Hydrogen as a Long-Term Large-Scale Energy Storage Solution to Support Renewables

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Abstract: This paper presents a case study of using hydrogen for large-scale long-term storage application to support the current electricity generation mix of South Australia state in Australia, which primarily includes gas, wind and solar. For this purpose two cases of battery energy storage and hybrid battery-hydrogen storage systems to support solar and wind energy inputs were compared from a techno-economical point of view. Hybrid battery-hydrogen storage system was found to be more cost competitive with unit cost of electricity at $0.626/kWh (US dollar) compared to battery-only energy storage systems with a $2.68/kWh unit cost of electricity. This research also found that the excess stored hydrogen can be further utilised to generate extra electricity. Further utilisation of generated electricity can be incorporated to meet the load demand by either decreasing the base load supply from gas in the present scenario or exporting it to neighbouring states to enhance economic viability of the system. The use of excess stored hydrogen to generate extra electricity further reduced the cost to $0.494/kWh.

Keywords: renewable energy; solar and wind; battery storage; hydrogen-based energy storage; hybrid energy systems; South Australia

1. Introduction

In efforts towards reducing the greenhouse gas emissions and mitigating the impact of climate change, countries around the globe have started to shift towards energy production through renewables. Energy generation from renewable sources such as wind and solar can help mitigate emissions produced through using traditional fossil fuel-based energy generation. However, renewable energy generation is highly weather-dependent and lacks the possibility of achieving a continuous supply on their own due to their inherent intermittency [1]. This can lead to issues, such as energy curtailment and wastage of energy and, hence, mismatching between supply and demand. While employing multiple generation systems as backups or demand management measures initiated by the end users could be the possible options, employing an optimally designed and sized energy storage system can be the most viable and sustainable solution [2]. Energy storage solutions can even be also employed in gird connected area (with or without renewables) for peak shaving or fill the reliability gap of the grids where reliability is of significant importance [3–5].

One of the technologies to store excess energy produced by renewable energy sources is generation and storage of hydrogen. This system includes the major components of an electrolyser, hydrogen storage tank, and a fuel cell system. The excess from the renewable sources (i.e., solar and wind) is directed towards an electrolyser to generate hydrogen by electrolysing water into hydrogen and oxygen. The hydrogen is stored in the storage tank and when the renewable sources fall short in meeting the demand, the fuel cell draws on this stored hydrogen and generates electricity (usually by taking oxygen from air) [6,7].

Hydrogen-based energy storage has high power rates (i.e., in the range of 10 MW) and is suitable for meeting long-term (seasonal) energy storage requirements [8]. Pumped hydroelectric storage system (PHS) has limited scope for further development in long-term storage applications due to its specific geographical requirements and possible environmental impacts [9]. Batteries that can be considered as another energy storage solution are efficient as short-term energy storage solutions; however, due to their uncertain lifetime, and quick degradation (i.e., due to charging cycles), sensitivity to environmental conditions (e.g., temperature), self-discharge, and limited storage capacity (per unit volume and mass), batteries are not perfect candidates for long-term and bulk energy storage applications [10–13].

This paper investigates the scope of application of hydrogen as a long-term large-scale energy storage solution through a case study for state of South Australia (SA) in Australia for hybrid energy input from solar photovoltaic (PV) and wind turbines to meet the state's load demand. The energy generation mix has evolved in SA with the increase in penetration of renewable energy. At the end of 2016, registered local generation comprised of 48.4% renewable energy generation with wind and solar energy contributing 39.2% and 9.2% respectively [14]. Moreover, the total of 1515 MW solar and 3178 MW of additional wind generation on existing 1698 MW was either committed or proposed as of 1 July 2017 [14]. In 2016–2017, SA's electricity generation capacity from gas was 49.1% of total capacity, with the increase in solar and wind capacity such that the combined generation capacity from these sources would reach 58% while gas would contribute 35% in total capacity [14]. Hence, as synchronous generation capacity decreases and intermittent renewable generation increases, more storage capacity will be required to maintain the stability of the grid. Figure 1 shows the map of SA. The total renewable energy generating capacity as per the target set by the state government would reach to 1515 MW of solar energy and 4876 MW of wind energy. However, apart from 100 MW of Tesla's battery storage installation, there are no significant storage options being invested for the state. Hence, lack of a concrete energy storage target and increase in renewable energy generation target can result in instability in the grid and power cuts. This case study will help understand the storage capacity and design requirements to support the SA's renewable energy target (RET).

Figure 1. Map of South Australia highlighted. SA has an area of 983,482 square km. and monthly average load demand is 1,321,549 kWh in which 560,600 is the base load supplied by gas or coal power plants and monthly average renewable supply is 760,499 kWh.

Limited studies are available in the literature on real world application of hydrogen as a large-scale energy storage solution in multiple renewable energy input scenarios. Most of the studies available in the literature focus on either small scale or medium size system (e.g., households or small communities). Zoulias et al. [15] in 2007 carried out a techno-economic analysis on a hydrogen-based energy storage system to replace batteries and diesel generator of an existing PV/diesel generator stand-alone system. The investigation was done to provide electricity to a remote community comprising of ten households. Giannakoudis et al. [16] in 2009 evaluated the optimum system design using hybrid inputs from solar and wind with hydrogen to store energy. However, in this case, arbitrarily load demand profiles were used. Recent review by Bahramara et al. [17] in 2016 has presented the list of research studies conducted on a system with hybrid energy inputs and hydrogen for storing energy. Other studies have reported in the literature on the viability of hydrogen-based energy storage solutions for supporting renewable energy systems in small-scale cases such as, telecommunication applications [2,18], stand-alone-households (e.g., [19,20]), rural villages (e.g., [21,22]), small communities and universities (e.g., [23,24]), islands (e.g., [25,26]), etc. There are also some limited number qualitative studies reported in the literature that discuss the applications of hydrogen for energy storage in large-scale long-terms energy scenarios with multiple renewable energy inputs [27–29]. However, quantitative analyses on real cases are required to confirm the findings suggested by these studies.

This paper presents a case study to investigate the techno-economics of using a hydrogen-based energy storage arrangement with a hybrid solar PV and wind turbine input to provide a reliable power supply to SA. The generation capacity considered in this study is based on most recent RET set by the SA state government in 2017. The aim of the study is to present an optimum system design using HOMER simulation software (Golden, CO, USA) (i.e., the Hybrid Optimisation Model for Electric Renewables) for above-mentioned scenario and compare the techno-economic performance of the systems with scenarios in which batteries on their own and in conjunction with hydrogen are used for energy storage. The results of this investigation will help provide direction on the feasibility of implementing battery and/or hydrogen-based energy storage technologies and help with making decision on the right option to be considered for implementation.

Section 2 of this paper will present an overview of previous studies on above-mentioned energy storage technologies used globally for large-scale/long-term needs with a particular focus on the use of hydrogen for energy storage in renewable energy generation systems. Section 3 will describe the method used to conduct this study and Section 4 will present the details of the case study such as inputs, assumptions, and energy modelling with analysis and discussion of these results. In Section 5 the results are provided and discussed. This section also provides ideas on alternative scenarios for better utilisation of the selected energy storage solution. Finally, conclusions will be presented in Section 6.

2. Previous Studies

2.1. Storage Technology Overview

There are a number of storage technology options available, which can be categorised into mechanical, thermal, electrical, and electrochemical and chemical energy storage. Examples of technologies available for each category are as presented in [30], summarised in Table 1.

Table 1. Energy storage methods.

Mechanical Energy Storage	Thermal Energy Storage	Electrical/Electrochemical Energy Storage	Chemical Energy Storage
Pumped hydro	Hot water	Super capacitors	Hydrogen
Compressed air	Molten salt	Superconducting magnets	Synthetic natural gas
Flywheel	Phase-change material	Batteries	Other chemical compounds e.g., ammonia, methanol
		Hydrogen-based energy storage	

Pumped hydro storage (PHS) is the leading technology, accounting for 97% of world's storage capacity, with a rated power of 159 GW, as it is cheaper and more technologically matured than any other storage methods available [31,32]. China has the largest rated power capacity of operational PHS plants with 32 GW, followed by Japan and USA, with 28.3 GW and 22.6 GW, respectively [33]. Compressed air energy storage (CAES) is another mechanical storage option with bulk energy storage capacity that stores air, compressed by electrical compressors. However, PHS and CAES, both have major challenges for their implementation. PHS can be implemented in specific locations with required geographical conditions (i.e., proper elevation difference, enough water availability, near to transmission lines, etc.). Such limitations suggest challenges with widespread and flexible use of this storage solution [34]. CAES is dependent on geographical structure as well, which is either underground, in abandoned mines, rock structures, or above the ground in vessels. Such limitations can be part of the reason that there are only two plants using this technology being currently operational worldwide. Germany has 290 MW and USA in Alabama has 110 MW power capacity CAES plants [35,36]. Considering the above-mentioned limitations with PHS and CAES, and some advantages offered by other storage solutions (e.g., hydrogen-based systems), they have started to receive less attention in recent years.

The increasing penetration of intermittent renewable energy sources, such as solar and wind, have prompted the need for development of battery-based energy storage technology. Global power output capacity at the end of third quarter of 2016 for electrochemical technology was 1.6 GW with the United States leading with 292 operational projects having combined capacity of 0.6 GW followed by South Korea and Japan with capacity of around 0.3 GW each [33]. As estimated by the International Renewable Energy Agency (IRENA), despite an increase in capacity of batteries from 360 MW to 14 GW in 2015, a total of 150 GW of battery storage would be required globally to meet the target of 45 per cent of energy from renewables by 2030 [37,38]. Power and energy ratings are inter-linked in batteries making them bulky and expensive for large-scale storage applications; moreover, issues such as self-discharge (when used for long-term energy storage) and their sensitivity to environmental condition exacerbate the situation in terms of their effectiveness to be used as long-term energy storage solution. On the other hand, along with having high gravimetric energy density and no self-discharge problem, power and energy supply duration are set independently in hydrogen fuel cell systems. That makes hydrogen-based energy storage system one of the promising technologies favourable for long-term large-scale energy storage applications [6,39,40]. While receiving rapidly-growing attention, hydrogen-based energy storage solutions for such applications areas yet to be further developed. Only seven projects were reported to be operational globally by 2016, having a combined capacity of just over 7 MW [33]. According to a recent report published research in August 2017 [41], the hydrogen-based energy storage and technology market had reached $3.6 billion in 2016 and is expected to reach around $5.4 billion by 2021 (all prices are in USD).

2.2. Hydrogen Storage System in a Renewable Energy Input System

As briefly discussed limited data has been reported in the literature on using hydrogen-based storage system for large-scale hybrid renewable energy input scenarios; however, a number of examples for the application of this technology in smaller scale systems have been reported to date. One of the earliest studies on this was conducted by Khan et al. in 2004 [42] for a remote household having a consumption of 25 kWh/day with a peak power demand of 4.73 kW. The study considered various combinations of components such as a diesel generator, fuel cell, batteries, a wind turbine, and solar PVs for system optimisation and concluded that the wind-diesel-battery system was the most cost-effective option for a remote house stand-alone system owing to the higher cost of PV arrays and fuel cells at the time. However, it was also presented that with the cost reduction of fuel cells to 65% of its market price at the time, wind-diesel-battery-fuel cell system would be more attractive, in which the size of the batteries could be significantly reduced while the hydrogen was the main player to take care of the energy needs of the household. The research also concluded that 85% reduction in fuel cell cost would completely replace the diesel generator making wind-fuel cell arrangement to be the most cost-effective option. This finding was in agreement with the results of the research published by Bezmalinovic et al. in 2012 [43] and later by Amutha et al. in 2014 [44]; both of which demonstrated that the use of diesel generators can be avoided but with increased cost of electricity, unless the cost of the fuel cell system is reduced. Hence, reduction in components of hydrogen storage was highlighted as a requirement for implementation of a cost-competitive hydrogen-based energy storage system integrated with a renewable energy system. However, these studies also emphasised that the cost competitiveness of the hydrogen systems is more within reach if used in conjunction with battery storage.

Research published by Ashourin et al. in 2012 [45] presented a feasibility analysis of PV-wind turbine systems along with battery and hydrogen storage for a small village in Tioman Island in Malaysia. The study demonstrated that solar-wind-battery system could offer the cheapest unit cost of electricity at $1.104/kWh. However, while the system provided power for most of the duration throughout the year, during some periods it could have reliability issues in terms of supplying enough power to meet the demands. The study then showed that introduction of fuel cell in the solar-wind-battery system resulted in a more stable power supply arrangement at a reasonable increase in unit cost, reaching $1.108/kWh. The advantage of achieving additional reliability by using a hybrid battery/hydrogen energy storage arrangement was also highlighted by the research conducted by Shabani et al. in 2015 for a remote telecommunication application [46]. This results also agreed with the findings of a more recent study by Das et al. [47] published in 2017 showing a slight increment in the cost of electricity with addition of a hydrogen-based energy storage unit from $0.323/ kWh to $0.355 kWh for a small island in East Malaysia. In this system wind turbines were not included as wind energy generation was not significant in the area, which is justified, as in another study by Ashourin et al. [45] had 9% of wind energy contribution for a similar location in Malaysia.

The present paper is an attempt to address this evident gap in the literature in terms of published analyses and data on the application of hydrogen-based energy storage solutions in large-scale hybrid renewable energy scenarios. A case study of a hybrid generation system in a state with a vast area of 984,377 square kilometres was selected for this research, which can be compared to many countries of such sizes around the world. The importance of this research is more pronounced considering the complimentary nature of renewable energy inputs used (e.g., wind and solar), which suggests the energy storage system to be sized smaller than when only one of these inputs are used. Contrary to many other studies, real generation capacities (proposed by the state government) were used as inputs to our analysis, rather than considering arbitrary input data. Previous literature has concluded that, while it provides the stability in power supply, the inclusion of hydrogen-based energy storage solutions can increase the cost of electricity generated. Hence, possible options for enhancing the economic viability of hydrogen system by its better utilisation are discussed in this study.

3. Method

This paper presents the discussion on significance of deploying hydrogen storage as a long-term large-scale application through a case study for SA. South Australia has an area of 983,482 square kilometres. This is a vast area for a state and is even bigger in size than many countries such as Germany, France, Spain, and Italy. With such vast land area and highly variable seasonal renewable energy inputs from wind and solar energy, SA is an ideal place to practice and identify the prospects of large scale long-term energy storage solution. Map of SA is highlighted in Figure 1.

The case study includes the techno-economic feasibility analysis of hybrid renewable energy system with storage systems. Battery storage and battery-hydrogen hybrid storage system are compared to determine the optimum system design for such a large-scale application. The HOMER tool is used to optimise the system design based and identify the storage capacity required. HOMER ranks the suitability of the designs according to their net present cost (NPC) while analysing the system feasibility for a continuous year round operation [48]. Meteorological data, such as solar irradiance, wind speed, and temperature, are fed into the software to evaluate hourly energy generation throughout the year.

South Australia has set its RET mostly based on generation through wind and solar energy. Wind turbines and solar PVs are considered as electricity generation components in HOMER. Half-hourly electrical load demand was collected from the Australian Energy Market Operator's (AEMO) data dashboard for the year 2017 for each month [49]. Before creating the load profile, it was assumed that the minimum load (base load) for the entire year was provided by electricity generation through gas and half-hourly load was subtracted from base load for each time step. The total load and the load that will be met by renewable generation are shown in Figure 2.
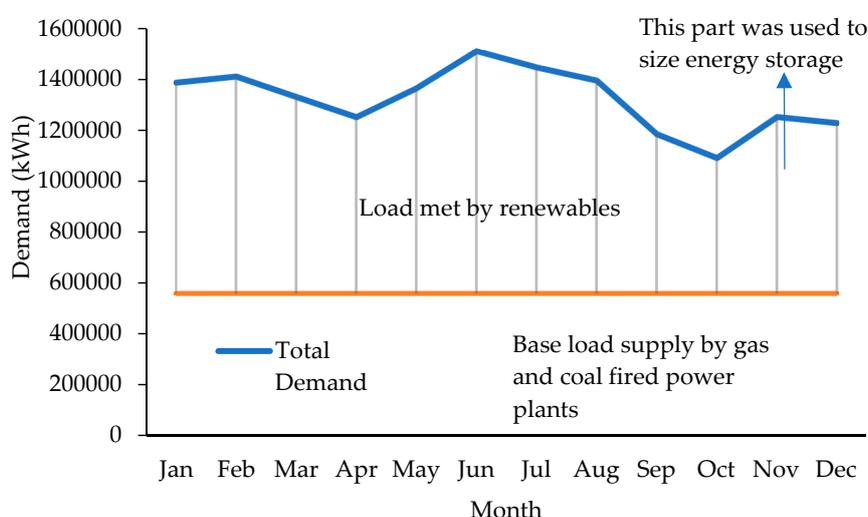
Figure 2. Representation of load met by renewables that will be used to size energy storage.

The resulting load values were imported to HOMER to create a load profile assuming that the remaining load, apart from assumed base load, would be provided by solar PVs and wind turbines. The seasonal and daily load profiles for a day in January as an example is shown in Figures 3 and 4 respectively. The seasonal profile shows high load demand for summer months mainly due to electricity demand for cooling, and winter months because of increased demand for heating. April and October have relatively lower load demands as both heating and cooling loads are at their minimum levels during these months. The increase in demand around midnight is due to time controlled switching of hot water systems, which is scheduled to set on at 11:30 p.m. for newly installed meters in SA. This is set as to take benefit of off-peak prices and hence, has caused 250 MW of time step increase in demand [50].
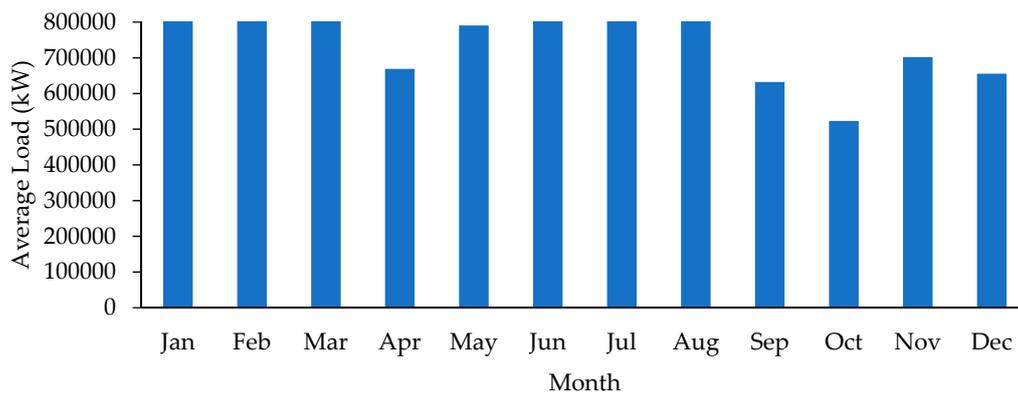
Figure 3. Seasonal load profile in SA.
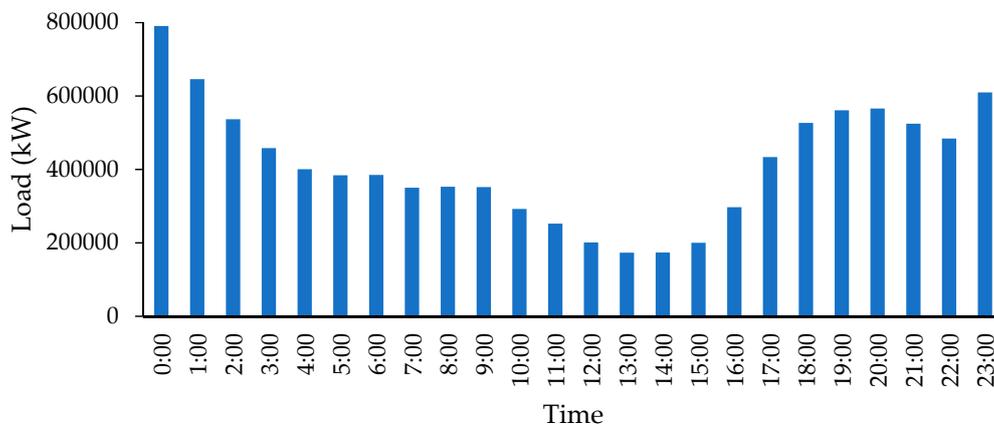
Figure 4. Daily load profile during January in SA.

As wind and solar energy is considered for the simulation, annual solar radiation and wind speed should be considered to determine the performance of solar PV panels and Wind turbines respectively. Global horizontal radiation and wind speed data is obtained from the NASA Surface Meteorology and Solar Energy database. Both hourly radiation and wind speed data is averaged monthly by HOMER for simulation. Monthly global horizontal radiation averages and average wind speed is shown in Figures 5 and 6, respectively.
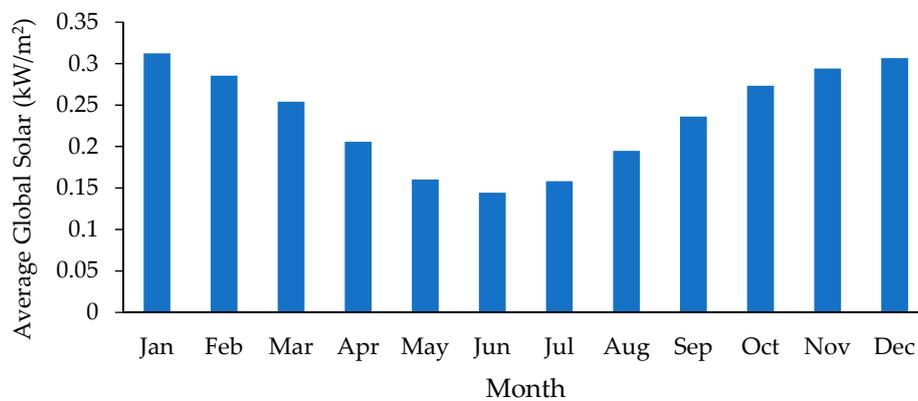
Figure 5. Monthly average global horizontal solar radiation (averages) in used in the HOMER simulation.
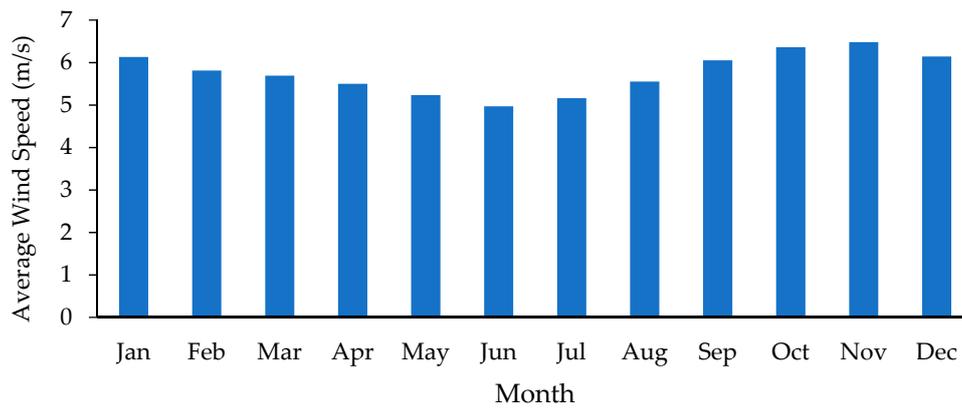
Figure 6. Average monthly wind speed average across the SA state) used for the simulation.

4. Energy Modelling Using HOMER

4.1. Scenarios and Modelling Structures

The case study investigates and compares the feasibility of using two energy storage options to support the entire generation from wind turbines and solar PVs: (1) solely battery bank as the energy storage system (2) hydrogen-battery energy storage.

Solar PVs and wind turbines are sized according to the RET suggested by the Australian state government; 1515 MW and 4876 MW, respectively. The energy storage systems are both sized to provide four days of autonomous operation, when none of the renewable energy generators are in operation in case of their unexpected unavailability: e.g., due to unfavourable weather conditions or grid system failure. Above-mentioned energy storage options to be investigated are schematically illustrated in Figure 7a,b, as extracted from HOMER.
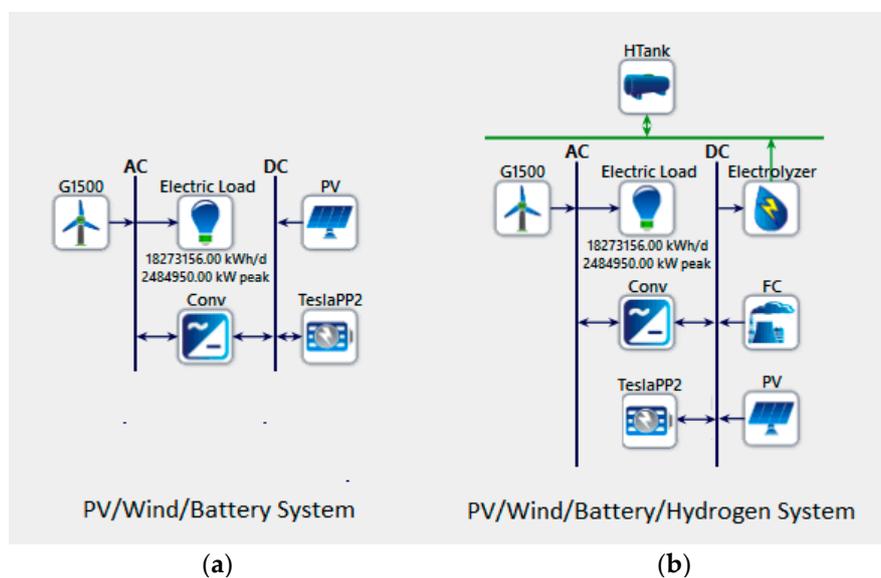
Figure 7. (**a**) PV/wind/battery system design; and (**b**) PV/wind/battery/hydrogen system design.

The electrolyser in the hydrogen system generates hydrogen from the excess electricity generated by wind turbines and solar PV, which is then stored in hydrogen tank to generate electricity through the fuel cell later to fill the gap between the supply and demand.

4.1.1. Battery Based Storage System

Flat plate PV modules and wind turbines were sized according to the RET of 1515 MW capacity of solar PV and 4876 MW of wind power generation. The generation capacity was constrained to evaluate the optimum size and design the storage system. The electrical energy efficiency of PV modules was adjusted to 13% [46] from its value at standard test conditions (STC) by considering the effect of ambient temperature, which is defined by the temperature resource taken from the NASA Surface Meteorology and Solar Energy database. Power output of the PV modules is rated at STC (i.e., a solar radiation input of 1 kW/m^2, 25 °C cell temperature, and in the absence of any wind blowing over the surface of the PVs). However, this does not fully reflect actual operating conditions. Hence, the efficiency of PV is less than that measured in standard test conditions. De-rating factor was assumed to be 85% for the modules considering the effects such as soiling of panels, aging, snow cover during the winter period, and other transmission losses. The effect of temperature on power output and nominal operating cell temperature were assumed to be −0.05%/°C and 47 °C respectively. Considering the RET of 4178 MW capacity, 3300 wind turbines, each having 1.5 MW capacity, and 80 m hub height was assumed for the simulation. The following equation is used to calculate the PV array output.

$$P_{pv} = Y_{pv}F_{pv}(G_t/G_{t,stc})[1 + \alpha_P(T_c - T_{c,stc})] \tag{1}$$

where

- P_{pv}: output of the PV array;
- Y_{PV}: rated capacity of PV array under STC;
- F_{PV}: derating factor (%);
- G_T: solar radiation incident on the PV array in a particular time step [kW/m^2];
- $G_{T,STC}$: incident radiation at STC;
- α_P: temperature coefficient of power [%/°C];
- T_C: PV cell temperature in a particular time step; and
- $T_{C,STC}$: PV cell temperature under STC

Tesla's Power Pack 2 (PP2) lithium-ion batteries were considered for this case study. Tesla recently completed installation of a 100 MW battery system in SA in November 2017 and further talks between government and Tesla is underway for large utility scale installation [51]. The cost of the system as announced by Tesla in November 2016 is $398/kWh [52], and the same was assumed for this study. This cost is in line with the total cost of 90 million Australian Dollars for Tesla battery storage system installed in SA in 2017 which is $505/kWh. However, this cost included total installation costs and extra costs to deliver the project in 100 days [53]. The round-trip efficiency (RTE) suggested by the manufacturer is 88%. However, such a level of RTE is not expectedly achievable when the batteries are used as a long-term energy storage solution (i.e., as required in the first case scenario). Hence, 50% RTE was assumed for the long-term storage application and 80% for the short-term when combined with hydrogen storage as required in the second scenario [46]. These batteries can be connected in various combinations of parallel and series depending on the site and system architecture. The nominal capacity of each battery is 210 kWh with nominal voltage of 380 V. Depth of discharge recommended by the manufacturer is 100% that is equivalent to 0% state of charge. However, to design a reliable system and preserve the lifetime of the batteries frequent full discharges have to be avoided. Hence, the state of charge for this case study was assumed to remain above 20% in all situations. This serves a dual purpose as this 20% of unused stored energy can account for unfavourable weather conditions and provide few days of autonomous operation in worst case scenario of zero generation through renewable energy sources (e.g., cased by natural disasters, unfavourable weather conditions, maintenance, etc.).

The size of the battery bank is not constrained as the main aim of the case study is to identify the storage capacity required for a fixed generation capacity by renewables. HOMER will give the

optimum battery bank size to maintain a reliable electricity supply with minimum NPC. The lifetime of lithium-ion batteries depends on their charging rates: it decreases as the charging rate increases and varies between 5 to 7 years [54]. Hence, as a conservative assumption the lifetime of batteries for this case study was assumed to be five years for outdoor industrial applications, which is in line with figures published by other researchers [15,46]. The cost and lifetime assumptions for all other components are taken from recently published articles or average value from supplier's websites [46,55,56] (Table 2). NPC is the difference between the present cost of the all the costs of installing and operating the components of the system and the present value of total revenue generated over the life time of the project and is calculated using the following equation [57]:

$$NPC = -Co + \sum Ct/(1+r)^t \qquad (2)$$

where:

- C_o: Initial Investment;
- C: Cash flow;
- r: Discount rate; and
- t: time.

4.1.2. Hybrid Battery-Hydrogen Storage System

The hydrogen-based energy storage system used in this study consists of and electrolyser, a fuel cell and a hydrogen tank. The properties and cost considered in the analysis set in HOMER are those of proton exchange membrane (PEM) type fuel cell. The fuel consumption rate was fed into HOMER as suggested in other studies [58,59] that translates into electrical energy efficiencies in the range of about 40–50% that is expected for a PEM fuel cell. The electrolyser produces hydrogen from surplus power generated by wind turbines and solar PV, and it was sized to accommodate the surplus of PVs and wind energy generators. The fuel cell was sized to generate enough electricity for maximum load demand. The hydrogen tank was not constrained to make sure that the system uses all the excess energy to produce hydrogen and enough space was assumed to be available in the tank to store hydrogen [60]. Energy efficiency of the electrolyser was assumed to be 70% while being capable of compressing hydrogen to 30 bars above atmospheric pressure ready for storage. Capital cost for the hydrogen tank was based on the mass production of the system. The economic assumptions for electrolyser, hydrogen tank, and fuel Cell have been taken from recently published reports by other researchers [47,61–63]. However, the cost for hydrogen storage may further decrease in years to come, and particularly in storage applications as large as that considered for this case study. The economic and lifetime details that have been fed into HOMER for the system's components are given in Table 2.

Table 2. Cost details of battery and hybrid storage based renewable System. All costs are in USD.

Components	Capital Cost ($/kw)	Replacement Cost ($/kW)	O&M Cost ($/Year)	Lifetime (Year)
Solar PV	831	831	145	25
Wind Turbine	2,535,000/unit	2,535,000	76,500	20
Battery	398 ($/kWh)	398 ($/kWh)	0	5
Converter	210	210	0	15
Electrolyser	2000	1200	20	15
Hydrogen Tank	438 $/kg	438 $/kg	0	25
Fuel Cell	600	500	0.08 $/op. h	40,000 h

Other economic assumptions for the case study include a nominal discount rate of 8% and inflation rate of 2%; the project lifetime was assumed to be 25 years as that used is other similar studies, e.g., [46,60,64,65].

5. Results and Discussion

5.1. Current Scenarios

The scenarios simulated include PV/wind/battery and PV/wind/hydrogen/battery arrangements. PV/wind/hydrogen systems were also simulated to completely replace the battery storage. However, it resulted in a very large system defying the technical infeasibility of this solution while the cost of the system turned out to be significantly high. Hence, this scenario has been discarded and was not considered as an option for the case study. The investigation indicated that the above-mentioned two options are more feasible and cost-effective to be practiced for the case of large-scale long-term energy storage application focused by this research. The optimum system sizes obtained from HOMER for PV/wind/battery and PV/wind/hydrogen/battery systems with zero unmet electrical load and the lowest unit cost of electricity (COE) are shown in Table 3.

Table 3. Optimised result for PV/wind/battery and PV/wind/battery/hydrogen.

Design	PV (MW)	Wind Turbine (Units)	Tesla PP2 (Units)	Electrolyser (MW)	Fuel Cell (MW)	Hydrogen Tank (kg)	COE ($/kWh)
PV/Wind/Battery	1515	3300	1,475,001	-	-	-	2.54
PV/Wind/Battery/Hydrogen	1515	3300	150,000	2400.8	2400	10,000,000	0.626

From Table 3, it is evident that significant reduction in unit cost of electricity can be achieved by introducing hydrogen storage unit to the PV/wind/battery system for a large-scale application. It can be accounted to the decrease in battery units due to the increase in overall efficiency of the system. 80% round-trip energy efficiency was assumed for the latter scenario as battery is used as a short-term energy storage only along with hydrogen-based energy storage unit taking care of the long-term energy storage requirements [46]. Simulation was carried out to design a cost-effective system, which could provide at least four days of autonomous operation for both scenarios during the month of July, when generation of energy is at minimum. State of charge (SOC) of a Tesla PP2 battery bank throughout the year is illustrated in Figure 8.
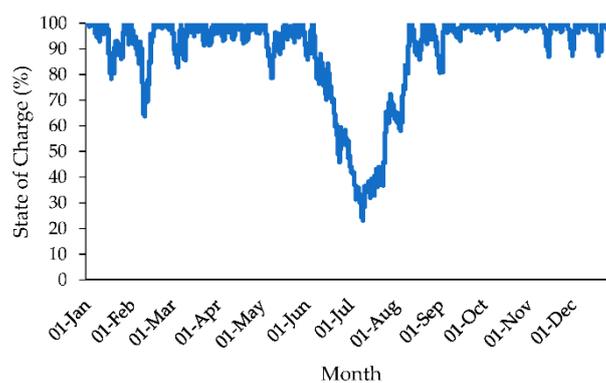
Figure 8. State of charge of a Tesla PP2 battery bank with 1,475,001 batteries at 50% roundtrip efficiency used for long term storage—Scenario 1.

A 20% minimum SOC was considered for batteries at all situations. SOC is lowest in July, the gap allows for 4–5 days of autonomous operation till the battery is fully discharged at 0% SOC as allowed by the manufacturer. The round-trip energy efficiency of batteries was assumed to be 50% when used as both long-term and short-term energy storage solutions. As shown in Figure 8, apart from month of July, battery storage has enough stored charge to operate autonomously. This creates the possibility of decreasing the base load, which is supplied by gas in the grid during summer months. This then enhanced the economic viability of the system. Figure 9 shows the amount of stored hydrogen tank throughout the year together with the state of charge in Tesla PP2.
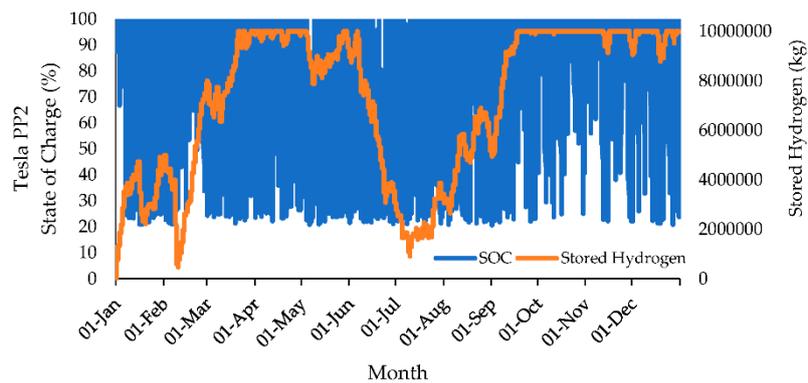
Figure 9. State of charge of a battery bank and variation in hydrogen level for a PV/wind/battery/hydrogen system with 150,000 batteries at 80% round trip efficiency, where batteries are used for short-term energy storage with hydrogen system used for meeting long-term energy storage requirement in Scenario 2.

The hydrogen tank was set to be started from zero in January as a practical proposition when the system is commissioned and start to operate for the first time. Hydrogen level in the tank follows almost a pattern similar to that obtained for batteries in PV/wind/battery system as illustrated in Figure 8. The stored hydrogen reaches its maximum during summer because more energy is generated by the solar PVs and wind turbines during this period. The excess energy available during summer time though can is used by the electrolysers to produce more hydrogen. By contrast the hydrogen level is at its lowest during winter months reaching its minimum in July due to low solar and wind electricity production. Hence, during this period most of the hydrogen stored earlier is used in the fuel cell to generate electricity and cover the supply gap. This combined system was also set to provide four days of autonomous operation in July. However, after July, hydrogen level reaches back to its maximum level and remains at highest possible level for rest of the year. This could result in excess amount of hydrogen than necessary to start the next year with. For a large-scale application, battery/hydrogen hybrid energy storage solution was found to be cheaper than a battery only energy storage solution. Moreover, the storage system with two types of storage (battery and hydrogen) offers more reliability than a system with a single energy storage solution. However, as batteries are more often charged and discharged in this design, the increased number of charging/discharging cycles may potentially affect the lifetime of the batteries. Hence, a detailed study on battery lifetime with respect to charging cycles in this context can be beneficial to shed more light on this effect. Requirement for hydrogen storage may not be really significant in regard to load demand in the present scenario for SA, where gas already provides the base load. To further enhance the benefit offered by the hydrogen/battery hybrid energy storage solution, the excess stored hydrogen can be utilised to generate electricity that is translated to an added value. This alternative scenario will be further explored in the following section.

5.2. Alternative Scenarios

The excess stored hydrogen produced throughout the year can be utilised for further electricity generation. Currently, SA has 49.1% of electricity generation capacity through gas [14]. The excess stored hydrogen can be used to reduce this base load supply from gas while keeping the same renewable penetration capacity (i.e., better utilising of this generation capacity). Alternatively, the excess electricity generated through the hydrogen system can be exported to the neighbouring states. Either of these solutions can offer opportunities to enhance the overall economic violability of the system. Simulation (in HOMER) was carried out by increasing electric load by considering the above-mentioned scenarios. The results showed that an additional 250,000 kW of maximum load demand could be met every hour for the month of March and April and the maximum of 600,000 kW from September to December. The variation of hydrogen level and SOC of the battery bank in case of increased load demand is shown in Figure 10.
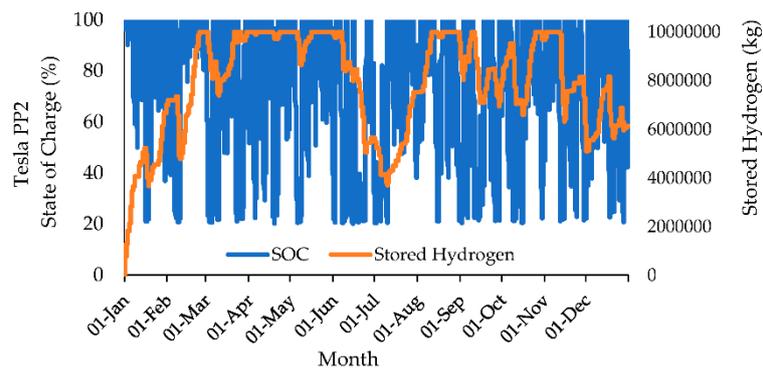
Figure 10. State of charge of battery bank and variation of hydrogen level for increased load demand.

Excess stored hydrogen is utilised at the end of the year as stored level of hydrogen is decreasing. At the minimum level of hydrogen and SOC of the battery bank in July, the system can still provide two days of autonomous operation. The optimum system design obtained from HOMER for the same inputs as in Scenario 2 is shown in Table 4.

Table 4. Optimum sizing and economic performance for the PV/wind/hydrogen battery system in which the excess hydrogen is used to reduce the base load or export electricity to the neighbouring states.

Design	PV (MW)	Wind Turbine (Units)	Tesla PP2 (Units)	Electrolyser (MW)	Fuel Cell (MW)	Hydrogen Tank (kg)	COE ($/kWh)
PV/wind/Battery/Hydrogen	1515	3300	150,000	2400.8	2400	10,000,000	0.494

As another possible scenario for future investigation, the possibility of using this excess hydrogen for fuelling hydrogen fuel cell cars to be operational across the state can be taken into account. One of barriers against expansion of this technology is the availability of hydrogen supply [66]. The excess hydrogen available can be part of the solution to lift this barrier and encourage the utilisation of hydrogen fuel cell vehicles.

It is important to consider this point that hydrogen fuel cell systems generate heat, as well as electricity [67,68]. Part of the total heat generated by the fuel cell that is available for recovery (i.e., Q in W) can be calculated from the following equation [69]:

$$Q = NI(1.25 - V_{out}) \tag{3}$$

where *N* is the number of cells in a fuel cell stack; *I (A)* is the current passing through the cells; and V_{out} *(V)* is the output voltage of the cell. According to Shabani [67] the amount of heat recovered from a fuel cell can be almost comparable with its output power (at its rated power) and the overall combined heat and power (CHP) energy efficiency of a fuel cell can reach over 80% [70]. Recovering the fuel cell heat this though enhances the round-trip energy efficiency of such hydrogen-based energy storage solutions. The heat recovered from fuel cell can be used in domestic applications (e.g., hot water or space heating), where low grade heat (at about 60 °C supplied by PEM fuel cells) is required [1]. Decentralised ustilisation of hydrogen fuel cell systems facilitates the possibility of recovering the fuel cell heat for such applications that can improve the economics of the system significantly. Detailed evaluation of this scenario remains out of the scope of this work; however, this is an important scenario to be fully assessed in order to fully understand the benefit that can be offered by a hydrogen-based energy storage solution in long-term large-scale energy storage applications.

6. Conclusions

This paper presented a case study for the state of SA in Australia to analyse the significance of hydrogen-based storage system as a large-scale long-term energy storage solution for a hybrid

renewable energy input from solar PVs and wind turbines. Generation capacity was constrained according to the RET set by the state government. HOMER simulation software was used to analyse the techno-economic feasibility of two systems including: PV/wind/battery and PV/wind/battery/hydrogen. System size and unit cost of electricity were the main parameters used as evaluation indicators in this study. Based on the results obtained, PV/wind/battery/hydrogen system was the most economical system. The inclusion of hydrogen system reduced the size of the battery bank significantly. This reduced the COE of the system from 2.54 $/kWh to 0.626 $/kWh. However, for the present generation mix and load demand of SA, this system design resulted in excess hydrogen stored after July. The stored hydrogen does not hold any significance unless it can be further utilised. Decreasing the base load supply from gas increased the renewable energy penetration with constrained generation capacity. This alternate scenario utilised the excess hydrogen which increased the overall economic viability of the system. The unit cost of electricity for this case decreased to 0.494 $/kWh. Other possibility is utilising this excess hydrogen to support the deployment of hydrogen fuel cell vehicles across the state. In fact more detailed investigation is required to evaluate the benefits and challenges of implementing this idea. Utilising the heat generated by the fuel cell can enhance its overall efficiency (i.e., as a CHP) unit. This scenario has not been investigated as part of the present study; however, the authors are suggesting this to be studied in details to fully understand its economic benefit and challenges, when practiced in long-term large-scale applications.

Author Contributions: Conceptualization, S.K. and B.S.; Methodology, S.K. and B.S.; Software and modeling, S.K. and B.S.; Formal Analysis, S.K. and B.S.; Writing-Original Draft Preparation, S.K.; Writing-Review & Editing, B.S.; Supervision, B.S.; Project Administration, S.K.

Conflicts of Interest: The authors declare no conflict of interest

Abbreviations

PHS	Pumped hydroelectric storage
SA	South Australia
PV	Photovoltaic
RET	Renewable energy target
CAES	Compressed air energy storage
HOMER	Hybrid Optimisation Model for Electric Renewables
IRENA	International Renewable Energy Agency
AEMO	Australian energy market operator
STC	Standard test conditions
RTE	Round-trip efficiency
PEM	Proton exchange membrane
O&M	Operations and maintenance
COE	Cost of electricity
SOC	State of charge
PP2	Power pack 2

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