*energies*

*Article*

# Strategies for the Adoption of Hydrogen-Based Energy Storage Systems: An Exploratory Study in Australia

**Cameron Wells [1], Roberto Minunno [1], Heap-Yih Chong [2,3,*] and Gregory M. Morrison [1,4]**

1 Curtin University Sustainability Policy (CUSP) Institute, Curtin University, Bentley, WA 6102, Australia
2 School of Engineering Audit, Nanjing Audit University, Nanjing 211815, China
3 School of Design and the Built Environment, Curtin University, Bentley, WA 6102, Australia
4 School of Engineering Design and Built Environment, Western Sydney University, Penrith, NSW 2751, Australia
* Correspondence: johnchong1983@163.com or heap-yih.chong@curtin.edu.au

**Abstract:** A significant contribution to the reduction of carbon emissions will be enabled through the transition from a centralised fossil fuel system to a decentralised, renewable electricity system. However, due to the intermittent nature of renewable energy, storage is required to provide a suitable response to dynamic loads and manage the excess generated electricity with utilisation during periods of low generation. This paper investigates the use of stationary hydrogen-based energy storage systems for microgrids and distributed energy resource systems. An exploratory study was conducted in Australia based on a mixed methodology. Ten Australian industry experts were interviewed to determine use cases for hydrogen-based energy storage systems' requirements, barriers, methods, and recommendations. This study suggests that the current cost of the electrolyser, fuel cell, and storage medium, and the current low round-trip efficiency, are the main elements inhibiting hydrogen-based energy storage systems. Limited industry and practical experience are barriers to the implementation of hydrogen storage systems. Government support could help scale hydrogen-based energy storage systems among early adopters and enablers. Furthermore, collaboration and knowledge sharing could reduce risks, allowing the involvement of more stakeholders. Competition and innovation could ultimately reduce the costs, increasing the uptake of hydrogen storage systems.

**Keywords:** hydrogen; distributed energy resources; energy systems; mixed methodology; exploratory study; Australia

check for updates

**Citation:** Wells, C.; Minunno, R.; Chong, H.-Y.; Morrison, G.M. Strategies for the Adoption of Hydrogen-Based Energy Storage Systems: An Exploratory Study in Australia. *Energies* **2022**, *15*, 6015. https://doi.org/10.3390/en15166015

Academic Editors: Vincenzo Liso and Samuel Simon Araya

Received: 30 June 2022
Accepted: 16 August 2022
Published: 19 August 2022



## 1. Introduction

The interest in finding solutions to limit climate change and decarbonise the current energy industry increases as companies and governments work towards net zero ambitions [1,2]. Large-scale electricity systems are usually supported by a centralised power generating and distribution system. Centralised electricity systems may include generation plants powered by fossil fuels such as coal or gas turbines and an expansive high-voltage power distribution infrastructure servicing entire cities and territories [3]. Due to challenges in electricity storage, in some countries such as Australia, a centralised approach is implemented to balance supply and demand in real time. The power plants perform predictably and can ramp up or ramp down depending on the load requirements. It has been argued that the generally monopolistic nature of current electricity grid systems has led to a lack of competition which has slowed grid innovation [4]. With renewable electricity supply to the electricity grids increasing, the reliance on conventional power generation decreases [1,5–9]. As a result, the cost of operating and maintaining the infrastructure is also increasing [3–10].

Most conventional power plants turn the spinning energy into electricity via a synchronous generator. Inertia in the electricity grid refers to the energy stored in large, mechanical rotating generators and is independent of power output [11]. Storing energy is imperative for the electricity grid's stability; if there is a failure in the power plant, the inertia can temporarily make up for the power loss and gives the mechanical system time to react and respond to the failure, avoiding a loss of power to customers. Renewable electricity penetration into these electricity grids decreases the demand requirement from the power generation units, and with this, the inertia also decreases [12–14]. Due to the natural intermittency of renewable energy, there is a requirement to find a solution to store and control the power output and frequency of these sources and find solutions for grid support to replace the loss of inertia [11]. Decentralisation of the electricity grid through microgrids coupled with energy storage systems is a potential solution to allow the continued increase in renewable penetration and solve the issue of grid instability. Microgrids are a subset of the broader electricity system and can include all the necessary components required to operate independently from the primary electricity grid [15]. The primary source of electricity in emergent microgrids is generally renewable sources. The type of renewable energy depends on the site's geographical location and availability of natural resources. The challenge with using renewable energy is the supply gap during periods of low generation in the off season and excess production during periods of minimum demand.

### 1.1. Hydrogen and Hybrid Storage Systems

The main components within a hydrogen storage system are a water purifier, electrolyser, storage device such as a pressure vessel, liquid storage tank or metal hydride cell, and a fuel cell [16,17]. The process of converting excess renewable electricity to hydrogen via electrolysis is also known as power-to-gas. This produced hydrogen can then be reconverted back to electricity using a fuel cell, (power-to-gas-to-power or P2H2P) or alternatively, blended into a natural gas pipeline, which is used for fertiliser production or vehicle refuelling stations. In this comparison, the focus is on the stationary P2H2P configuration.

There are four types of electrolysers: alkaline, polymer electrolyte membrane, anion exchange, and solid oxide [18]. According to IRENA, alkaline and polymer electrolyte membrane electrolysers are available commercially, whereas anion exchange and solid oxide are still at a lab scale [19]. In a P2H2P-only configuration, when the power generated by the renewable energy supply is greater than the load requirement, the electrolyser is activated, produces hydrogen gas, and stores it using the excess electricity generated [16,17]. When the power generated by the renewable energy supply is less than the load requirement, the fuel cell is charged and supplies the power requirement.

The most common hydrogen storage options are: compressed hydrogen gas, liquid hydrogen, material storage with metal hydrides, as well as storage within other molecules such as ammonia. According to Alam, Kumar and Dutta (2021), compressed hydrogen gas is the most mature, economic, and viable hydrogen storage technology [20]. However, dealing with compressed hydrogen brings new hazards to control such as flammability and extreme high-pressure storage requirements (~350 bar) compared to liquid natural gas, and it has a destructive capability (hydrogen embrittlement) [10]. Hydrogen can perform the role of supplying short- and long-term storage [21], although the roundtrip efficiency of the P2H2P system is 40–80% depending on the method of electrolysis and scale of the system, which is lower than that of the Li-ion battery [22].

The energy management strategy affects the optimal performance, utilisation, and cost effectiveness of the P2H2P system [10,13]. The expected lifespan of P2H2P system components is 15–20 years, greater than that of the Li-ion battery [23].

### 1.2. The Adoption of Hydrogen-Based Energy Storage Systems

The inclusion of an energy storage system may also provide affordable and clean energy, develop sustainable communities, and foster climate action [24]. Energy can be stored in several ways, such as in batteries, pumped hydroelectric power, hydrogen, compressed air, flywheels, and other less-used methods [25]. The most advanced and prominent stationary and mobile energy storage systems are lead-acid and lithium-ion batteries [26]. Pumped hydroelectric power is applied on a larger scale under suitable conditions and provides the needed grid inertia with rotating equipment. The other methods stated above are less prominent and are not discussed in the same level of detail [18]. Hydrogen was the chosen topic of focus among these storage technologies due to its high energy density; at 33.6 kWh/kg, hydrogen has a significantly higher energy density than other forms such as diesel (12–14 kWh/kg), natural gas (13.6 kWh/kg), and lithium-ion batteries (0.100–0.265 kWh/kg) [10]. Hence, hydrogen storage is versatile for short-term and long-term storage applications.

However, the potential for hydrogen implementation as storage for utility-scale distributed energy resources and larger microgrid applications needs further investigation [27]. Scaling the technology by diversifying hydrogen across multiple sectors and applications may further reduce costs and improve performance [28]. Non-techno-economic barriers such as government policies or incentives, including feed-in tariffs and capital grants, should be reviewed [29]. Countries such as the USA, the United Kingdom, Australia, Japan, France, Norway, and other European countries have introduced hydrogen policies and roadmaps, highlighting international interest. The 2021 European Hydrogen Backbone was introduced to accelerate the decarbonisation journey in Europe. The traditional centralised electricity grid approach is being phased out in areas with large expanses of space between communities and towns, such as Western Australia. Energy storage can eliminate the need to build expensive new power plants and long transmission lines [27].

### *1.3. Exploration in the Australian Context*

The methodology of this paper complements the existing body of quantitative analyses with qualitative data obtained from industry professionals. Industry professionals provide insights into developing strategies to address technical, economic, and perceived barriers to the application of hydrogen-based storage at a larger scale [30,31]. Hydrogen storage is a technology being researched to solve the challenges of long-term energy storage and grid support [1,20]. Against this backdrop, this research investigated stationary, hydrogen-based energy storage systems for microgrids and distributed energy resources in the Australian dynamic energy sector. This research applied a mixed methodology under its exploratory study to pursue this investigation. First, a systematic literature review was employed to position the research in the literature. Second, the systematic literature review findings were used to inform a list of questions used to conduct semi-structured interviews.

Experienced Australian professionals with knowledge of the topic and university professors were engaged to consider their views and opinions. A thematic analysis was carried out to review the data obtained from the semi-structured interviews. This thematic analysis identified key themes and trends, which formed the basis of the report's results, conclusion, and recommendations. The succeeding sections cover the findings from the systematic literature review. The methodology included a collection of primary and secondary data, a synopsis of the results, their discussion, and a conclusion. The systematic literature review investigated more technical themes related to storage technologies and configurations, whereas the results and discussion sections investigated the management, economic, and regulatory themes that emerged from the interviews. Finally, this research identified potential use cases for hydrogen-based energy storage systems and barriers inhibiting their implementation, as well as outlined recommendations to accelerate hydrogen storage systems' uptake.

## 2. A Mixed Methodology

Hydrogen-based energy storage systems are still at an early stage of development and deployment. The research on their adoption is explorative at this stage. Hence, a mixed methodology was designed to investigate the use of stationary hydrogen-based energy storage systems for microgrids and distributed energy resources. The mixed methodology consisted of a systematic literature review and interview. The systematic literature review was conducted first to form the basis for a series of semi-structured interviews. The results of the systematic review were integrated with the insights gained from the expert interviews to provide the final three themes analysed in the Discussion section, namely, use cases for hydrogen-based storage systems (Section 4.1), challenges inhibiting the uptake of hydrogen-based storage systems (Section 4.2), and finally, recommendations to accelerate the uptake of hydrogen-based storage systems (Section 4.3). Figure 1 illustrates the adopted methods, steps, and guidelines in this research.

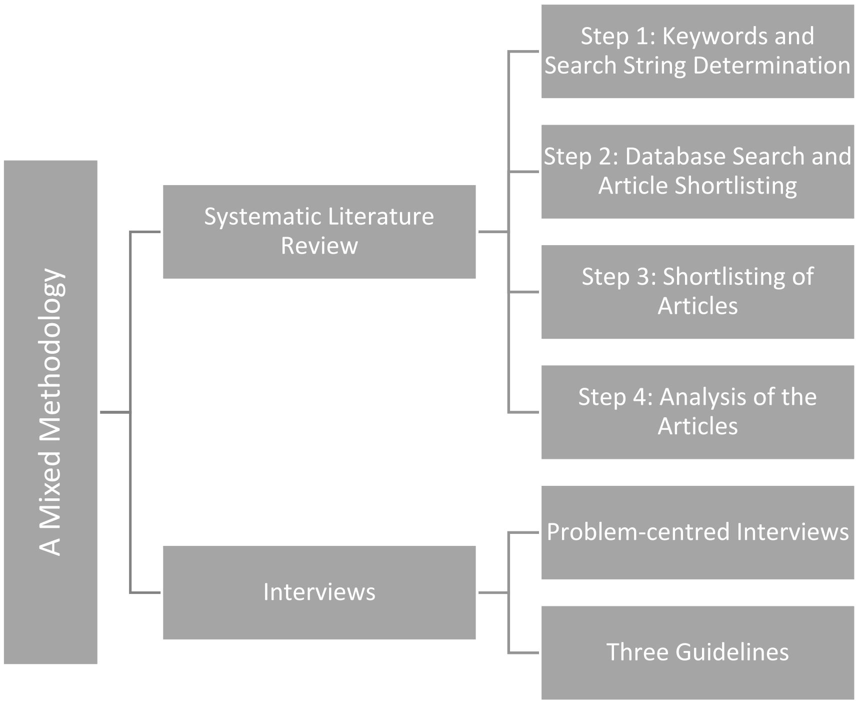


**Figure 1.** Overview of the mixed methodology.

### *2.1. Systematic Literature Review*

A systematic literature review (SLR) was completed to identify the current state-of-the-art literature governing hydrogen-based energy storage systems. SLRs are widely employed as a comprehensive, stringent, and reproducible method to categorise and report the findings of a literature review [32–34]. The review was completed in four main steps and provided the basis for the semi-structured interviews.

Firstly, a string of relevant keywords was identified for a Boolean search string. The keywords were determined from the research gaps and combined into a Boolean search string: Hydrogen AND Storage AND (Microgrid OR "Micro Grid"). A keyword comprising two words was included within quotation marks, and the search engines automatically searched for the plural spelling of the exact keywords. The search string was applied to the Web of Science, Scopus, ProQuest, and Science Direct databases. First, the data were exported into Endnote X9 and Microsoft Excel. Second, duplicate articles and copies were eliminated. Third, the titles and abstracts of the remaining articles were analysed, and an exclusion criterion enabled the shortlist selection of articles related to hydrogen-based energy storage systems. Finally, the shortlisted articles had their data extracted and analysed. More details concerning the systematic literature review method were collected in the Supplementary Materials of this paper.

### *2.2. The Interview Methodology*

The reviewed, shortlisted articles produced a clear picture of the common themes, which paved the way for the primary data collection stage. It was evident from the articles, particularly the comparative studies, that when hydrogen technology is used in the storage configuration, the cost of electricity increases due to the higher capital costs of electrolysers and fuel cells (see, for example, studies by [16,35]). Moreover, as Dawood et al. (2020) [10] explained, it became evident that hydrogen-based energy storage configurations have a preferential economic performance in larger-scale projects with longer project lifecycles. Further, hydrogen-based energy storage systems' management and technical performance proved to be well understood.

Semi-structured interviews were proposed due to their ability to extract detailed and in-depth information on a complex yet poorly understood topic (as explained in [36]). Recent, relevant studies related to decentralisation [37] and decarbonisation [38] used a methodology to create practical contributions and empirical findings from experts in the energy sector. Moreover, semi-structured interviews allow the interviewer and interviewee to express an answer or delve into an idea in more depth [39]. Therefore, semi-structured interviews were chosen as the data collection method to minimise any preformed bias that may be present in the participants.

Development of the Interview Structure and Questions

The interview technique was structured around the strategies in problem-centred interviews (PCIs). The goal of a PCI is to allow an open conversation to occur whilst the interviewer facilitates the direction and scope of the conversation. As the topic of renewable hydrogen is relatively new and underdeveloped, the interviewer allowed the participants to fully express their personal views to ensure in-depth information could be obtained and compared against the similar or opposing opinions from the remainder of the participants. The interviews followed three guidelines [40,41].

The first guideline proposed to understand the broader context of the topic at hand, i.e., energy storage systems. This process included prompts on the importance of energy storage systems from small-scale residential to utility and grid-scale applications and probed whether the interviewee believed hydrogen has/may have a role within these systems. In many cases, the interviewees naturally answered what would have been the second prompt, which was specifically regarding the role hydrogen may/will have within future energy storage systems. This first guideline allowed the interviewees to express their opinions and expertise from their vested industry or academic interests early, before more hydrogen-specific prompts were used. The open-ended nature of the first two prompts minimised the risk of a short, articulated answer (e.g., no) when asked (for example) if hydrogen may have a role in energy storage systems, which could have led to the early cessation of the interview. Instead, the open-ended nature allowed the interviewee to attribute knowledge and emergent ideas to the broader energy system.

The interviewees were asked to identify the industry's current challenges in implementing hydrogen-based energy storage systems within the second guideline. The question did not specify the challenges present, such as political, technical, or economic challenges. This open-ended question was used to identify the challenges and obstacles present with hydrogen-based energy storage systems. The method of storing hydrogen is an area of interest that was identified within the systematic literature review. Therefore, the second prompt within the second guideline was to ask the interviewees their opinion on the most practical method of storing hydrogen for both small-scale and large-scale applications. This prompt on storage methods provided a comparative analysis of the different storage methods and their implications.

The third guideline was designed to identify solutions to overcome the challenges mentioned above. The interviewees were asked to outline areas along the hydrogen value chain that need the most research and identify drivers for adopting these technologies. Finally, to conclude the interview, the interviewees were asked their opinion on the structure and nature of the future energy and electricity system. This question ultimately combines the information learned and discussed during the interview with their personal opinion of how the electricity grid transition may unfold. It was then possible to provide recommendations on key areas of future research to the reader from this information. Table 1 shows the main questions in the interview.

**Table 1.** Main questions.

| Number | Main Question |
|---|---|
| 1 | Why is there a requirement for electricity storage systems? |
| 2 | Do you believe hydrogen has a role to play in these storage systems? If yes, what role? |
| 3 | What are the options for storing hydrogen? |
| 4 | What are some of the challenges inhibiting the uptake of hydrogen-based energy storage systems? |
| 5 | What are some strategies that could be adopted to overcome these challenges? |

The study was undertaken in Australia from August 2021 to September 2021 under the ethics approval number HRE2021-0443 through the Curtin University Human Research Ethics Committee (EC00262). The participants are experts primarily located in Western Australia (WA), although they operate across the entire country. Therefore, although the results might be transferable to other countries with similar conditions, the context must be considered. For example, WA's energy system is more dynamic than others due to the large availability of natural resources, temperate climate, and large expanses of inhabited space [42]. In total, ten expert participants were interviewed during August and September 2021. The sample consisted of high-profile experts such as an energy transition consultant and founder of a renewable energy company, the chairman of a renewable energy business, and the managing director of an emerging renewable energy company, as shown in Table 2. The range of participants allowed for a diversity of perspectives, ranging from technical complexities to economic and policy considerations.

**Table 2.** Characteristics of the ten interviewees and their associated interviewee number.

| Interviewee Number | Area of Expertise and Experience |
|---|---|
| **Industry Experts** | |
| I01 | Energy transition consultant and founder of renewable energy company |
| I02 | Chairman of a renewable energy company |
| I03 | Managing director of an emerging renewable energy company |
| I04 | Senior member of a large energy supplier |
| I05 | Senior member of a large-scale electricity supplier |
| I06 | Decarbonisation and energy project manager and researcher |
| **Policy Experts** | |
| P01 | Strategy manager for an electrical utility company |
| P02 | Senior strategy analyst for a large-scale energy producer and retailer |
| P03 | Executive of a government body which provides industry-matched funding to energy lighthouse projects |
| **Academic Experts** | |
| A01 | Professor with research interests in energy storage, renewable electricity, and microgrids |

The interviewees were selected using a combination of personal and university contacts and were recruited through LinkedIn and email. The duration of the interviews ranged from 20 to 60 min. It is recognised that the opinions of interviewees provide a bias towards their vested interests, which was considered carefully when analysing the results [37,43].

Four categories resulted from the content analysis: the need for hydrogen as energy storage, the challenges of bringing hydrogen-based energy storage technologies to market, the method of storing hydrogen, and the perception of the future of decentralised electricity systems. These categories provided the basis for analysing the transcripts from the interviews. The interview content was analysed according to the context in which relative keywords were mentioned [37]. The system for presenting the data was adapted from [44]. The interviewees' quotes and statements aligned with the research objectives and categories for analysis were used to present the research findings. Similarities, contradictions, and conclusions were then derived from the interview transcripts.

## 3. Research Findings

### *3.1. Requirement of Energy Storage Systems*

All ten interviewees expressed a growing concern around the requirement for solutions to store the excess intermittent electricity produced from renewable sources during times of high electricity production and low demand. This is predominantly a result of the rapid uptake of rooftop solar panels in the residential, industrial, and commercial sectors due to the decreasing cost of solar PV systems and government subsidies (I01, I03). The uptake of rooftop solar panels is causing stress on the energy system, which was not designed for bidirectional flow and for the consumers to become *prosumers* (I06), the latter meaning both producers and consumers of energy.

The uptake of all forms of renewable energy results in the need for electricity storage to ensure that electricity is available for the receiving communities. Be it at a grid, community, or residential level, the requirement is still there (P02). Furthermore, electricity storage is an intermediary between the intermittent generation source and the load. As stated by I03, electricity storage enables the maximum economic value of an investment in renewables (I03). With the decreasing inertia in the electricity grids, there is a further requirement to develop solutions to increase the stability of electricity grids by providing a controllable electricity supply. This stability can be achieved using large-scale electricity storage (A01). With the decreasing cost of renewable energy, the goal is to produce electricity at a low cost and store it for use when there is a lack of extended access to low-cost energy, for example, in stand-alone power systems (I03). Operators of utility grids, micro-grids, and embedded networks who aspire to achieve 100% renewable penetration will need some form of electricity storage. Storing excess renewable electricity will also further offset the requirement for fossil fuel-powered generators (I05).

### *3.2. Opinion on Hydrogen's Role in These Energy Storage Systems*

Solving the use case for hydrogen as pure electricity storage in a stationary form has proven challenging (I01, I06). This challenge is due to the advancement and steep reduction in battery technology costs, hydrogen's main competitor. It is more apparent in smaller, residential, or single-dwelling-sized applications as the advantages of economies of scale do not apply (I03).

A significant factor affecting the feasibility of hydrogen energy storage is where it is to be implemented (P02). In metropolitan areas, there is further opportunity to balance/share the electricity supply and demand with other users who have solar and battery storage systems, making it more complex to justify a use case for hydrogen storage. Hydrogen energy storage in metropolitan areas becomes feasible when embedded networks are introduced, and the operator of those networks wants to achieve 100% renewables (P02). Hydrogen storage systems have the potential to make 100% renewable energy practical and economically feasible. However, further research and demonstration on a few technical and economic aspects of the systems are still required before investment decisions can be made by grid operators and owners (I02). The best use case for hydrogen energy storage will be diesel displacement in remote microgrids, stand-alone power systems, and communities such as mine sites (A01, P02, P03, I02, I03, and I05). The use of diesel in these locations is expensive and, with the potential of on-site production and utilisation, hydrogen becomes a viable alternative (I02). There is also no opportunity to balance the load supply and demand, making electricity storage necessary for sustainability and economic reasons (P02).

In addition to this, there is the possibility of transporting any additional hydrogen to the point of use should there not be enough availability through local production (I02).

The many uses of hydrogen are an advantage of using this technology (I02). In addition to storing and generating electricity, hydrogen can be used for transport where fuel cell vehicles are operating (I02). This feature allows grid operators, companies, or local governments to have a complete strategy around hydrogen. Moreover, I01, I03, P02, I06, P03, and A01 included heavy transport as a potential use case for hydrogen storage systems. Although excess renewable electricity can be stored as hydrogen, it is not the most efficient way to store electricity. Therefore, it makes sense to use it in different areas such as transport, space heating, and cooking. Blending hydrogen into existing gas networks and storing it there is the cheapest form of storage available. Although this may be the only feasible option where gas networks already exist, there are still challenges around maintaining blending volumes within the network and modifying end-use appliances to be compatible with high (>15%) proportions of hydrogen (I04).

A use case for hydrogen is the provision of a controllable source of energy for grid support at a utility scale. The advantages of hydrogen are the easy expansion of storage and the long-term storage capabilities. Moreover, hydrogen storage systems have become more economically viable (A01).

### *3.3. Challenges in Implementing Hydrogen-Based Storage Systems*

The costs of electrolysers and fuel cells are the biggest inhibitors to implementing hydrogen-based energy storage systems (I01, I02, I03, I04, P03, and A01). The high cost is due to the electrolyser and fuel cells' dependency on rare earth metals (as explained by A01), the limited demand for the technology, and the requirement for bespoke engineering for each project. There is insufficient demand to warrant a mass assembly line and standardised equipment production (I04, I05). Despite these barriers, the cost of hydrogen storage system components has decreased by ~50% in five years (I04).

The efficiency of the electrolyser and fuel cell system can be up to 80% for solid oxide fuel cells when the heat produced (approximately 800–1000 degrees Celsius) during operation is used to heat the gases in the process (A01). As explained by A01, due to high operating temperatures, solid oxide fuel cells are only suited to large-scale grid-support projects.

Low-temperature fuel cells, such as the proton exchange membrane, have only achieved ~30–45% efficiency, whereas batteries are far more efficient (depending on the type) at ~80–90%, making the use case for hydrogen storage systems challenging (A01 and I02). Such low efficiency makes hydrogen storage systems unsuitable for frequency control and support for the primary electricity grid. It will often need to be used with batteries (A01). To further enhance the challenges, there is a lack of industry expertise around hydrogen-based energy storage systems, and therefore, a higher risk tolerance is required for projects to go ahead. Furthermore, as the technology is still in the research and development phase, the market is dominated by small-scale manufacturers and suppliers, creating a challenge for grid operators in bringing equipment from different suppliers together (I02, I05).

Another challenge in implementing hydrogen-based storage systems is a significant knowledge gap in the integration of controls and the operation and maintenance requirements of these systems (I02). Indeed, "*there is a deficit in the electrical industry and understanding how to integrate that technology into an operational environment and be able to maintain that power quality and reliability*", as described by I05. This lack of industry expertise and experience leaves gaps in the lifecycle costing for companies when considering the costs associated with operating and maintaining hydrogen-based energy storage systems, making investment decisions difficult (I02). In addition, I05 is concerned about "*a real lack of regulation in Australia around the generation of hydrogen, the use of hydrogen and hydrogen for power generation, especially within the health and safety environment*". Furthermore, with the certainty of safety risks associated with hydrogen and any new technology, it only takes one incident for regulators to freeze the deployment and operation of the systems. Finally, many companies cannot absorb this additional risk (I02).

### 3.4. Methods of Storing Hydrogen

The ease of storage capacity expansion with compressed hydrogen storage makes it a suitable option for very large-scale grid-support electricity storage (A01). Although technologically feasible, compressed hydrogen storage is not a scalable option for residential, commercial, and industrial scales (I02, I03 and A01). This is because, "*the compression and depression are energy-intensive; [ . . . ] from a conversion efficiency, it's a very inefficient loop, and you are wasting a lot of electrons in pushing the molecules together*" (I02). From a lifecycle cost perspective, any pressure vessels are typically prohibitive. High costs are typically due to their building, fitting, certification, and testing operations. According to the Australian norm, they have to be recertified every 12 months to a very high compliance regime (as explained by I02): "*The cost of mass manufacture is high; the costs of regulatory maintenance and certification are high, and there are no ways of avoiding those*". Moreover, the exceptionally high parasitic load associated with compressed hydrogen storage, which results from the compression and decompression processes, further increases the overall cost of the storage system (I02).

With a different perspective, interviewee I04 believed the most practical and cost-effective method of storing hydrogen was in a gaseous state within the existing natural gas network. Hydrogen stored in metal hydrides is the best option for smaller-scale applications due to the low pressure and operating temperatures. However, the technology is still in the research and development phase and is very expensive (I02, A01). Hydrogen stored within metal hydrides has a slow reaction time and, in most cases, will need to be coupled with a battery to provide frequency support (A01). Conversely, hydrogen stored in a liquid state or within carrier liquids such as ammonia may be a viable option due to storing a more significant amount of hydrogen in the same volume of space and at a lower pressure than the gaseous alternative (I02, I03). A statement from A01 regarding the requirement of cryogenic temperatures for liquid hydrogen emphasises challenges in supplying the energy and equipment to maintain these temperatures and that fuel cells operate at ambient temperatures. Carrier liquids such as ammonia are also in the development phase and have not yet proven economically feasible at a smaller scale (I02). Hydrogen storage options, both as liquid hydrogen and within a carrier liquid, have low round-trip efficiencies, making them less efficient and difficult to solve at the commercial and industrial scales (I02, I03). Energy companies and grid operators are restricted to options that reflect their response when going out to industry for a proposed project. Industry responds to the capability and skillset currently available in the market (I05).

### 3.5. Other Comments and Recommendations

Simultaneously, there is a need to mobilise hydrogen industries and ecosystems to develop the whole value chain. Otherwise, solving one aspect of the value chain might prove ineffective for the whole hydrogen storage system (I02, I03, I04, P03, A01). Incentivised, hard-to-reach targets and strict policies set by governments will encourage the industry to look for alternatives (P02, P03). Significantly, large companies within energy-intensive industries such as mining and transport could impact the development of hydrogen if they are incentivised to increase investment, as they will act as large off-take partners. When large companies pursue new objectives, they can create demand for a product/service that stimulates all the associated supporting industries (I03). Government subsidies in pilot and research projects might encourage energy-intensive industries and companies to adopt and trial new technologies (P02, I03). Furthermore, it is important to publicly share the learnings that result from government-subsidised and -funded projects with the broader industry to foster a faster and more widespread innovation system (I05). Indeed, "*local councils, state governments and possibly even federal governments are important off-take customers through their procurement of fleets, trains and public transport*" (P03).

Cross-industry collaboration and the sharing of learnings from pilot and trial projects is the preferred approach to drive the adoption and uptake of hydrogen storage technology. There is an opportunity to share the transport industry's findings and carry them over to the static generation space (I05). The broader market uptake of hydrogen systems, such as in vehicles, results in the miniaturisation of scale production that can be transferred across industries (I01, I02, I03, I06 and A01). Knowledge sharing allows more people to work on the technology, increasing competition and innovation and reducing the cost curves (I05).

Large projects may pave the way for the broader adoption of hydrogen storage systems. For example, the proposals for hydrogen highways in New Zealand and WA are the projects needed to mobilise a new industry (A01). Projects of this magnitude require research and collaboration to ensure all aspects of hydrogen production, storage, transport, power generation, and enabling technologies are developed simultaneously to achieve a successful result (A01).

## 4. Discussion

The insights gained from the expert interviews presented in the sections above were used in conjunction with the results from the systematic literature review to identify three critical themes. The first theme considers the variety of use cases for hydrogen storage systems, which could develop into case studies to advance applications and the research on hydrogen developments further. As much as it is essential to create use cases, it is also essential to evaluate the challenges that inhibit the uptake of hydrogen-based storage systems. Thus, the second theme discussed here is the evaluation of such challenges. From the discussion of these two themes, the third theme is a collection of recommendations to accelerate the uptake of hydrogen-based storage systems.

### *4.1. Use Cases for Hydrogen-Based Storage Systems*

This theme summarises the most common use cases for hydrogen-based storage systems, detailing how these cases can be employed and including their limitations and related challenges.

- *Microgrids and stand-alone power systems*. Ayodele, Mosetlhe et al. (2021) [7] demonstrated that hydrogen-based energy storage systems are best suited for microgrids and stand-alone power systems. Additionally, they can successfully be used to serve remote communities where the distance from the nearest grid connection is substantial. In most cases, long-term storage will be required to provide the reliability of electricity to the community or customer it is servicing. Where there is an opportunity to displace diesel, on-site hydrogen production and utilisation become a viable option. That is typically the case in the remote areas that are widespread in the Australian outback.
- *Small-scale applications*. Due to the current high cost of equipment and uncertainty regarding operational, maintenance, safety, and regulatory requirements, hydrogen-based electricity storage units are not yet suited for pure electricity storage within small-scale residential, industrial, and commercial applications. Generally, these features are better suited when an opportunity exists to balance the electricity load with other users. Furthermore, the uptake of rooftop solar panels, batteries, and battery-cell electric vehicles will provide enough storage within the electricity grid to prevent the need for deep storage at the individual unit level, except for individuals and entities making investment decisions based on reasons other than economic and financial considerations.
- *Embedded network*. Pure hydrogen energy storage systems may be applicable in situations where embedded networks exist. The operators of these networks aim to achieve 100% renewables, and their customers are willing to pay more for their electricity. Hydrogen can be used as long-term storage and large-scale grid support but needs to be in conjunction with batteries to provide frequency support to the grid. The expensive capital cost of equipment is less evident at a larger scale. A hydrogen storage system is a viable option for these applications where the ease of expansion

of storage capacity can be achieved without upgrading the entire system. Moreover, there is an opportunity to use rather than curtail the excess electricity generated by renewables during off-peak times through conversion and storage as hydrogen within the existing gas networks for heating and cooking, but not for re-electrification.

### 4.2. Challenges Inhibiting the Uptake of Hydrogen-Based Storage Systems

The cost and low efficiency of hydrogen storage systems are the most significant inhibitors of the implementation of hydrogen-based electricity storage systems, as demonstrated by [10,35,36], and in the interview results reported above. For this reason, many companies cannot afford to absorb the additional risk of uncertainty in their cost plans when planning projects of this nature. As the competitiveness of hydrogen-based storage systems increases, so does that of its competitors. Recent battery technologies make it increasingly challenging for hydrogen to compete as a pure electricity storage option.

Another challenge is storing hydrogen, which has proven difficult to overcome. Substantial research and investment efforts are ongoing. Contrary to the results reported by [20], it is believed that compressed hydrogen gas storage is not a scalable option for residential, commercial, and industrial applications due to the safety risks, expense of manufacture, and high cost of regulatory maintenance and certification. Compressed hydrogen storage may be applicable for large-scale utility grid-support storage and is being trialled in projects such as in Denham, Western Australia [45]. Storage in a liquid form within a carrier liquid or metal hydrides is more likely to be adopted at a smaller scale.

In addition to the high costs associated with hydrogen-based energy storage systems, there is limited real-life practical expertise to reach out to for support. Therefore, only projects backed by governments and early adopters of technology who can accept a higher risk tolerance will be completed. The learnings from privately funded projects generally remain confidential as intellectual property to benefit a single organisation, which confines the broad uptake of the technology. Research articles by [13,22,46,47] have demonstrated the successful energy management of hybrid energy storage systems. However, there is minimal practical industry knowledge concerning the introduction of these systems into an operational environment whilst maintaining power reliability.

### 4.3. Recommendations to Accelerate the Uptake of Hydrogen-Based Storage Systems

Four recommendations arise from the review of the literature and the interview results. These recommendations are summarised in the list below and are discussed in more detail in the following paragraphs.

First, it emerged that research and implementation of a complete hydrogen strategy for a remote town or community, such as diesel displacement, should be planned to achieve a better capital performance of equipment and stimulate development across the entire hydrogen value chain. Second, learnings from government trial projects should be disseminated across industry sectors to stimulate cross-industry collaboration and competition in the private sector. Third, governments and policymakers should enforce incentivised stretch targets for emission reductions and operating requirements for the private sector. Finally, to assist the governments in the uptake of hydrogen energy storage systems, the private industry should collaborate and form joint ventures to share the risks and learnings from early pilot projects.

A whole strategy around hydrogen is required for its successful implementation. Such a strategy could start implementing hydrogen for electricity storage, power generation, and transport for diesel displacement. An entire ecosystem around hydrogen could be developed, as mentioned in the National Hydrogen Roadmap by CSIRO [48] and Green Hydrogen Cost Reduction by IRENA [19]. This may lead to the capital performance of the initially expensive equipment, as the electrolysers and fuel cells will be operating more frequently than in a pure electricity storage scenario. Furthermore, government-subsidised trial projects with shared public learnings are crucial for cross-industry collaboration and competition. These government-backed projects would allow smaller companies without significant financial backing to get an opportunity to break into the energy market that large, multinational conglomerates have traditionally dominated. The increase in competition may drive innovation and demand, which might, in turn, lower the cost curves. Stretch targets and strict government policies coupled with incentives are powerful tools to guide industries in a particular direction. Private industry can collaborate to assist the governments by creating joint ventures to share the risk of the pilot projects whilst allowing all parties to benefit from experience in the project.

## 5. Conclusions

This exploratory study investigated the technology associated with stationary hydrogen-based storage systems and their use cases through a systematic literature review, which informed semi-structured interviews with experts. First, the systematic literature review concluded that hydrogen-based energy storage systems could be used as the sole electricity storage medium or as a hybrid with other storage devices such as batteries. Hydrogen-based storage systems are best suited to a hybrid configuration with batteries. The batteries provide frequency control, short-term storage, and supply peak demands to the grid, whilst the hydrogen storage system fulfils the long-term storage requirements for periods of extended low generation. Hydrogen storage systems are less economically feasible and inefficient compared to batteries and are more economically viable at a larger scale. Second, the interviews conclude that hydrogen-based energy storage systems are not suited for pure electricity storage within the urban environment unless embedded networks exist and operators wish to achieve 100% renewables. Hydrogen-based energy storage systems are best suited to large-scale grid-support storage, remote microgrids, and stand-alone power systems where deep storage is required and sufficient space is available to install the primary renewable electricity sources, such as solar photovoltaic systems. For example, if an entire strategy around hydrogen for diesel displacement can be developed for a remote town or community, then this would increase the feasibility and practicality of using hydrogen as electricity storage by developing an entire ecosystem to support it.

Increased government support in strict policy development, funding of pilot projects, and enabling technology advancement will stimulate collaboration and competition in the industry. Moreover, CSIRO's "Low Emissions Technology Roadmap" report [49] and statements by interviewees agree that governments need to act as the early adopters of emerging technology and be the off-take partners through their procurement of public infrastructure and assets. Regulated bodies and customers need to be incentivised to take risks. Industry support through joint ventures and public–private partnerships will help mitigate risks for the early projects whilst providing shared learnings to those involved.

Nevertheless, certain limitations of this exploratory study need to be considered. First, this research does not include an in-depth technical study of the detailed performance of energy storage systems, nor does it provide a comprehensive economic analysis or comparison against current electricity prices. Another limitation is the limited number of experts interviewed. To some extent, ten interviewees sound reasonable, as they allowed the authors to propose four challenges and recommendations and discover three critical themes as discussed in the paper. On the other hand, the limited number of participants highlights the immature condition of the DER and hydrogen market in Australia. This limitation highlights the need for more research and applications of hydrogen DER in this country. Additionally, due to the developed subject area surrounding the use of hydrogen, this research does not delve into the specific aspects of hydrogen production, storage, utilisation, and the various regulations and policies governing its use. Therefore, this research should be a step toward a more detailed topic analysis. These limitations and other identified gaps in the knowledge set the basis for future research opportunities. From a perspective of business viability, further research should be conducted on the business and operating models of complete hydrogen strategies for diesel displacement in regional towns or communities, including how they may be able to integrate with proposed hydrogen highways and other infrastructure developments. As a result of decentralising the electricity system, alternative business models to the traditional one-way flow of energy and security need to be tested to allow customers to supply clean, reliable, and affordable energy to the community. This would include how customers will be rewarded for their participation and how the risks will be shared amongst network members, including the network operator.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15166015/s1, File S1.

**Author Contributions:** Conceptualization, H.-Y.C., R.M. and G.M.M.; methodology, G.M.M., R.M. and C.W.; software, C.W.; validation, R.M. and G.M.M.; formal analysis, R.M. and G.M.M.; investigation, C.W.; resources, G.M.M.; data curation, R.M.; writing—original draft preparation, C.W and R.M.; writing—review and editing, H.-Y.C., R.M. and G.M.M.; supervision, R.M. and H.-Y.C.; project administration, G.M.M.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** The study was conducted in accordance with the human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), with the Approval Number HRE2021-0443.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available within the article.

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

## References

1. Hanley, E.S.; Deane, J.P.; Gallachóir, B.P.Ó. The role of hydrogen in low carbon energy futures—A review of existing perspectives. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3027–3045. [CrossRef]
2. Zhao, N.; You, F. Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition? *Appl. Energy* **2020**, *279*, 115889. [CrossRef]
3. Mermelstein, J.; Cannova, C.; Cruz, M.; Anderson, B. Field Demonstration of a Novel Reversible SOFC System for Islanded Microgrid Energy Storage. *ECS Trans.* **2017**, *78*, 2907–2912. Available online: https://iopscience.iop.org/article/10.1149/07801.2907ecst (accessed on 10 May 2022). [CrossRef]
4. Alam, A.; Islam, M.T.; Ferdous, A. Towards Blockchain-Based Electricity Trading System and Cyber Resilient Microgrids, 2nd. In Proceedings of the International Conference on Electrical, Computer and Communication Engineering, ECCE 2019, Chittagong, Bangladesh, 7–9 February 2019.
5. Cárdenas, B.; Swinfen-Styles, L.; Rouse, J.; Hoskin, A.; Xu, W.; Garvey, S.D. Energy storage capacity vs. renewable penetration: A study for the UK. *Renew. Energy* **2021**, *171*, 849–867. [CrossRef]
6. Takatsu, N.; Farzaneh, H. Techno-Economic Analysis of a Novel Hydrogen-Based Hybrid Renewable Energy System for Both Grid-Tied and Off-Grid Power Supply in Japan: The Case of Fukushima Prefecture. *Appl. Sci.* **2020**, *10*, 4061. [CrossRef]
7. Ayodele, T.R.; Mosetlhe, T.C.; Yusuff, A.A.; Ogunjuyigbe, A.S.O. Off-grid hybrid renewable energy system with hydrogen storage for South African rural community health clinic. *Int. J. Hydrog. Energy* **2021**, *46*, 19871–19885. [CrossRef]
8. Carroquino, J.; Roda, V.; Mustata, R.; Yago, J.; Valiño, L.; Lozano, A.; Barreras, F. Combined production of electricity and hydrogen from solar energy and its use in the wine sector. *Renew. Energy* **2018**, *122*, 251–263. [CrossRef]
9. Obara, S.; Hamanaka, R.; El-Sayed, A.G. Design methods for microgrids to address seasonal energy availability—A case study of proposed Showa Antarctic Station retrofits. *Appl. Energy* **2019**, *236*, 711–727. [CrossRef]
10. Dawood, F.; Shafiullah, G.M.; Anda, M. Stand-alone microgrid with 100% renewable energy: A case study with hybrid solar pv-battery-hydrogen. *Sustainability* **2020**, *12*, 2047. [CrossRef]
11. Denhom, P.; Mai, T.; Kenyon, R.W.; Kroposki, B.; O'Malley, M. Inertia and the Power Grid: A Guid without the Spin. National Renewable Energy Laboratory (NREL). 2020. Available online: https://www.nrel.gov/docs/fy20osti/73856.pdf (accessed on 10 May 2022).
12. Yu, Y.; Cai, Z.; Liu, Y. Double deep Q-learning coordinated control of hybrid energy storage system in island micro-grid. *Int. J. Energy Res.* **2021**, *45*, 3315–3326. [CrossRef]
13. Phan, B.C.; Lai, Y.C. Control strategy of a hybrid renewable energy system based on reinforcement learning approach for an isolated Microgrid. *Appl. Sci.* **2019**, *9*, 4001. [CrossRef]
14. Konstantinopoulos, S.A.; Anastasiadis, A.G.; Vokas, G.A.; Kondylis, G.P.; Polyzakis, A. Optimal management of hydrogen storage in stochastic smart microgrid operation. *Int. J. Hydrog. Energy* **2018**, *43*, 490–499. [CrossRef]
15. Gust, G.; Brandt, T.; Mashayekh, S.; Heleno, M.; DeForest, N.; Stadler, M.; Neumann, D. Strategies for microgrid operation under real-world conditions. *Eur. J. Oper. Res.* **2021**, *292*, 339–352. [CrossRef]

16. Acakpovi, A.; Adjei, P.; Nwulu, N.; Asabere, N.Y. Optimal Hybrid Renewable Energy System: A Comparative Study of Wind/Hydrogen/Fuel-Cell and Wind/Battery Storage. *J. Electr. Comput. Eng.* **2020**, *2020*, 1756503. [CrossRef]
17. Amirkhalili, S.A.; Zahedi, A.R. Techno-economic Analysis of a Stand-alone Hybrid Wind/Fuel Cell Microgrid System: A Case Study in Kouhin Region in Qazvin. *Fuel Cells* **2018**, *18*, 551–560. [CrossRef]
18. Salkuti, S.R. Energy Storage Technologies for Smart Grid: A Comprehensive Review. *Majlesi J. Electr. Eng.* **2020**, *14*, 39–48.
19. IRENA. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal*; IRENA: Abu Dhabi, United Arab Emirates, 2020.
20. Alam, M.; Kumar, K.; Dutta, V. Design and Economic Evaluation of Low Voltage DC Microgrid based on Hydrogen Storage. *Int. J. Green Energy* **2021**, *18*, 66–79. [CrossRef]
21. Mariama, S.M.; Scipioni, A.; Davat, B. Study of a micro-grid with renewable energy sources with hydrogen storage. *Int. J. Innov. Appl. Stud.* **2018**, *24*, 208–219.
22. Serra, F.; Lucariello, M.; Petrollese, M.; Cau, G. Optimal integration of hydrogen-based energy storage systems in photovoltaic microgrids: A techno-economic assessment. *Energies* **2020**, *13*, 4149. [CrossRef]
23. Singh, S.; Chauhan, P.; Aftab, M.A.; Ikbal, A.; Suhail Hussain, S.M.; Taha Selim, U. Cost Optimization of a Stand-Alone Hybrid Energy System with Fuel Cell and PV. *Energies* **2020**, *13*, 1295. [CrossRef]
24. Morton, S.; Pencheon, D.; Squires, N. Sustainable Development Goals (SDGs), and their implementation: A national global framework for health, development and equity needs a systems approach at every level. *Br. Med. Bull.* **2017**, *124*, 81–90.
25. Khalilpour, K.R.; Vassallo, A. A generic framework for distributed multi-generation and multi-storage energy systems. *Energy* **2016**, *114*, 798–813. [CrossRef]
26. Yekini Suberu, M.; Wazir Mustafa, M.; Bashir, N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renew. Sustain. Energy Rev.* **2014**, *35*, 499–514. [CrossRef]
27. Andersen, G. Powering Into the Future The Question Isn't Can We Afford to Upgrade the Electric Grid, but Can We Can Afford Not to Representative Jeff Morris Washington Senator Pat. State Legislatures, May 2018; pp. 24–27. Available online: https://www.ncsl.org/bookstore/state-legislatures-magazine/powering-into-the-future.aspx (accessed on 10 May 2022).
28. Satyapal, S. Research and Development to Enable Hydrogen at Scale. *Chem. Eng. Prog.* **2019**, *115*, 28–32.
29. Haghi, E.; Raahemifar, K.; Fowler, M. Investigating the effect of renewable energy incentives and hydrogen storage on advantages of stakeholders in a microgrid. *Energy Policy* **2018**, *113*, 206–222. [CrossRef]
30. Hemmati, R.; Mehrjerdi, H.; Bornapour, M. Hybrid hydrogen-battery storage to smooth solar energy volatility and energy arbitrage considering uncertain electrical-thermal loads. *Renew. Energy* **2020**, *154*, 1180–1187. [CrossRef]
31. San Martín, I.; Ursúa, A.; Sanchis, P. Integration of fuel cells and supercapacitors in electrical microgrids: Analysis, modelling and experimental validation. *Int. J. Hydrog. Energy* **2013**, *38*, 11655–11671. [CrossRef]
32. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110935. [CrossRef]
33. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
34. Krupinski, E.A. Writing Systematic Reviews of the Literature—It Really Is a Systematic Process! *J. Digit. Imaging* **2019**, *32*, 199–200. [CrossRef]
35. Abdin, Z.; Mérida, W. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. *Energy Convers. Manag.* **2019**, *196*, 1068–1079. [CrossRef]
36. DiCicco-Bloom, B.; Crabtree, B.F. The qualitative research interview. *Med. Educ.* **2006**, *40*, 314–321. [CrossRef] [PubMed]
37. Ecker, F.; Hahnel, U.J.J.; Spada, H. Promoting decentralized sustainable energy systems in different supply scenarios: The role of autarky aspiration. *Front. Energy Res.* **2017**, *5*, 1–18. [CrossRef]
38. Elsner, I.; Monstadt, J.; Raven, R. Decarbonising Rotterdam? *City* **2019**, *23*, 646–657. [CrossRef]
39. Gill, P.; Stewart, K.; Treasure, E.; Chadwick, B. Methods of data collection in qualitative research: Interviews and focus groups. *Br. Dent. J.* **2008**, *204*, 291–295. [CrossRef]
40. Seidman, I. *Interviewing as Qualitative Research: A Guide for Researchers in Education and the Social Sciences*; Teachers College Press: New York, NY, USA, 2006.
41. Alvial-Palavicino, C.; Garrido-Echeverría, N.; Jiménez-Estévez, G.; Reyes, L.; Palma-Behnke, R. A methodology for community engagement in the introduction of renewable based smart microgrid. *Energy Sustain. Dev.* **2011**, *15*, 314–323. [CrossRef]
42. Shafiullah, G.M.; Carter, C.E. Feasibility study of photovoltaic (PV)-diesel hybrid power systems for remote networks. In Proceedings of the 2015 IEEE Innovative Smart Grid Technologies—Asia, ISGT ASIA, Bangkok, Thailand, 3–6 November 2015.
43. Moore, D.; Healy, P. The Trouble With Overconfidence. *Psychol. Rev.* **2008**, *115*, 502–517. [CrossRef]
44. Anderson, C. Presenting and evaluating qualitative research. *Am. J. Pharm. Educ.* **2010**, *74*, 141. [CrossRef]
45. CSIRO. Denham Hydrogen Demonstration Plant. Available online: https://research.csiro.au/hyresource/denham-hydrogen-demonstration-plant/ (accessed on 1 April 2022).
46. Mohseni, S.; Moghaddas-Tafreshi, S.M. A multi-agent system for optimal sizing of a cooperative self-sustainable multi-carrier microgrid. *Sustain. Cities Soc.* **2018**, *38*, 452–465. [CrossRef]
47. Samy, M.M.; Elkhouly, H.I.; Barakat, S. Multi-objective optimization of hybrid renewable energy system based on biomass and fuel cells. *Int. J. Energy Res.* **2021**, *45*, 8214–8230. [CrossRef]

48. Bruce, S.T.M.; Hayward, J.; Schmidt, E.; Munnings, C.; Palfreyman, D.; Hartley, P. *National Hydrogen Roadmap*; CSIRO: Canberra, Australia, 2018.
49. Campey, T.; Bruce, S.; Yankos, T.; Hayward, J.; Graham, P.; Reedman, L.; Brinsmead, T.; Deverell, J. *Low Emissions Technology Roadmap*; Commonwealth Scientific and Industrial Research Organisation (CSIRO): Canberra, Australia, 2017.