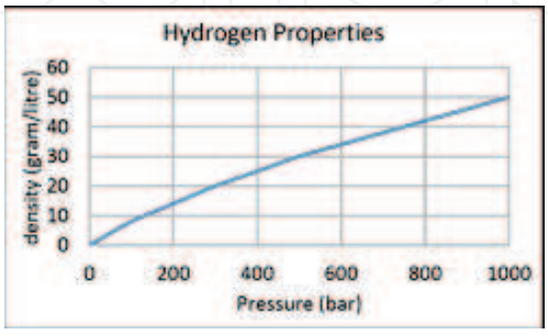


Figure 4. Increasing density of hydrogen with pressure for compressed hydrogen storage [13].

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Liquid hydrogen is stored in cryogenic tanks at ~20 K at ambient pressure because of the low critical temperature of hydrogen (33 K) [17]. Key issues with liquid hydrogen tanks are hydrogen boil-off estimated at 1%/day [14], and the large amount of energy required for hydrogen liquefaction [14], as well as tank cost [13]. Liquid hydrogen storage has the largest energy requirement and for storage times longer than a week the boil-off rate is problematic. For compressed hydrogen, the storage cost is eventually limited by the compressor electricity cost. One option for compressed gas storage is to increase the operating pressure of the system. This increases the cost of the pressure vessel and compressor, but the reduction in tank size can result in an overall savings [18]. The hydrogen stored can be used in a wide range of energy management techniques discussed in the next section.

Hydrogen is envisioned to emerge in niche decentralised markets and can be used for energy management of renewable energy as well as the use in transport. In this sense, hydrogen could form the basis of a synergistically operating buffer mechanism facilitating the integration of intermittent renewable energy, reducing CO_2 emissions as well as enhancing indigenous energy supply and increasing energy security. For the investigation of the hydrogen buffer operation if an unconstrained system using surplus renewable electricity during low demand hours for hydrogen generation and storage is considered the system may result in hydrogen not being produced if there is no excess wind. This would mean a lack of energy security within the system. Alternatively, the use of a hydrogen buffer system for energy management that constrains the wind energy for hydrogen production instead of demand to provide some security to the system could be alternatively considered, **Figure 5b** as a solution.

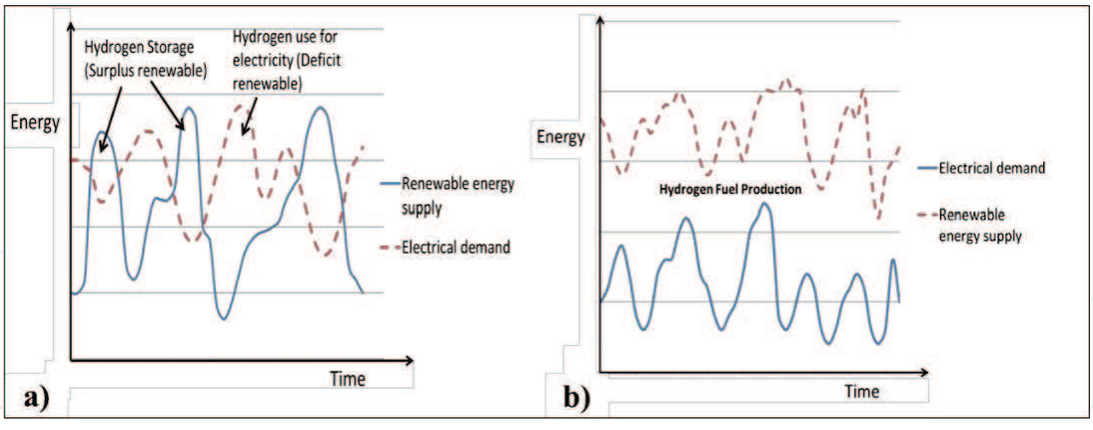


Figure 5. Comparison of (a) hydrogen storage for meeting demand when required leaving the system vulnerable to a lack of hydrogen energy available in storage, (b) hydrogen use as a buffer allowing excess hydrogen to be accessed if required.

System dynamics is a system modelling tool that uses various control factors and observes how the system and variables behave in response to time-based trends. In system dynamic models, there are main stock and flow quantities. Stocks represent the status of the system, the quantities that exist at any given moment (e.g. hydrogen storage). Rate variables show the speed of flow in or out of the stocks (e.g. hydrogen production and use), and they serve as the

decision making variables in a system. From a system dynamics model, the cost of electricity calculated varies from 0.4 to 0.97 €/kW h when the system is ran with no energy buffer, **Figure 6**. Although with optimum cost for the high wind scenario, this system is vulnerable to a large increase in the price with low wind energy. With this operation, the hydrogen production and use are not managed. When there is extra wind in the system, hydrogen is produced; when there is a deficit of energy within the system, hydrogen is converted to electricity (**Figure 5b**). **Figure 5b** shows the operation of a hydrogen buffer with increased security in the system with the hydrogen storage acting as a buffer for the wind energy. The system is managed and constrained to ensure that hydrogen is available if there is now renewable energy available in the system. In the system that constrains, the use of hydrogen for peak times only the cost of electricity from hydrogen ranges from 0.74 to 0.85 €/kW h. The estimated cost of electricity from hydrogen ranges from 0.28 to 0.6 €/kW h in literature [19]. The results highlight the potential use of a hydrogen buffer storage system to manage decentralised renewable energy systems.

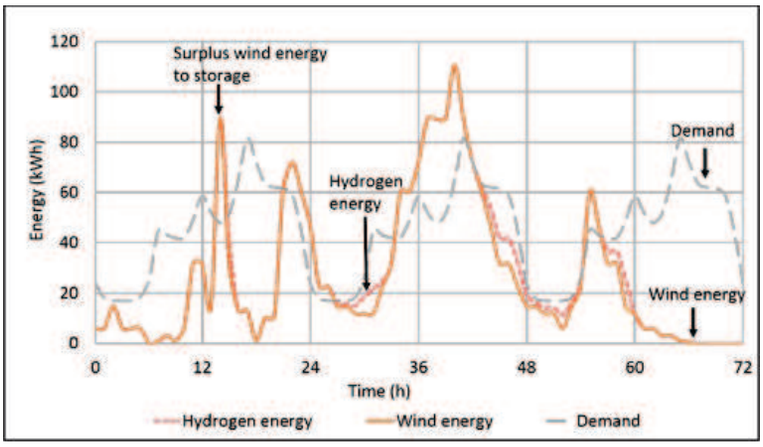


Figure 6. Energy versus time diagram for system operation without energy management of hydrogen storage as a buffer. Excess wind energy produces hydrogen for storage; however, not enough hydrogen is available to prevent the requirement of grid energy but reduces curtailment in the system.

3.2. Redox flow batteries

Redox flow batteries (RFBs) have promising storage characteristics and, as the power and energy capacity of the battery are independent of each other, the RFBs can be optimised to maximise the performance and minimise the cost [20, 21]. RFBs are rechargeable systems that have the storage medium in the form of electrolyte kept in tanks external to the active cell. The electrochemical reactions and the charging and discharging battery cycles are taking place in the battery stack as the electrolyte flows through the two membrane-separated chambers of the active cell, **Figure 7** [20, 21]. The energy is stored in the separated reactants (electrolytes), while the power is controlled by the stack, **Figure 7** [20, 21]. In general, RFBs share similar flow geometries and the main differences typically occur in the electrolyte that is used [21–23]. The RFBs can operate at low temperatures (from -10 to +45°C) as long as the electrolytes remain stable and their precipitation does not occur.

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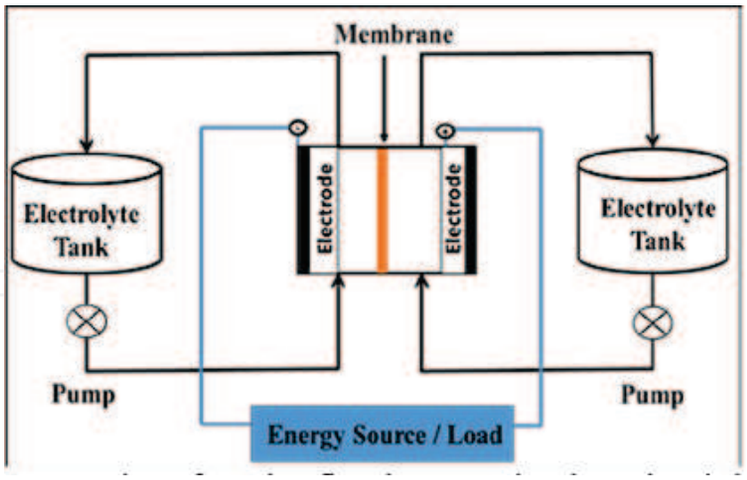


Figure 7. Schematic representation of a redox flow battery. The electrolyte is kept in outside tanks and pumped in the two membrane-separated chambers of the active cell.

3.2.1. Vanadium redox flow batteries

The vanadium redox flow batteries (VRFBs) have promising energy storage characteristics and can respond to unpredictable changes in wind speed. The VRFB has a high efficiency in the range of 65–80%, but it has a relatively low energy density and this represents one of the main disadvantages [24–26]. The theoretical energy density is 30–47 Wh/l, but the practical achievable energy density is lower at 15–25 Wh/l [26]. When storage capacity needs to be increased, the low energy density leads to large electrolyte volumes. The electrolyte is evenly split in VRFB between the positive and negative tanks. The reactions that occur within the cell during charging, and discharging cycles are shown in **Table 2**.

	VRFB	**All-Iron RFB**
Positive side	$VO^{2+} + H_2O - e^- \rightarrow VO_2^+ + 2H^+$	$Fe^{2+} \leftrightarrows Fe^{3+} + e^-$
Negative side	$V^{3+} + e^- \leftrightarrows V^{2+}$	$Fe^{2+} + 2e^- \leftrightarrows Fe^0$

Table 2. The chemical reactions occurring at the negative and positive side of the VRFB and all-iron RFB.

There are several advantages of using VRFB for energy storage applications: long cycle life (>10,000 cycles), high reliability, deep discharge capability and high power density. Although the electrodes do not store energy, they are important for charging and discharging of the battery, influencing, together with the electrolyte and separation membrane, the life-time of the battery, the energy losses and, consequently, the overall efficiency. It is anticipated that efficiency improvements can be made with regard to the correct selection of electrodes, for example using carbon black or its activated composites [27]. Other advantages include the popularity of the battery with regard to research and also the many VRFB installations worldwide.

3.2.2. All-iron redox flow batteries

The all-iron RFB like VRFB employs the use of a single chemical element (in this case iron) in several oxidation states on both sides of the active cell, **Table 2**, while the electrolyte is kept outside in the storage tanks. The positive electrode of the all-iron battery is the ferric/ferrous redox couple, and the negative electrode involves iron plating from Fe (II) [22]. An advantage of all-iron RFB is the readily available electrolyte with an estimated low cost of 0.23 $/l [23]. In the traditional all-iron RFB, at the negative side, the ferrous ions are reduced during charge. Their plating as iron metal onto a graphite electrode of the stack occurs leading to a coupling between energy and power. On the positive side of the battery, ferrous ions are oxidised to ferric ions during charge remaining in the solution. Reactions are opposite on discharge. Cheap aqueous electrolytes, inexpensive separators and the widespread availability of iron (~230 billion metric tonnes of iron) give the all-iron RFB, the potential of reduced storage system cost, while the plating and, consequently, the coupling between the energy and power represents its main disadvantage [22, 23].

To avoid this disadvantage, a slurry electrode containing electrically conductive carbonaceous particles can be made by flowing them in an electrolyte containing the dissolved iron species [22]. Such conductive particles can include carbon black and/or carbon allotropes with different surface areas and enhanced conductivity, carbon micro-flakes, nanofibres, nanotubes etc. Thus, iron is plated onto the carbon particles at the negative side while charging. The carbon particles can then carry the iron metal to be stored in the external tanks allowing for energy storage capacity and power decoupling, allowing the economic advantages of scaling inherent to RFB to be recovered [22]. The carbons and their properties influence the electronic conductivity of the slurry electrodes that have to be greater than the ionic conductivity of the electrolyte. This allows for the iron deposition to occur only onto the slurry particles and not on the current collector leading to a better control of the current distribution [22]. The electrode surface area plays an important role in determining the all-iron (hybrid) RFB efficiency and lifetime. For slurry all-iron RFB, this role becomes secondary. Presently, the slurry all-iron RFBs are still in the development stage putting them at a disadvantage to the already commercialised VRFB. Typically, the energy density of the all-iron hybrid battery is 12.7 Wh/l with a specific energy 10.9 Wh/kg. Energy efficiency is 55% with operating temperature $T_0 = 40°C$ [22, 27].

3.2.3. Energy storage integration

There is much focus on the introduction of storage systems; however, the integration of different storage systems to complement the use should also be considered. For example, research was conducted on the integration of compressed hydrogen storage and VRFB. From system dynamics modelling, it was identified as a result of higher available wind energy for storage and the hydrogen system is able to provide more energy to the system due to its capability as a bulk energy storage medium. In contrast, the RFBs are capable of providing more energy to the system with reduced availability of wind energy for storage, as a result of higher efficiencies. Therefore, VRFBs or all-iron RFBs are more efficient energy storage at times when there are no high periods of curtailment.

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The storage systems benefit from increased value regarding technical and economic factors when integrated with other complementary energy storage technology [28]. This is as a result of the capability of hydrogen for bulk energy storage and VRFB with higher efficiencies is complementary. Furthermore, the effect of the integrated systems depends on the level of excess wind sent to either the hydrogen or VRFB storage system. In independent systems, all the excess wind is sent to each individual storage technology; however, with an integrated approach, the excess wind must be split between the two storage systems.

Storage systems benefit from increased value regarding technical and economic factors when integrated with other complementary energy storage technology.

4. Decentralised hydrogen airport scenario

4.1. Decentralised energy systems

Decentralised energy systems are gaining focus due to energy security and climate change considerations along with the high GHG emissions from centralised fossil fuel plants. Decentralised energy systems can potentially allow for the changes required in the energy sector [29–36]. Advantages include their ability to operate with more than one source of energy and also their potential to be integrated with renewable energy and storage systems [33, 34]. Currently, the majority of energy systems consist of centralised power plants. Centralised energy generation benefits from high economies of scale, base load power capacity and reliability (if energy resources are available) [35]. However, it is clear a transition from these conventional fossil fuel power plants is required. Challenges of decentralised energy include technical challenges of operating the power plants and reliability of the overall system as if the power plant is relying on non-dispatchable generation, the capacity can be affected and require investments in back-up power [33].

Energy management is required for planning energy generation for consumption. Energy management is important for mitigating energy problems. It allows for the optimum operation of energy generation and storage systems to maximise efficiency. It is evident that within renewable decentralised systems, energy storage and energy management of these systems will play an important role. The complexity of the integration of the systems will require management to optimise the generation, storage and use of energy. Decentralised energy systems are envisioned for a hydrogen economy to emerge. Both compressed and liquid hydrogen energy systems can provide valuable green energy carrier if produced from zero/low carbon emission methods.

The next section will further highlight the different applications and importance of liquid hydrogen with a discussion on the decentralised use of liquid hydrogen in an airport scenario.

4.2. Hydrogen as a cryogen

An additional application for liquid hydrogen (20 K) is as a cryogen for superconducting technologies. Interest has grown in finding a suitable low temperature cryogen as a result of

predicted helium shortages and price increases. There is a predicted and well-documented incoming shortage of helium for superconducting applications [37–42],] and hydrogen as a cryogenic coolant has been envisaged as a viable and more economically justified cooling option for superconducting devices [37]. There are many novel engineering designs that can be made possible by using medium-temperature MgB_2 superconducting wires, as developed originally in Cambridge [43] that include the following; a self-contained fully electric superconducting ship, DC fault current limiters, high DC current homopolar motors, cheaper superconducting MgB_2 magnets for fusion [41], SMES [41–43] and MRI systems. Development of liquid hydrogen indirectly cooled MgB_2 superconducting high voltage DC cables especially for computer data centres present ideal candidates for early implementation [44]. Hydrogen's use as a coolant, as well as an energy carrier, will spin off new research and developments in superconducting materials and efficient energy use.

As the quantity of hydrogen liquefied is increased, less energy is wasted and the more efficient and cost-effective the process. The liquefaction process can occur by the Joule–Thomson expansion cycle. The hydrogen is compressed at ambient pressure and passed through a heat exchanger in which the temperature is reduced. As a result of hydrogen cooling on expansion, the temperature should be below the inversion temperature $T_{inv} = 200$ K. A nitrogen precooling step is introduced, before the hydrogen is passed to the expansion valve. The energy required for the compressor and expansion valves reduces the overall efficiency of the process. As liquid hydrogen is a cryogen with a low boiling temperature of $T_{boil} = 20$ K (under normal pressure), it must be stored in insulated cryogenic containers which are designed with double walls and an insulating space between the two walls to reduce heat transfer to the liquid. Heat transfer causes the liquid to evaporate and form gas a process called boil-off. Heat also arises from the ortho-para conversion of hydrogen. To minimise boil-off of the hydrogen for longer storage, an ortho-para conversion must be completed before liquefaction. The use of catalysts facilitates the ortho-para conversion of hydrogen [45].

Considering liquid hydrogen safety, direct cooling can only be handled by highly specialised organisations and companies, but indirect liquid hydrogen cooling, (iLH_2), can be a viable option. In iLH_2 installations, a helium gas exchanger can be used, transferring cooling power of the hydrogen bath at ~20 K to the desired cryomagnetic installation [45]. A pertinent example of indirect cooling by liquid nitrogen is given by McDonald et al. that designed a cooling system for a 15 T pulsed copper solenoid magnet to a desired temperature of 30 K in order to reduce the resistance of the Cu, thereby reducing the power requirements of the system [45]. The design as proposed cooled the magnet via a closed helium loop circulated through a heat exchanger filled with liquid hydrogen from a storage Dewar. It is clear hydrogen both compressed and liquefied will have important implications for different aspects of energy systems.

4.3. Airport scenario

As a further development of hydrogen storage, a decentralised vision of low-carbon airport systems will be analysed. Low-carbon systems integrated with hydrogen will be important as a result of the increasing threat of climate change, resource consumption and increasing energy

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demand. Storage systems alone will not be able to solve these problems, and innovative solutions integrated with storage systems are required such as that depicted in **Figure 8**.

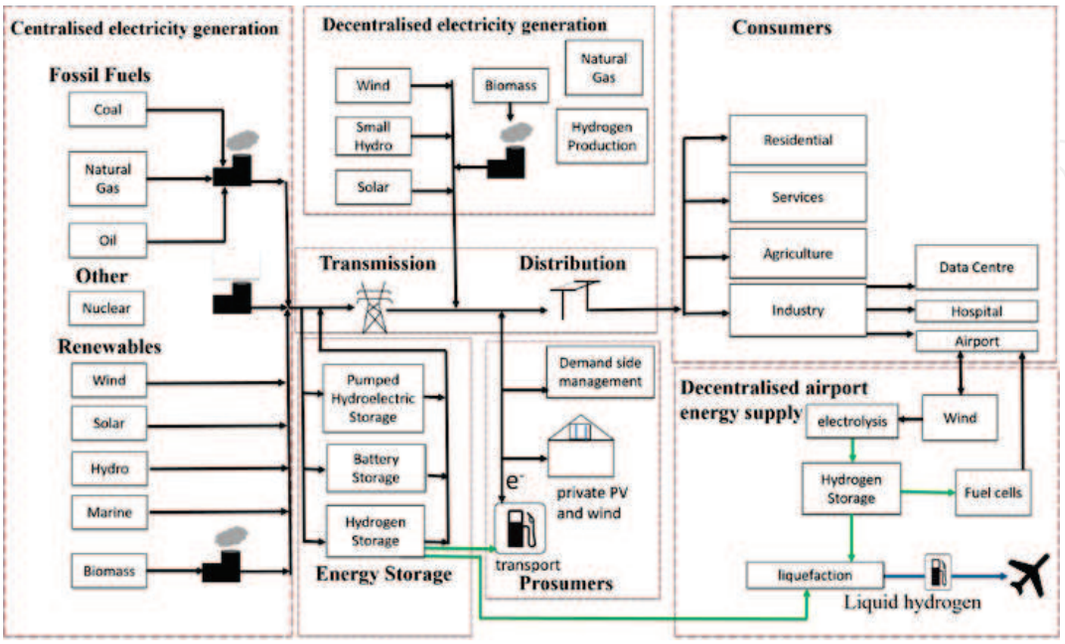


Figure 8. Future integrated hydrogen energy systems utilising added value of liquid hydrogen.

Figure 8 highlights a more complex depiction of **Figure 3** with the use of hydrogen not only for storage and electricity generation but also as a fuel for the aviation industry. It should be noted the flexibility of hydrogen as an energy vector being capable of being used for passenger transport, aviation, thermal and cryogenic applications as well as bulk energy storage and electricity generation. With the increasing energy problems and aims to reduce carbon dioxide emissions and energy dependence, the use of hydrogen can now be seen as a viable solution. The support of necessary policy measures can allow the hydrogen economy to emerge in an attempt to mitigate fossil fuel use other energy problems as mentioned.

A centralised hydrogen vision can be considered with the use of low-carbon systems such as nuclear energy and steam methane reforming integrated with carbon capture and storage; however, from **Figure 8**, a decentralised vision can alternatively be considered as a potential solution. Airbus, a leading aircraft manufacturer, has received a patent for the design of a supersonic passenger plane operated on hydrogen, **Figure 9**. The plane has three different engine types, and the plane is fuelled by hydrogen and liquid oxygen. The fuel cell is to be held in the cargo hold with the liquid hydrogen tank and heat exchangers located in the tail. The fuel cell in the aircraft transforms chemical energy from the hydrogen into electricity through a chemical reaction with oxygen with waste of water, heat and oxygen-depleted air allowing reduced operation emissions. Such an aircraft can have implications for the aviation sector. Additionally, it is predicted that the water produced can be used to reduce the water required on-board that can reduce the weight and therefore fuel consumption of the aircraft.



Figure 9. Concept from Airbus for the hydrogen fuelled aircraft [44].

5. Conclusions

The results of the investigation into the various energy storage technologies available for energy management of decentralised renewable energy systems highlight the large potential of hydrogen as a storage medium for energy management of decentralised energy systems but also further highlight one concept in which the further value of hydrogen is explored in with regard to an airport scenario. With large focus on the decarbonisation of electricity systems, the need for further opportunities for decarbonisation within the heat and transport sector is required. Decentralised hydrogen energy systems can be a solution to the aircraft industry requirement to lower emissions and reduce dependence on fossil fuels. Hydrogen and other storage technologies can allow a suitable energy carrier for managing the transition to a decarbonised energy system.

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