

Design and Economics of Hydrogen based Standalone Energy Storage System for Household Application

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Abstract - Renewable energy sources provide electricity that is intermittent, making it difficult to utilise readily and efficiently. The growing need for clean energy sources has led to many research works in hydrogen energy. Clean energy must be stored and reused in order for it to be widely adopted, which is possible to achieve with hydrogen and reversible fuel cell technology. We can already see many applications of hydrogen fuel in automobile industries, but less in residential applications as hydrogen storage has been a concern for a long time. In this paper, we study reversible fuel cell, different hydrogen storage methods and design and examine the economics of a hydrogen-based stand-alone energy storage system for an average American residence, taking into account current market conditions and system component availability. The key financial metric used in this study is the levelized cost of electricity storage (LCOS). The result indicates that the LCOS of RFC systems is calculated to be 29.3\$/kWh, which is more than the LCOS, 8.8\$/kWh of Li-ion batteries.

Key Words: Renewable energy, Reversible fuel cell, Metal hydride, Hydrogen fuel, Hydrogen storage, Green Hydrogen.

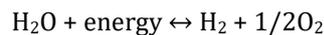
1. INTRODUCTION

The imbalance between energy production and consumption necessitates the development of effective energy storage systems, especially when renewables are used as major energy sources[25]. Renewable energy sources are distinguished by non-uniform power output that varies over time. The most promising strategy to regulate fluctuations and use extra electric power is to employ hydrogen as an efficient energy transporter. The biggest impediment to the application of hydrogen energy storage systems is the safe, convenient and affordable storage and delivery of hydrogen [27]. Designing and integrating various hydrogen equipment such as Reversible Fuel Cell and Metal Hydride storage can make use of hydrogen for residential as well as utility-scale backup power viable. The Economics of this integrated system also plays a major role in its adoption. In this article, we have designed a system by integrating commercially available components and analysed the economics of the system for an American household as all

of the components are easily available in America but this can also be extended to other parts of the world in further studies.

1.1 Reversible Fuel Cell

A reversible/regenerative fuel cell (RFC) is a single device that may operate in either electrolyser or fuel cell mode [9]. Water dissociates into hydrogen and oxygen in the first part of a reversible process, and recombination of constituent elements creates water in the second half:



The water-splitting reaction is used in an RFC system; in E-mode, electrical energy is used to split water into hydrogen and oxygen gas. When the stored hydrogen and oxygen are supplied back into the RFC in F-mode, it regenerates electricity and recombines water molecules. The RFC concept relies heavily on the capacity to perform reversible water splitting and reformation reactions[10]. If air is used to supply oxygen, RFCs can form a long-term integrated electrical energy storage system when paired with a hydrogen storage system.

Discrete regenerative fuel cells (DRFC) and unitised regenerative fuel cells (URFC) are the two forms of RFC (URFC). The electrolysis unit for creating hydrogen and oxygen gases is separate from the fuel cell unit for generating power in a DRFC system, however, the two devices are integrated into a single system [14,15]. The DRFC system is primarily a system integration technique that utilizes commercially available components. A URFC is a single piece of equipment or mechanism that can execute the dual operations of electricity generation and water splitting, instead of two independent units of the electrolyser and fuel cell. The fundamental benefit of a DRFC over a traditional separate electrolyser, hydrogen storage, and fuel cell system is that all functional elements may be integrated into a single compact package. As a result, DRFC has the potential to be a stand-alone electrical energy storage device, competing directly with batteries. Furthermore, in DRFC, a closed-loop water cycle is feasible, in which product water from F-mode can be restored to the storage of water for E-mode operation. This is also useful in stationary power supply operations

when freshwater supply is restricted. Because the electrolyser and fuel cell are kept independent, DRFC allows users to design and optimise the respective performance and economics of these two components. It also permits the cell's capacity to be modified individually in the two different modes. The electrolyser's efficiency could be tuned independently of the fuel cell's so that the entire system's overall roundtrip energy efficiency can be improved. Moreover, because the electrolyser and fuel cell are fully distinct devices that can run at the same time, the DRFC can work in both E and FC modes simultaneously (if the overall system structure allows). In a URFC, on the other hand, the same cell is used in both modes, so the ratio of E-mode to FC-mode capacity is fixed by the cell characteristics. It really is difficult to increase the efficiency and effectiveness of this single cell in both E and FC-modes because distinct catalysts are required on the oxygen side for maximum results, so a mixed catalyst must be used [16], making it unsuitable for our application. As a result, the URFC's roundtrip energy efficiency is often lower than that of an equivalent DRFC. Therefore taking these factors into consideration we opted for the DRFC type of RFC.

1.2 Hydrogen Storage

Hydrogen can be stored in three states of matter: liquid, gaseous and solid. The chemical energy per mass of hydrogen (142 MJ kg^{-1})[3] is at least three times larger than that of other chemical fuels (for example, the equivalent value for liquid hydrocarbons is 47 MJ kg^{-1})[3]. At room temperature and atmospheric pressure, 4 kg of hydrogen occupies a volume of 45 m³. This corresponds to a balloon of 5 m diameter. For hydrogen to become a competitive energy carrier, its volume density must be increased by reducing the volume that hydrogen occupies under normal conditions. Currently, hydrogen is stored either in high-pressure tanks in compressed form or in liquid form in cryogenic tanks by decreasing the temperature below the critical temperature. The desorption of hydrogen from compressed gas takes place at very high pressure, which makes it difficult to use in small scale applications. In solid-state hydrogen is stored in the form of hydrides, which can be stored in basically three ways. First, through physisorption (sorbent materials) in which the hydrogen atom is weakly bonded on the surface of the base metal and here the desorption of hydrogen takes place at a very low temperature. Second, through chemisorption (complex hydrides) in which the hydrogen atom is chemically bonded with the base metal with a strong bond and here the desorption takes place at a very high temperature. Third, we can use nanostructured materials to store hydrogen, here the bonding between the hydrogen and base metal is weaker than chemisorption but stronger than physisorption. The

hydrides can be then classified into metal hydrides and complex hydrides (Examples-Amide hydrides and borohydrides). Complex hydrides consist of light metal hydrides (MgH_2 , salts of AlH_4 (alanates), NH_2 (amides), borohydrides such as NaAlH_4 , LiNH_2 , Li_2NH and $\text{Mg}(\text{BH}_4)_2$) and chemical hydrides (NaBH_4 , $\text{C}_{10}\text{H}_{18}$ and NH_3BH_3). The addition of light elements such as Mg or Ca into LaNi_3 alloys leads to alloys with higher hydrogen storage capacities, Ex.- RE-Mg-Ni alloy (RE = Rare Earth) with a gravimetric density of about 1.8%[2] and LaMg_3 alloy with a gravimetric density of about 3%[2]; low-cost Fe addition into Ti-10Cr-18Mn-32V solid solution alloy increases the equilibrium pressure and capacity. Reducing the size of complex hydrides to the nanoscale regime can improve the thermodynamics and kinetics of hydrogen storage. Limitations of hydrogen storage show that metal hydrides are reversible under ambient temperatures but are too heavy. Simple chemical hydrides are reversible at high pressure and temperature. Complex chemical hydrides show poor reversibility, while sorbent materials show good reversibility at very low temperatures.

1.2.1 Nanostructure

Grain refining can also be used to store hydrogen in solid form in nanostructures. Experiments reveal that grain refinement, especially to the nanoscale, increases the hydriding and dehydriding kinetics of metals and alloys dramatically. Ball milling is the most common process for refining hydride grains. Reducing grain size to the nanometre scale can reduce reversible storage capacity by reducing intragrain volume in particular circumstances. When the grain size is less than 1.3 nm, the hydrogen desorption energy reduces dramatically. Nanocatalysis can also aid in the dissociation of H_2 molecules or the recombination of hydrogen atoms. Ball milling is a simple and effective method for dispersing and introducing catalysts into hydrides, resulting in nanosized catalysts. Improved hydrogen storage performance is demonstrated in the nanocomposite of two (or more) hydrides, in which appealing features of components are combined. More crucially, the hydriding properties of nanocomposites outperform those of the individual components, which is likely due to interaction between component hydrides at high volumetric density phase borders. Ball milling nanostructured graphite for 80 hours in a 1-MPa hydrogen environment yields up to 0.95 H atoms per carbon atom, or 7.4% mass percent. At a temperature of more than 600 K, 80% of this hydrogen is desorbed. Planar graphitic structures can clearly achieve somewhat high hydrogen absorption at low temperatures. At low temperatures, significantly more hydrogen may be adsorbed in the tube than on a flat surface; however, as the temperature rises, the ratio falls sharply, from 55 at 50 K to 11 at 77 K.[3]

1.2.2 Hydride

Tetra and hexahydro aluminates (alanates), tetrahydroborate (borohydrides), and amides are the three types of complex hydrides used in hydrogen storage applications. Alanates- Catalyzed sodium alanate ($\text{NaAlH}_4 + 2\% \text{ Ti}$) is one of the best-performing and well-studied reversible complex hydrides. The reversible capacity of the catalysed sodium alanate system is almost twice that of common metal hydrides such as $\text{Na}_2\text{LiAlH}_6$, KAlH_4 , K_3AlH_6 , K_2LiAlH_6 , and K_2NaAlH_6 . However, all of these compounds have lower gravimetric hydrogen densities, whereas LiAlH_4 , Li_3AlH_6 , $\text{Mg}(\text{AlH}_4)_2$, $\text{Ca}(\text{AlH}_4)_2$, and $\text{Ti}(\text{AlH}_4)_4$ have high gravimetric hydrogen densities.) Alkali borohydrides have a high decomposition enthalpy and require prohibitively high temperatures to liberate H_2 . Because of its high hydrogen content (18.4 wt%), LiBH_4 has received a lot of interest. However, because hydrogen desorption from this molecule is very endothermic, it necessitates a high temperature, such as 80-600 degrees Celsius. Transition metal borohydrides ($\text{Mg}(\text{BH}_4)_2$, $\text{Ca}(\text{BH}_4)_2$, 13 $\text{Zr}(\text{BH}_4)_4$, 14 $\text{Zn}(\text{BH}_4)_2$ 14) are less stable than alkaline earth borohydrides. The entropies of solid reactants and products can contribute significantly to the overall entropy shift in complex hydrides comprising light elements (B, N, etc.). When it comes to desorbing hydrogen, the most complicated hydride systems have serious kinetic issues. $\text{Mg}(\text{BH}_4)_2$, $\text{Al}(\text{BH}_4)_2$, and LiBH_4 are examples of complex hydrides that can achieve high-density requirements but are constrained by their irreversible nature. RT intermetallic hydrides with volumetric densities comparable to complex hydrides, such as $\text{TiFeH}_{1.7}$ and LaNi_5H_6 , are another option.

Reversible and non-reversible storage media can be used to trap hydrogen in a chemical process. The term "non-reversible" refers to a material that does not readily hydrogenate under normal pressure and temperature. As a result, non-reversible hydrides have a wide range of decomposition enthalpies, ranging from light (for example, AlH_3 $\text{DH} = 7 \text{ kJ/mol H}_2$) to strong (for example, LiBH_4 $\text{DH} = 67 \text{ kJ/mol H}_2$ for partial breakdown). Decomposition enthalpies for reversible hydrogen carriers are typically 20–55 kJ/mol H_2 . [4]. The hydrogen atoms are chemically bound to the metal in a typically reversible metal hydride, and the hydrogen is released when the thermodynamic conditions change (decreasing pressure or increasing temperature). Transition metals make up all reversible hydrides that work at room temperature and pressure; as a result, the gravimetric hydrogen density is limited to less than 3 wt%; for example, the gravimetric hydrogen density of LaNi_5H_6 is just 1.4 percent. More heat is required to desorb hydrogen as the hydride becomes more stable. LiBH_4 is the chemical with the highest known gravimetric hydrogen density at room temperature (18

mass percent) [3]. When LiBH_4 melts at 280°C , three of the four hydrogens in the compound desorb and the complex decomposes into LiH and boron. With the addition of SiO_2 , the desorption process can be catalysed, and considerable thermal desorption can be observed as early as 100°C . The melting point of $\text{Al}(\text{BH}_4)_3$ is 65°C , and it is liquid at room temperature. This is the only liquid hydride at room temperature, other than covalent hydrocarbons. Around room temperatures, reversible hydrogen storage capabilities of up to 3% mass percent have been found. Mg produces the ionic, translucent MgH_2 with a hydrogen content of 7.6 mass percent. However, it takes an incredibly long time to form from bulk magnesium and gaseous hydrogen, and in thermodynamic equilibrium, a plateau pressure of 1 bar demands a temperature of 300 degrees Celsius, not ambient temperature. Another technique is to add Mg before the hydride occurs: Mg_2Ni generates the ternary complex hydride Mg_2NiH_4 , which still contains 3.6 mass percent hydrogen. Mg_2Cu , $\text{Mg}_{17}\text{La}_2$, and MgAl , as well as certain other known Mg alloys or intermetallic compounds, quickly react with hydrogen and breakdown into MgH_2 and another compound or hydride (MgAl after ball milling). $\text{Mg}_2\text{Cu H}_2$, for example, decomposes to MgH_2 MgCu_2 . At high temperatures, the reactions are reversible.

Several factors influence the selection of metal hydride materials for hydrogen storage and compression applications. First, the hydride synthesis and breakdown processes must be reversible within the application's working temperature and hydrogen pressure range. Second, in the working conditions, the material must have a large reversible hydrogen storage capacity. According to engineering, three types of metal hydrides are commonly used: AB type (Ex. Ti-Fe-C , Ti-Fe-ca , Ti-Fe , Ta , Ti-Fe-Mm , etc), AB2 type (Ex. Ti-Cr-Fe , Ti-Zr-Cr-Fe , Ti-Zr-Cr-Fe-Mn-Cu , etc), and AB5 type (Ex. Ti-Cr-Fe , Ti (Ex.- Ca-Mm-Ni-Al , Mm-Ni-Mn-Co , etc). The A element, which is a commonly rare earth or alkaline earth metal, forms a stable hydride. The B element is frequently a transition metal that can only form unstable hydrides. AB Alloys- TiFe is a low-cost, well-known AB-type hydrogen storage material. It has a 1.9 wt percent H_2 storage capacity and releases hydrogen at ambient temperatures. However, there are certain disadvantages to this alloy in terms of hydrogen activation. Easy activation, fast kinetics of hydrogen absorption and desorption, and relatively high stability of hydrogen sorption properties during cyclic hydrogenation/dehydrogenation characterise AB5-type intermetallics, which include A 14 rare-earth metal (RE), B 14 Ni, Co, Al, Mn, Sn, and others (including the operation in H_2 gas containing impurities of oxygen and water vapours in moderate concentrations). LaNi_5 is one intermetallic that has been thoroughly studied (AB5 based intermetallic hydride). When exposed to moderate hydrogen pressures

at room temperature, this hydride rapidly generates LaNi₅H₆ hydride (1.2 wt percent H₂).

Two medium-scale energy storage devices were demonstrated under the supervision of IPCP and HySA Systems. For hydrogen production by water electrolysis, the systems can use a variety of primary sources of power (grid, solar panels, wind turbine). The produced low-pressure hydrogen is compressed by a metal hydride hydrogen compressor and sent to main hydrogen storage facilities in the form of gas cylinder packs (150e200 atm). In addition, hydrogen is collected and stored in metal hydride hydrogen storage units at pressures below 100 atm. Both hydrogen storage facilities can provide up to 30 kW of electric power to PEM fuel cell stacks; the high-pressure cylinder packs can also provide hydrogen for refuelling fuel cell vehicles and other uses. According to another recent study, this method can be utilised in conjunction with renewable energy sources, with the heat generated from a concentrated solar power plant as the starting source. In this example, hydrogen is discharged into a secondary storage vessel during the day from a high-temperature hydride getting heat from the concentrated solar plant; at night, useful heat is generated from the exothermic absorption of hydrogen in the high-temperature hydride.

Therefore, the hydrides chosen for storage applications with high hydrogen storage densities are lithium hydride(~10.5 wt%)[1], sodium borohydride, magnesium aluminium hydride(~9.27 wt%)[1], lithium aluminium hydride(~10.54 wt%)[2] and ammonia borane(~12.9 wt%)[2].

Table -1: Hydrogen Gravimetric Density in Selected Materials[1]

materials	hydrogen (wt%)	materials	hydrogen (wt%)
LiAlH ₄	10.54	NaAlH	7.41
MgH ₂	7.69	Mg(AlH ₄) ₂	9.27
LiNH ₂	8.78	NaNH ₂	5.15
Mg(NH ₂)	7.15	nNH ₃ BH ₃	12.9
NaBH ₄	10.57		
Al(BH ₄) ₃	16.78		
NH ₃ BH ₃	19.35		
(H ₂) ₄ CH ₄	50.00		

2. DESIGN

Designing the system for DRFC is based primarily on selecting right commercially available components and integrating it to form a synchronized hydrogen Uninterruptible Power Supply (UPS). We assumed a typical American home with a daily energy demand of around 5KW. RFC (electrolyser and fuel cell combined), Hydrogen storage (metal hydride storage), Solar Photovoltaic Power Plant, Water tank, and other essential accessories are the components of the system. We chose components that can synchronize well, and connected each component with the Central Processing Unit for better-synchronised operation.

The solar photovoltaic power plant, which is also responsible for the electrolysis of water from the water tank to generate hydrogen, provides electricity throughout the day. All of the appliances in this house run on Direct Current (DC), which eliminates the need for inverters and improves efficiency. Electricity usage at night is roughly 1400 watts (Television-24 watts, 3 fans (20 watts)-60 watts, 5 led lights (12 watts)-60 watts, refrigerator - 100 watts, air conditioner (1 ton) - 500 watts, miscellaneous devices - 500 watts). To meet this requirement, a fuel cell creates electricity by combining hydrogen stored in metal hydride storage with oxygen from the air, reforming water and storing it in a water tank for later use.

We choose RFC with a rated power of 1800-2000w and 910 litres Metal hydride storage, which when coupled is expected to supply energy for needed load for 8 hours at night, after considering all factors. While considering solar systems for American households we took official data about average energy consumption per day and designed a system of 7KW considering 6KW for household appliances and 1KW for Electrolysis to produce hydrogen in daytime.

Integration of components is illustrated in fig 2. Red arrows indicate flow of electricity or energy, Blue arrows indicate flow of water, Green arrows indicate flow of hydrogen gas and Oxygen required is directly absorbed from air and released in air. Selected Components with brand name and model number are presented in Table 2.

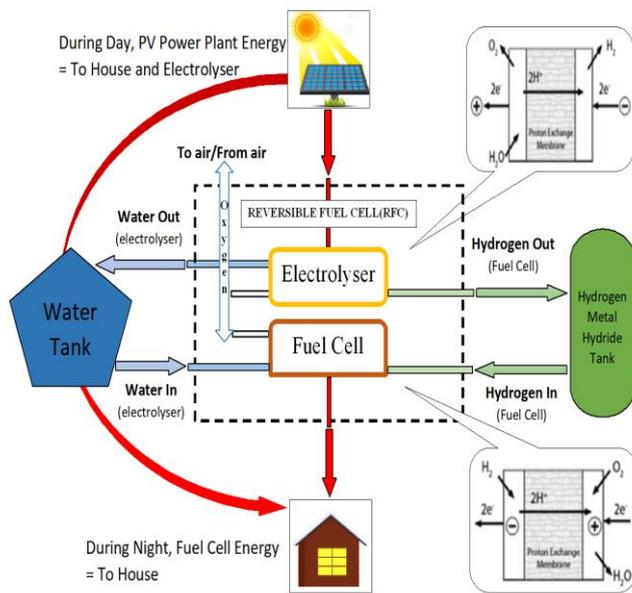


Fig -1: Design of System

Table -2: Selected components of the system

Components of System		
Component Name	Brand Name	Model Name
Fuel Cell (RFC)	Fuelcell Store	GreenHub 2 PRO 2000
Electrolyser (RFC)	Light Bridge, Inc	LBEX-P200
Metal Hydride Storage	Hydrogen Components, Inc,	MyH2 7000
6KW Solar Photovoltaic System (Solar Panels, Mounting)	Trina Solar	-
Miscellaneous (CPU, Cooling Fans, Pressure Control and Connecting Valves, etc)	Generic Brands	-

3. ECONOMICS

The efficiency and economics of proton exchange membrane (PEM) reversible fuel cells are inextricably linked. The fuel cell efficiency is a function of the power density at which the fuel cell is running, not a single value. At maximum power production, the efficiency is usually the lowest. The fuel cell's optimal nominal efficiency, which produces the least expensive power, is determined not only by its performance characteristics but also by its economics, i.e., the fuel cell's capital cost and the cost of hydrogen. The fuel cell's efficiency and economics have

been studied for a variety of load profiles as well as various development and cost scenarios[25]. In our case, we have accumulated the cost and lifespan of all the components in the standalone hydrogen storage system from standard commercial company quotations to find the Levelized Cost of Storage(LCOS) for the current market and energy conditions. This study is based on practical assumptions rather than any hypothetical considerations and portrays the current economics of this system. Moreover, for solar system installation, we considered 2USD per watt and considering our system it was found out to be 14,000 USD. Although it is observed that components survive much higher than the warranty period, the lifespan of every component was assumed to be at the end of the warranty period. According to that assumption, the average lifespan of a hydrogen storage system is approximately 10 years but the solar system has a higher lifespan of 25 years.

In the energy storage systems (ESS), the levelized cost of energy storage (LCOS) is a quantitative metric for calculating the cost of storing and transforming energy into a usable source. The capital cost of the ESS, the price of energy, the number of cycles between charging and discharging modes, the efficiency of the ESS, and the capacity of the storage system all affect LCOS. To compute LCOS for RFC, the following formula was adopted from Ref. [30] and then modified:

$$LCOS = \frac{TIC \left(\frac{r}{1-(1+r)^{-N}} \right)}{\sum_{t=0}^t kWh_{dis,t}} + \frac{\sum_{t=0}^{8760} P_t}{t \cdot \eta_{RTE}} + C_{O\&M}$$

where:

- TIC is the total installed system cost,
- r is the discount rate.
- N is the ESS life in years,
- kWh_{dis} is the total discharge capacity of the system in one full charging/discharging cycle.
- Pelec,t is the average price of the electricity,
- t is the number of hours (t = 2920 h/year),
- η_{RTE} is the ESS round-trip efficiency, and.
- O&M is the estimated operation and maintenance cost in \$/kWh of electricity discharged from the ESS.

After substituting all the values such as TIC(RFC+Storage = 36,300USD), kWh_{dis}(76,650), η_{RTE}(60%) and assuming 8 as r in LCOS equation, LCOS value for this system was estimated to be 29.3USD/KWh. The cost and lifespan of various components are depicted in Table 3.

Table - 3: Cost of System

Costs of components of the system		
Component Name	Lifespan (Years) (based on Manufacturers warranty)	Cost (USD)
Fuel Cell (RFC)	15	20,275
Electrolyser (RFC)	15	5,600
Metal Hydride Storage	17	10,425
6 KW Solar Photovoltaic System (Solar Panels, mountings)	25	14,000 (2/W)
Maintenance	-	1,000
Miscellaneous (CPU, Cooling Fans, Pressure Control and Connecting Valves, etc)	-	2,000
	Total Cost	53,300

4. RESULT AND CONCLUSIONS

The LCOS of RFC systems is assessed to be 29.3\$/kWh, which is more than the 8.8\$/kWh of Li-ion batteries. Based on the LCOS value, the LIB system appears to have a better economic benefit than the RFC system, although it lacks the flexibility of the RFC system.

Despite the increased acceptance of renewable energy systems in recent years, the energy sector is still struggling to make maximum use of it due to the intermittent nature of renewable energy sources. Energy storage systems such as Li-ion batteries and reversible fuel cells can provide a long term solution to increase the resiliency of power grids and to allow rapid adaptation for higher percentages of renewables in their power mix in the future. Using currently accessible system components, this article offered a techno-economic model for energy storage reversible fuel cells as energy storage technologies.

Hydrogen-based systems are not yet mature for use in household applications because they are not economically

viable due to their high LCOS of 29.3USD/KWh. However, this system has great potential because the main issue, cost, can be easily brought down to affordable levels through economies of scale. Bloomberg has forecasted that investment in hydrogen technologies would skyrocket in the near future. Furthermore, this system has a number of benefits, including low energy degradation, the use of only water as a fuel, green fuel production and lower maintenance costs, energy storage capacity, operational charging/discharging flexibility, and the impact on improving grid resiliency, especially during prolonged power outages. In the future, research could be done on developing a catalyst that can substitute platinum, lowering the cost of RFC-based systems and allowing for broad market implementation.

REFERENCES

- [1] Puru Jena, "Materials for hydrogen storage: Past, Present and Future", The Journal of Physical Chemistry Letters, 2011, 2, 206–211, DOI: 10.1021/jz1015372
- [2] Ping Chen and Min Zhu, "Recent progress in hydrogen storage", Materials today, vol. 11, Dec. 2008, Number 12
- [3] Louis Schlapbach and Andreas Züttel, "Hydrogen-storage materials for mobile applications", Nature, vol. 414, 15 Nov. 2001
- [4] Jason Graetz, "New approaches to hydrogen storage," The Royal Society of Chemistry, Chem Soc Rev, 22 Oct. 2008, DOI: 10.1039/b718842k
- [5] Tarasov BP et al, "Metal hydride hydrogen storage and compression systems for energy storage technologies", International journal of hydrogen energy, <https://doi.org/10.1016/j.ijhydene.2020.07.085>
- [6] Li Zhou, "Progress and problems in hydrogen storage methods", Renewable and Sustainable Energy Reviews 9 (2005) 395–408, 19 May 2004, doi:10.1016/j.rser.2004.05.005
- [7] Andreas Züttel, "Hydrogen storage methods", Naturwissenschaften (2004) 91:157–172 DOI 10.1007/s00114-004-0516-x, Published online: 17 March 2004
- [8] Poojan Modi and Kondo-Francois Aguey-Zinsou, "Room temperature metal hydrides for stationary and heat storage applications: A review", Frontiers in energy research, Published: 9 April 2021, doi: 10.3389/fenrg.2021.616115
- [9] Frank DG., "The effects of cell design and materials of construction on the electrolysis performance of a proton exchange membrane unitized regenerative fuel cell", Master of Applied Science thesis. University of Toronto; 2000.

- [10] Andrews J, Doddathimmaiah AK. "Regenerative fuel cells". In: Gasik M, editor. Fuel cell materials. Cambridge: Woodhead Publishing; 2008.
- [11] Andrews J, Doddathimmaiah AK, Ali SM, Akbarzadeh A. "Solar hydrogen systems for remote area power supply from a triple bottom line perspective". in: Proceedings of the Solar World Congress; 2005
- [12] Doddathimmaiah AK, Andrews J. "The use of PEM unitised regenerative fuel cells in solar- hydrogen systems for remote area power supply". in: Proceedings of the World Hydrogen Energy Conference; 2006.
- [13] Yao W, Yang J, Wang J, Nuli Y. "Chemical deposition of platinum nanoparticles on iridium oxide for oxygen electrode of a unitized regenerative fuel cell". *Electrochem Commun* 2007;9:1029-34.
- [14] Pettersson J, Ramsey B, Harrison D. "A review of the latest developments in electrodes for unitised regenerative polymer electrolyte fuel cells". *J Power Sources* 2006;157:28-34.
- [15] Zhigang S, Baolian Y, Ming H. "Bifunctional electrodes with a thin catalyst layer for unitized proton exchange membrane regenerative fuel cells". *J Power Sources* 1999;79:82-5.
- [16] Jung HY, Park S, Popov BN. "Electrochemical studies of an unsupported PtIr electrocatalyst as a bifunctional oxygen electrode in a unitized regenerative fuel cell". *J Power Sources* 2009;191:357-61.
- [17] Amica G et al., "Light metal hydride-based hydrogen storage system: Economic assessment in Argentina", *International Journal of Hydrogen Energy*, <https://doi.org/10.1016/j.ijhydene.2020.05.036>
- [18] Keith S., "Chapter 1: introduction to electrolysis, electrolyzers and hydrogen production". In: *Electrochemical methods for hydrogen production*, ISBN 978-1-78801-604-9. p. 1e27. <https://doi.org/10.1039/9781788016049-00001> [From Book Series: Energy and Environment Series].
- [19] Sigal A, Leiva EPM, Rodríguez CR. "Assessment of the potential for hydrogen production from renewable resources in Argentina". *Int J Hydrogen Energy* 2014;39:8204e14.
- [20] Jepsen J, Bellosta von Colbe JM, Klassen T, Dornheim M. "Economic potential of complex hydrides compared to conventional hydrogen storage systems". *Int J Hydrogen Energy* 2011;37:4204e14.
- [21] Bartels JR, Pate MB, Olson NK. "An economic survey of hydrogen production from conventional and alternative energy sources". *Int J Hydrogen Energy* 2010;35:8371e84.
- [22] Penner S. "Steps toward the hydrogen economy". *Energy* 2006;31:33e43.
- [23] Ball M, Wietschel M, Rentz O. "Integration of a hydrogen economy into the German energy system: an optimising modelling approach". *Int J Hydrogen Energy* 2007;32:1355e68.
- [24] Glatzmaier G, Blake D, Showalter S. "Assessment of methods for hydrogen production using concentrated solar energy". Technical report: NREL/TP-570-23629. 1998.
- [25] F. Barbir and T. Gomez, "Efficiency and economics of proton exchange membrane (pem) fuel cells", Vol. 22, ht. *J Hydrogen Energy* 1997.
- [26] Dell RM, Rand DAJ. "Energy storage e a key technology for global energy sustainability". *J Power Sources* 2001;100:2e17
- [27] Zhang F, Zhao P, Niu M, Maddy J. "The survey of key technologies in hydrogen energy storage". *Int J Hydrogen Energy* 2016;41:14535e52
- [28] Ilja Pawel, "The cost of storage - how to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation", Elsevier Ltd *Energy Procedia* 46 (2014) 68 - 77, doi: 10.1016/j.egypro.2014.01.159
- [29] Ahmad Mayyas, Assia Chadly, Saed Talib Amer, Elie Azar, "Economics of the Li-ion batteries and reversible fuel cells as energy storage systems when coupled with dynamic electricity pricing schemes", *Energy*, Volume 239, Part A, 2022, 121941, ISSN 0360-5442, <https://doi.org/10.1016/j.energy.2021.121941>.
- [30] Reznicek E, Braun RJ. "Techno-economic and off-design analysis of stand-alone, distributed-scale reversible solid oxide cell energy storage systems" *Energy Convers Manage* 2018;175:263e77