Metal Hydride Hydrogen Storage for Domestic Photovoltaic

MEng Final Project Report

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“I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.
I believe that the man who will discover a method of using the latent heat in water will have made a greater discovery than that of the steam engine.”

— Jules Verne, *The Mysterious Island*, 1874

Ethics

This project has received ethical approval from the Research Governance and Compliance review board. The approval was granted on 14 February 2024, with reference number #3520-3423. For any queries or further information regarding the ethical approval, please contact research-ethics@bath.ac.uk.

Abstract

Solar radiation does not match human energy demand. Nor do most renewable energies. If renewable energies ought to become the primary energy source in a carbon–neutral future, this time mismatch is to be resolved. Changing anthropic consumption habits is unpractical, therefore, research is focusing onto efficient and capacious energy storage solutions. Common solar photovoltaic domestic installations use batteries to store this energy. This projects proposes the use of hydrogen as an energy carrier. Specifically this report analyses the problems related with its storage.

Hydrogen has a high gravimetric energy density but very low volumetric one, this is why its storage is challenging to this day. Among the evaluated storage systems, solid–state storage based on Metal Hydrides proved greater potentials due to high volumetric capacity in a safe, efficient, compact and reversible way.

Addressing the thermal requirements of metal hydrides led to the design of a specific tank using an internal heat exchanger with liquid cooling. The novel idea of recycling the heat waste of hydrogen consumers, resulted in improved storage loop efficiency and reduced cost of the tank. Magnesium Hydride (MgH_2) demonstrated several advantages including high storage density, stability and environmental sustainability. Overall the hydrogen storage through metal hydrides proved to be a feasible solution for long–term energy storage withing the domestic sector.

(216 Words)

Contents

1 Introduction **1**
1.1 Drivers . . . 1
1.2 Application and Rationale . . . 2
1.3 The Storage Problem . . . 3
1.4 Objectives . . . 4

2 Hydrogen Storage Technologies **5**
2.1 Physical–based Storage . . . 5
2.1.1 Compressed . . . 5
2.1.2 Liquid . . . 6
2.1.3 Cryo–compressed . . . 6
2.2 Chemical–based Storage . . . 7
2.2.1 Chemical Sorption . . . 7
2.2.2 Hydrogen Carriers . . . 7
2.3 Assessment of Storage Systems . . . 8
2.4 Problems to address . . . 9

3 System Implementation **11**
3.1 Metal Hydrides . . . 11
3.1.1 The Chemistry . . . 11
3.1.2 Heat of Reaction . . . 12
3.1.3 Material Selection . . . 13
3.2 Tank Geometry . . . 14
3.3 Thermal Coupling . . . 16
3.4 Hybrid Energy Storage System . . . 16

4 System Validation **19**
4.1 Testing . . . 19
4.1.1 Heat Dissipation . . . 19
4.1.2 Flow Rates . . . 20
4.1.3 Life Cycle . . . 20
4.2 Tank size . . . 21
4.3 Efficiency . . . 22
4.4 Life Cycle Assessment . . . 23
4.5 System Costs . . . 23

5 Conclusions and Future Outlook **25**
5.1 Conclusions . . . 25
5.2 Future Outlook . . . 26

6 Project Review **27**

7 Acknowledgements **28**

A Appendix **29**
A.1 The duck curve . . . 29
A.2 Hydrogen Pipelines . . . 30
A.3 Annual Sunshine . . . 32
A.4 Project costing . . . 32

List of Figures

1 Share of world total energy consumption by source (2019), taken from [1] 1
2 Photovoltaic–Hydrogen Energy Storage system. 2
3 Three groups of storage technologies based on power and energy capacity costs, taken from [13] 3
4 Various mechanisms for hydrogen storage, reproduced from [17] 5
5 Hydrogen absorption or desorption with metals, inspired by [14, 17] 11
6 Compacted disc of MgH_2 powder (a) and the SEM image showing the result of pressing (b), taken from [25]. 12
7 Volumetric and gravimetric hydrogen density of some selected hydrides compared with compressed, liquid and hydrocarbons, taken from [21]. 13
8 The cross section of a single tank showing the heat transfer techniques (a) and its assembly in a quad formation (b). 15
9 Basic structure of a HESS, reproduced from [30]. 16
10 System architecture of an off–grid HESS integrating electricity, hydrogen and heat. 17
11 Solid-H BL-18 MH tank alone (a) and stacked in series for increased volume (b) [34]. 19
12 Total refuelling cost per cycle of different storage systems by capacity (a) and their distribution (b), taken from [40]. 24
A.1 The duck curve (orange) showing the difference between the grid demand (blue) and the renewable electricity supply (grey) [42]. 29
A.2 Installation of a FRP pipeline suited for hydrogen gas transportation, taken from [7]. 30
A.3 Stylised representation of underground salt caverns for hydrogen molecule (H_2) storage, taken from [13]. 31

List of Tables

1 Densities and efficiency comparison of the hydrogen storage techniques 8
2 Estimate storage size based on different scenarios 21
A.1 Selection of some European capitals by sunshine duration in hours [43]. 32

Acronyms

CO_2 carbon dioxide

COP Coefficient Of Performance

DHW Domestic Hot Water

ES Energy Storage

FC Fuel Cell

GHP Gas absorption Heat Pump

H–ES Hydrogen Energy Storage

H_2 hydrogen molecule

HESS Hybrid Energy Storage System

LCA Life Cycle Assessment

MgH_2 magnesium hydride

MH Metal Hydride

NO_x nitrogen oxides

PEM Proton Exchange Membrane

PV Photovoltaic

Glossary

absorption The process of taking something into another substance

covalently Type of chemical bond in which two atoms share one or more pairs of electrons

desorption The process of releasing something from another substance

electrolysis A process that uses an electric current to drive a non-spontaneous chemical reaction

endothermic A reaction that absorbs heat

exothermic A reaction that releases heat

hydride Class of chemical compound in which hydrogen is combined with other elements

ionically Type of chemical bond in which two ions are joined due to their charge difference

lattice The structure formed by cations in the metallic bond

metallically Type of chemical bond in which positively charged atoms are joined sharing free electrons

thermolysis Chemical decomposition of a substance by heat

1 Introduction

1.1 Drivers

The urgent need to address climate change and attain net–zero carbon emissions has led to a surge in the adoption of renewable electricity sources. However, it is important to understand that electricity only covers 20% of the global energy demand (Figure 1) [1], while the remaining is satisfied by fossil fuels. The harmful impacts of combustion are devastating the environment and ultimately endangering anthropic wellbeing on the planet. To this end, a global energy transformation is necessary, rather than solely focusing on the development of renewable electricity supply [2].

Moreover, the stochastic nature of the renewable inputs, mostly solar irradiation and wind speed, poses a significant challenge. Energy Storage (ES) systems are therefore becoming a major component of the energy transition, providing a reliable and efficient means to fully harness the potential of renewable energy sources [3]. While various Energy Storage options exist, such as pumped hydro, thermal, flywheel, and batteries, many of these are not suitable for domestic applications due to factors like scale, cost, and practicality.

The first driver of the project is therefore the need for a superior energy storage system that can also create a link with the neglected energy demand.

The second driver for this project is the untapped potential of hydrogen as an energy carrier. A concept that dates back to the 18th century when hydrogen was referred to as 'flammable air'. One of the first internal combustion engines was even powered by hydrogen, and its success continued for another century until it, along with other renewable energies, was replaced by the cheaper and more widely available petroleum [4].

In recent years, hydrogen has re–emerged as a critical intermediary for the energy transition [2]. It can be produced from renewable energy sources, consumed to provide electricity and heat, and stored for long periods. This versatility is driving the vision of a hydrogen economy.
The primary objective of hydrogen as an energy carrier is to demonstrate the feasibility of replacing the current fossil fuel economy and move towards the integration of renewable energy sources into energy systems [5].

One of the key advantages of hydrogen is its high gravimetric energy density, offering three times more energy than petrol[1], and its ability to be stored in both small and large quantities. This makes hydrogen an increasingly viable clean, green energy carrier for the future, especially considering its consumption produces only water as a byproduct [7].

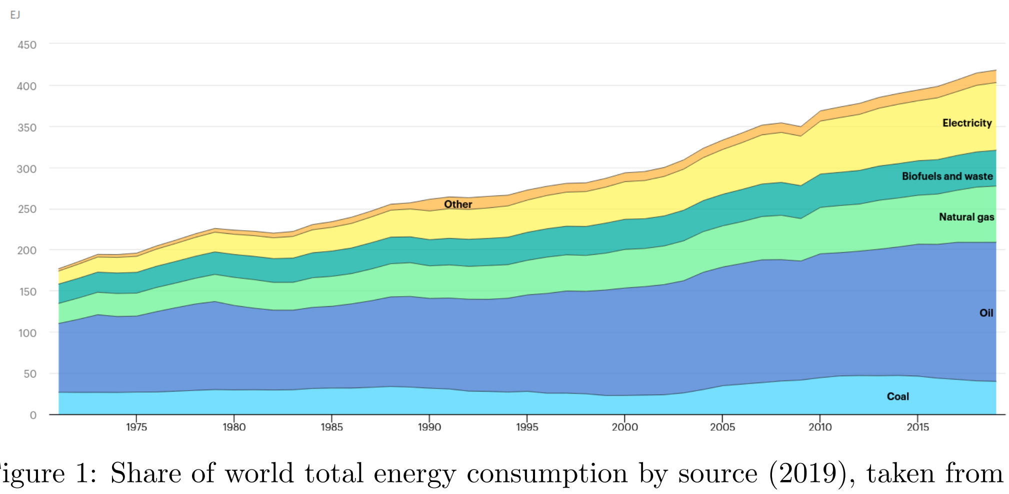


Figure 1: Share of world total energy consumption by source (2019), taken from [1]

[1]Hydrogen contains 39 kW h energy per kilogram, compared to 13 kW h of petrol and diesel [6].

1.2 Application and Rationale

In recent times, there has been a growing trend, particularly among the climate conscious, to address the issue through small individual actions. As the residential sector accounts for 13% of the global energy consumption [1], one approach is to create a more sustainable residence by integrating a solar Photovoltaic (PV) system. The residential sector has a slight advantage, compared to global demand, as 40% of its energy is already covered by electricity. The remaining energy, primarily used for heating, can be either converted to use renewable electricity or replaced with an alternative fuel which eliminates any carbon dioxide (CO_2) emission [1, 4].

Currently, domestic energy storage is provided by batteries. These offer a partial solution as once fully charged they enter a floating state and, the larger their capacity, the more time they spend in this state. During this period, solar chargers (MPPTs[2]) restrict the current, wasting valuable energy [8, 9]. At present the alternative to batteries is a grid–connected system, where excess power is supplied to the grid. Even though this eliminates the need for ES, it generates minimal revenue [9, 10] due to the lack of demand during peak solar generation. This phenomenon is further explained in section A.1 of the Appendix.

This is where a Hydrogen Energy Storage (H–ES) system becomes beneficial. It involves the conversion of excess energy into a chemical compound, the hydrogen molecule. The hydrogen is then stored and can be converted back into energy in the form of electricity with a Fuel Cell or heat through combustion [11]. Currently methane is used to produce hydrogen on a large scale in a process called steam reforming [12]; however, since hydrogen can be produced from water electrolysis, a system could be devised for in–home generation and storage (Figure 2).

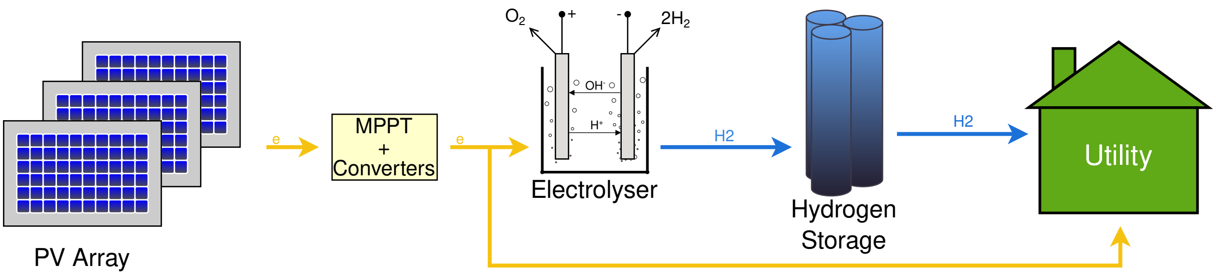
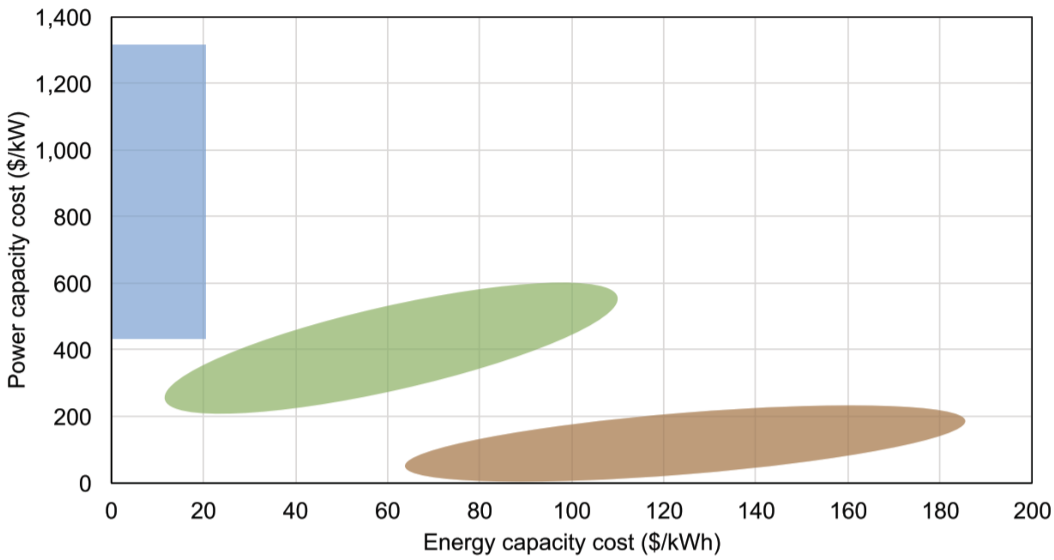


Figure 2: Photovoltaic–Hydrogen Energy Storage system.

The primary advantage of hydrogen is the decoupling of the power and energy characteristics of the storage system. In hydrogen–based storage, unlike batteries, an increase in stored energy, for a given amount of required power, does not necessitate an increase in power [5]. In other words, hydrogen storage is considered a technology with low energy–capacity costs but high power–capacity costs (blue area in Figure 3), making it more suitable for longer duration storage applications and less frequent charge–discharge cycles [9, 13]. The stable chemical nature of hydrogen supports this application, in contrast to batteries, which rapidly decay over time when subjected to deep cycling [14].

According to Figure 3, batteries and supercapacitors still maintain the advantage of a low power–capacity costs. This is because batteries have the fastest response time of any storage technology, making them the suitable option for short–term storage and system frequency control [15]. Instead of favouring one technology over the other the ultimate solution would be to combine the two, creating a Hybrid Energy Storage System (HESS). The result is a small battery pack that handles demand fluctuations within an hour to a day, while the hydrogen system addresses disparities from days to an entire year [8].

[2]Maximum Power Point Tracking is a technique used by PV systems to keep power transfer at highest efficiency with a variable incident radiation [8].



The blue region, with high power and low energy capacity costs, includes thermal, chemical (e.g., hydrogen), metal-air battery, and pumped storage hydro technologies. Lithium-ion batteries fall in the brown area, with low power, but high energy-capacity costs; flow batteries fall in the intermediate, green region.

Figure 3: Three groups of storage technologies based on power and energy capacity costs, taken from [13]

The final advantage of a hydrogen system is the potential to provide ancillary services in a grid–connected scenario. Similar to vehicle–to–grid (V2G) chargers[3], a large electrolyser could act as an energy sink. When the generation in the grid surpasses demand, the electricity price drops and therefore extra hydrogen could be produced inexpensively (see Figure A.1).

1.3 The Storage Problem

While hydrogen has the highest gravimetric energy density of any fuel, its low volumetric density at ambient temperature and pressures results in a low energy density per unit volume [5]. This low density presents a significant challenge, potentially requiring extremely large storage vessels and making hydrogen storage the key enabling technology for the development of a hydrogen–based economy [7].

Abe et al. [14] pointed out that current hydrogen storage technologies have not yet fully satisfied the techno–economic feasibility requirements. Therefore, the development of efficient and cost–effective hydrogen storage solutions is essential for a sustainable hydrogen energy transition. As hydrogen becomes an increasingly important intermediary for the energy transition, the need for suitable storage technologies becomes ever more critical.

This project is devoted to addressing these challenges, with a particular focus on the domestic small–scale environment. In contrast to large industrial–scale applications, domestic PV installations present unique constraints and requirements for hydrogen storage systems [9]. The primary challenges lie in developing compact, safe, and affordable storage solutions that can effectively integrate with existing domestic renewable energy systems. Additionally domestic systems should not require expert personnel, intensive maintenance and frequent repair [5].

By tackling these issues, this project aims to contribute to the advancement of hydrogen storage technologies and facilitate the wider adoption of renewable energy in domestic settings.

[3]a smart charger synchronised to the grid using the vehicle to balance grid loads.

1.4 Objectives

To the best of our knowledge, no previous studies have demonstrated the feasibility of renewable energy storage using hydrogen in the residential sector. Several researches and pilot projects are using hydrogen as means of storing energy but they focus on the large scale industrial or national application. This project aims to analyse the current hydrogen storage technologies and from those devise the future domestic system. The initial project plan [16] included the prototyping and testing of the hydrogen storage solution. Due to the complex nature of the task the objectives were adapted to the following.

1. SELECT SUITABLE STORAGE AMONG EXISTING TECHNOLOGIES
   Explore state of the art hydrogen storage solutions and evaluate them in the context of small–scale storage.

2. LAY THE FOUNDATIONS OF THE SYSTEM
   Sketch the final hydrogen storage system with the chosen storage method in mind, including the surrounding apparati and auxiliary equipment.

3. INVESTIGATE THE CHALLENGES
   Evaluate any challenges that might arise from the storage system that are specific to domestic environments. Find plausible solutions or mitigation.

4. SET THE FUTURE STEPS TO ACHIEVE A WORKING SYSTEM
   Identifies the area of improvement and those yet to be evaluated together forming the aims of the next stage of the project.

2 Hydrogen Storage Technologies

As previously mentioned, hydrogen has a very low volumetric density of just 0.1 kg/m^3 [14]. Because of this, its storage requires special techniques to have a meaningful quantity of stored energy. Hydrogen storage technology offers a range of diverse options, each with its own strengths and weaknesses. These alternatives can be summarised in two major groups: physical–base and chemical–based. The former founded on the state of matter of the hydrogen molecule (H_2) and the latter founded on hydrogen bonding to other atoms to create molecules which are easier to store. Figure 4 provides an overview of the available storage alternatives.

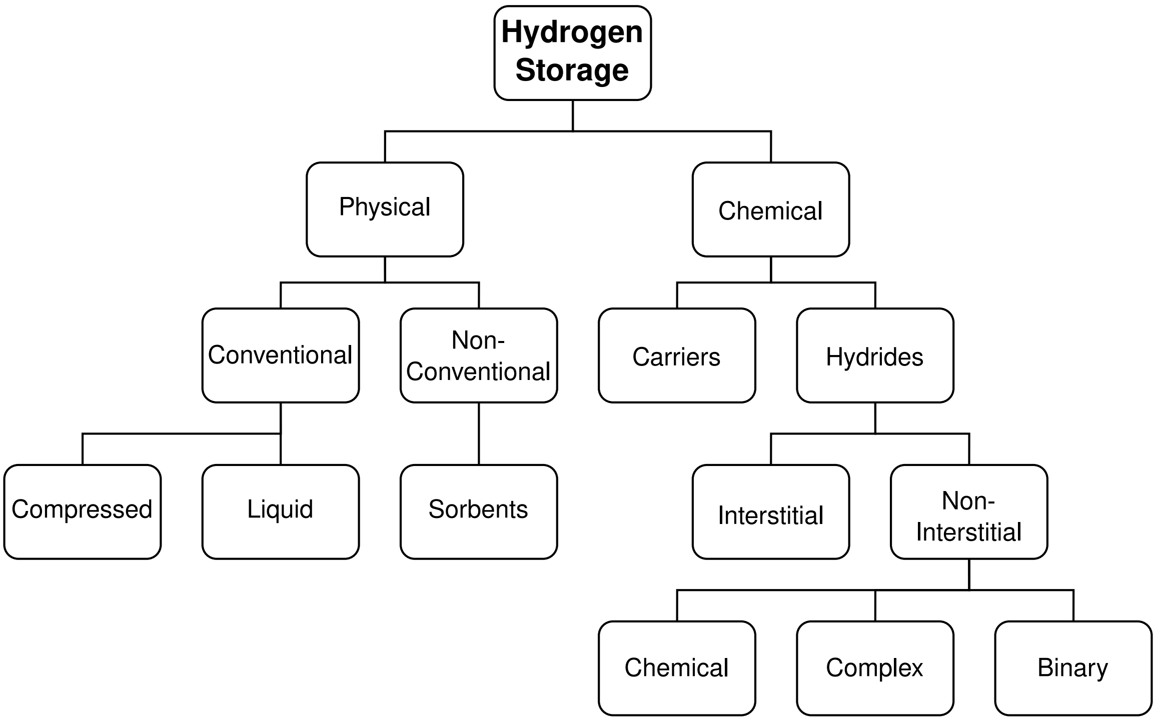


Figure 4: Various mechanisms for hydrogen storage, reproduced from [17]

All alternatives but sorbents are explored, with cryo–compressed added instead.

2.1 Physical–based Storage

2.1.1 Compressed

Since the discovery of hydrogen, mechanical compression has been the primary method of increasing the density of gaseous hydrogen. This makes it the most established physical storage method. The pressure ranges are very wide but most systems use steel gas cylinders under a pressure of up to 700 bar [18]. At this pressure hydrogen reaches a volumetric density of up to 42 kg/m^3 [4].

However, compressing hydrogen presents several challenges and disadvantages. On the technical end, compression is associated with sealing problems in rotating machinery and annexed pipes. This is because hydrogen is a tiny molecule — with a low molar mass — capable of diffusing through extremely small gaps. The leakage rate in steel is estimated to be three times higher than natural gas [5, 14]. Another issue to be addressed is the heat transfer process during compression. During the charging and discharging cycles the cylinder is subject to temperature changes (Joule–Thomson effect), which over several cycles could lead to fatigue of the vessel material and severe consequences [6, 19]. For this reason the gas cylinders require a wealth of sensors in addition to regular inspection or replacement to keep the safety levels high. This makes the solution not viable for domestic applications where the end customer does not possess the level of expertise and cannot afford the extra costs. Compressed storage is fairly efficient with only 10% of the stored energy lost to the compression stage and and additional 5% lost to leakages [6, 7, 20].

Low pressure (30 bar) storage of hydrogen was initially explored but was found to be incompatible with long–term energy storage due to the low energy content per volume required. On the other hand, this method offers the advantage of readily available hydrogen gas without pre– or post–processing and could be used as a buffer to increase the responsiveness of the system.

At large scales, hydrogen can be stored underground, just like natural gas, in salt caverns shown in Figure A.3 [4, 13, 14]. This method uses lower compression (200 bar), but it needs specific ground formations. As these specific requirements are not achievable for domestic storage, the method was not considered for this project rather it is further discussed in section A.2 of the Appendix, where the concept of a hydrogen economy is explored.

Overall, compressed hydrogen storage presents several safety and maintenance challenges, making it a less advantageous option for domestic PV installations.

2.1.2 Liquid

Another method of physically storing hydrogen in a small volume is in the form of cryogenic liquid. Hydrogen liquefies at 20 K, and at this temperature, the volumetric density can reach 71 kg/m^3 [4, 14]. However, liquefying hydrogen is both time and energy consuming, with about 40% of the energy being lost during the liquefaction process [6]. At the moment, liquid hydrogen is mainly reserved for special high–tech applications or where high densities are essential, such as space travel or shipping, consequently it has not yet been widely commercialised [2, 7].

Safety is a significant concern for liquid storage. Cryogenic vessels have an additional protection layer, in the form of a vacuum chamber, to mitigate heat leakage. In case of accidents this layer would lessen the impacts preventing pressure releases or severe explosions [7, 14].

While more compact and lighter cryogenic pressure vessels provide better storage volumes than compressed hydrogen vessels, the persistent boil–off of hydrogen and the excessive energy required for liquefaction restrict the potential use of liquid hydrogen [19]. This is particularly true for long storage requirements. Overall, liquid hydrogen storage is not a practical or efficient solution for domestic PV installations.

2.1.3 Cryo–compressed

Cryo–compressed hydrogen is a supercritical cryogenic gas that offers some promising aspects regarding storage and safety levels. Unlike liquefaction, gaseous hydrogen is compressed at a temperature of about 40 K without undergoing phase transition, this allows to reach the highest physical storage density up to 80 kg/m^3 [7].

However, cryo–compressed storage only offers a slight improvement in density over liquefied hydrogen and requires the same complex storage cylinders. Additionally, it necessitates high energy for compression and cooling, making it less energy–efficient.

While mentioned briefly for completeness, this report will not explore cryo–compressed hydrogen storage any further due to its limited practicality and the challenges it shares with other storage methods.

2.2 Chemical–based Storage

Chemical–based hydrogen storage — sometimes referred to as solid hydrogen — is another option that is achieved by combining hydrogen with other materials through chemical reactions. The underlying idea is that with this method, the problem of storing hydrogen is replaced with the storage of hydrogen–based compounds, which are easier to handle.

2.2.1 Chemical Sorption

Chemical sorption involves the storage of atomic hydrogen, bound ionically, covalently, or metallically within a compound. Examples of materials that use this method include microporous materials, interstitial metal hydrides, and complex hydrides [6, 17]. Metal Hydride (MH) for instance, can store hydrogen at a density far greater than seen in its liquid form without the need for liquefaction and its associated energy, making them an attractive option [2]. This is because it is possible to pack more atoms of hydrogen into a metal hydride lattice, thanks to the adsorption onto the surface of the material, reaching densities as high as $150\,\mathrm{kgH_2/m^3}$ (Figure 7)[19].

A metal hydride is technically formed via a chemical reaction but acts like a physical storage method. The reaction is completely reversible, and the hydrogen can be liberated whenever required by thermolysis [17]. In the containers, the chemical reactions occur under moderate pressure, usually between 3 bar and 30 bar, and with temperatures ranging from ambient up to $300\,^{\circ}\mathrm{C}$, depending on the hydride type [6, 14]. This makes the system safer and more efficient than any other solutions so far, since leakage cannot be spontaneous, and the containing vessel cannot violently explode.

On the other hand, these tanks are very heavy compared to compressed or liquid ones as they are filled with solid metals [14]. These advantages make chemical sorptions, in particular metal hydrides, one of the most feasible solutions to store hydrogen at home.

2.2.2 Hydrogen Carriers

A completely different approach to storing hydrogen is to not stock hydrogen but instead transform the hydrogen into a stable compound that can be in turn used to store and release energy later on. While chemical sorptions rely on bonding the hydrogen to form an hydride and later braking those bonds to recover the hydrogen, it is also possible to combine hydrogen with other molecules to produce synthetic fuels or liquid organic hydrogen carriers [13].

Some examples include methanation or the Fischer–Tropsch process which involves combining hydrogen with carbon to form methane (CH_4) or liquid hydrocarbons [13]. These are common fuels today, therefore would have several applications. The problem with these processes is the sourcing of elemental carbon — most often taken through carbon dioxide sequestration from the atmosphere — which is energy intensive.

A more promising method is the electrochemical synthesis of ammonia (NH_3). Ammonia is denser than liquid hydrogen, it conveniently exists in liquid form and has high volumetric energy density [19]. The nitrogen required for ammonia synthesis can be extracted from the air as nitrogen is its main component. Although ammonia is harmful to the environment, it has been found to enhance the hydrogen storage of metal hydrides when used in smaller quantities [19].

While ammonia and methane can be used in common internal combustion engines to power the current transportation fleet [11], the extraction of carbon dioxide or nitrogen from the air was deemed too complex for domestic application.

2.3 Assessment of Storage Systems

From the complexity of the solutions analysed, it is clear why hydrogen storage has faced some difficulties in making a significant appearance in the consumer market. The most feasible option, in contrast to pressurised or liquid hydrogen, appears to be Metal Hydrides (MHs), which hold the promise of linking hydrogen storage with a future hydrogen economy.

Most of the research on the use of hydrogen as a fuel focuses on the transportation sector, which has demanding requirements for the weigh of the storage systems used to supply hydrogen. This is why Metal Hydrides have never been fully studied or developed outside of laboratory contexts. However, given the stationary application of this project, the weigh and volume issues are not as critical, since in most scenarios, they can be situated on the ground. Therefore, the main advantage of hydrides, namely their compactness, can be used to the full extent.

Furthermore, Metal Hydrides have little energy requirements and a higher degree of safety over compressed or liquid hydrogen due to the much lower pressure, safer temperature and non–combustibility [12].

Table 1 summarises all the evaluated storage methods. Metal Hydride stand off both for their hydrogen storage density and for their energy density, while their efficiency is not clear and will be investigated in section 4.3.

Table 1: Densities and efficiency comparison of the hydrogen storage techniques

Type	**Hydrogen Density** [kg/m^3]	**Energy Density** [kW h/m^3]	**Efficiency**	**Source**
H_2 STP	0.1	3.9	100%	[6, 20]
H_2 Compressed	42	1,638	85%	[2, 4, 7, 14, 18, 20]
H_2 Liquid	71	2,769	60%	[2, 4, 6, 7, 14]
H_2 Cryo–compressed	80	3,120	50%	[7]
Metal Hydride (MH)	150	5,850	?	[2, 6, 7, 14, 19]
Methane (gas)	0.7	9.8	99%	[13, 19]
Ammonia (liquid)	682	2,046	98%	[11, 13, 19]

2.4 Problems to address

Despite the major advantages of Metal Hydride storage, there are some important aspects that require further attention. One of the main challenges is thermal management during the charge and discharge cycles, including heat dissipation during the exothermic hydride formation, heat supply for the endothermic hydrogen release, and the energy efficiency of this process. The thermal cycling of the storage vessel is key to ensure safe and efficient operations.

Ensuring multi–cycle reversibility and stability against oxygen and moisture impurities are also crucial for the long–term viability of MH storage systems [14]. Charging and discharging of the hydride can be performed multiple times as long as the material does not become contaminated with impurities, that degrade the metal preventing further hydrogen absorption.

Moreover, Metal Hydride tanks may require testing for hydrogen embrittlement, which affects high–pressure or low–temperature storage. This phenomenon can impact the material in contact with hydrogen, and it is an important concern when it comes to steels [7]. Abe et al. [14] point out that enhancing the charge–discharge kinetics and controlling the formation of unwanted gases during desorption remain significant challenges for MH technologies.

Overall, while metal hydride storage systems show promise, some challenges are still to be addressed. The following sections cover some of these aspects and set some tests to validate their performance in order to have a real indication of the technology's maturity.

3 System Implementation

The previous section focused on the hydrogen storing properties of different material and selected the most appropriate. However, it is also necessary to consider how the storage integrates into a full system, specifically in domestic applications. Such work is not readily available in the literature and therefore constitutes the novelty of this project.

This section will discuss in greater detail the technology of metal hydrides to understand their workings and challenges. With this in mind the tank can be shaped accordingly and interconnected with the remaining upstream and downstream components.

3.1 Metal Hydrides

3.1.1 The Chemistry

To further expand on metal hydrides and their chemical workings, it is important to understand the two main methods by which they store hydrogen. As seen from Figure 4 these two methods are:

1. Forming bonds within the interstitial spaces of a metal
2. Forming covalent or ionic bonding with other elements

The first method involves the formation of metallic bonds within the interstitial spaces of a lattice, resulting in the expansion of the latter. In this process, the addition of enough energy diffuses the hydrogen atoms into the bulk forming a solid solution (α *phase*). As more energy is added to the system, the hydrogen content increases, and a hydride phase (β *phase*) forms, allowing the metal to absorb hydrogen in larger amounts and grows until the metal becomes saturated with hydrogen [21]. This type of bonding is relatively weak favouring the hydrogen release under practical conditions. Additionally, the released products can be assumed to be pure hydrogen, with little concern for unwanted by–products and the systems can demonstrate extreme cyclability [17].

The second method involves hydrogen that is bonded ionically or covalently with the other constituent elements. As a result of this stronger bonding, liberating hydrogen from these materials generally requires conditions that are more severe, with decomposition temperatures generally in excess of 200 °C for the bulk solid. Despite this disadvantage, since non–interstitial hydrides comprise lighter elements, the gravimetric storage capacity is higher, approaching 20 wt.% for some materials [17].

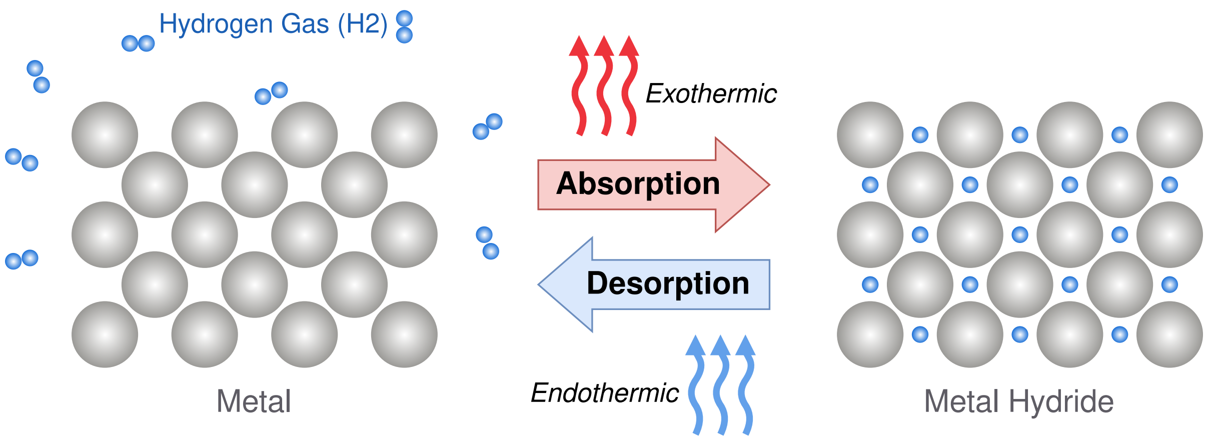


Figure 5: Hydrogen absorption or desorption with metals, inspired by [14, 17]

In both methods, the interaction of hydrogen with the metal or other elements results in a typical reaction written as:

$$\mathrm{Me} + \frac{\mathrm{x}}{2}\mathrm{H_2} \rightleftharpoons \mathrm{MeH_x} + \Delta\,\mathrm{H_R} \qquad \Delta\mathrm{H_R} > 0 \tag{1}$$

Figure 5 gives a visual representation of this reaction clearly showing the hydrogen molecules dissociating into atoms and diffusing into the bulk of the metal or compound.

3.1.2 Heat of Reaction

In the hydride paradigm, the storage and host system must be closely coupled at the heat transfer level, as the absorption and desorption of hydrogen in MHs are reversible processes that involve heat exchange as shown again in Figure 5. However, it's important to note that the primary challenge with MH is not the absorption but the desorption process. This is because hydrogen tends to strongly bond with the lattice, making it difficult to break free and be released. The kinetics of these processes and the amount of hydrogen stored by mass can vary depending on the type of metal hydride and the operating conditions, while some MHs may require catalysts or other additives to improve their performance [5, 14].

To store the hydrogen, typical metals require pressures as low as 1.7 bar and up to 30 bar which is only a few times greater than the atmosphere [12]. The PEM electrolyser used to produce hydrogen for the ES system can generate hydrogen directly at a pressure of 30 bar, which can simplify the system design [22].

Charging and discharging of the hydride tank can be performed multiple times, as long as the hydride material does not become contaminated [23]. The study of the thermal properties is essential to ensure the safe and efficient operation of the system. The shape of the metal material is also an important factor, as it can affect the hydrogen absorption and heat dissipation properties. Materials in powder form are generally better for hydrogen absorption but worse for heat dissipation [24]. To solve this issue the powder is to be compacted to form solid discs (Figure 6a) which could enhance the thermal conductivity up to 30 times while retaining enough porosity (Figure 6b) for good H_2 absorption [25].

(a) Compacted disc

(b) Scanning Electron Microscope (SEM) image

Figure 6: Compacted disc of MgH_2 powder (a) and the SEM image showing the result of pressing (b), taken from [25].

3.1.3 Material Selection

Metal hydrides can be also categorised based on on the constituent components, namely:

1. Binary hydrides (MH_x)
2. Intermetallic hydrides (AB_xH_y)
3. Complex hydrides (MEH_x)
4. Chemical hydrides

where M is a main group[4] or transition metal[5], A is a strong hydride–forming element, B is a weak hydride–forming element and E is boron, nitrogen or aluminium [6, 17].

Binary ionic hydrides are the simplest type, comprising of a single metal ionically bound to hydrogen. Magnesium hydride (MgH_2) (Figure 6) is the most extensively studied binary hydride due to its low cost and high storage capacity, both gravimetric and volumetric (7.6 wt.% and 110 kgH_2/m^3) [10, 19]. Magnesium is also readily available, contained at 0.13 wt.% in sea water and 2.7 wt.% in the Earth's crust [17]. However, MgH_2 is considered a high–temperature MH, due to the very strong bond created a temperature greater than 300 °C is required for desorption [26].

Aluminium hydride (AlH_3) or alane is another common binary hydride with a theoretical capacity of 10.1 wt.% and a volumetric capacity of 148 kgH_2/m^3. Additionally, bulk decomposition also occurs at lower temperatures compared to magnesium hydride (150 °C to 200 °C). Despite these qualities AlH_3 is by the complexity and economics associated with its synthesis and its instability in ambient conditions due to high reactivity towards water and oxygen [17].

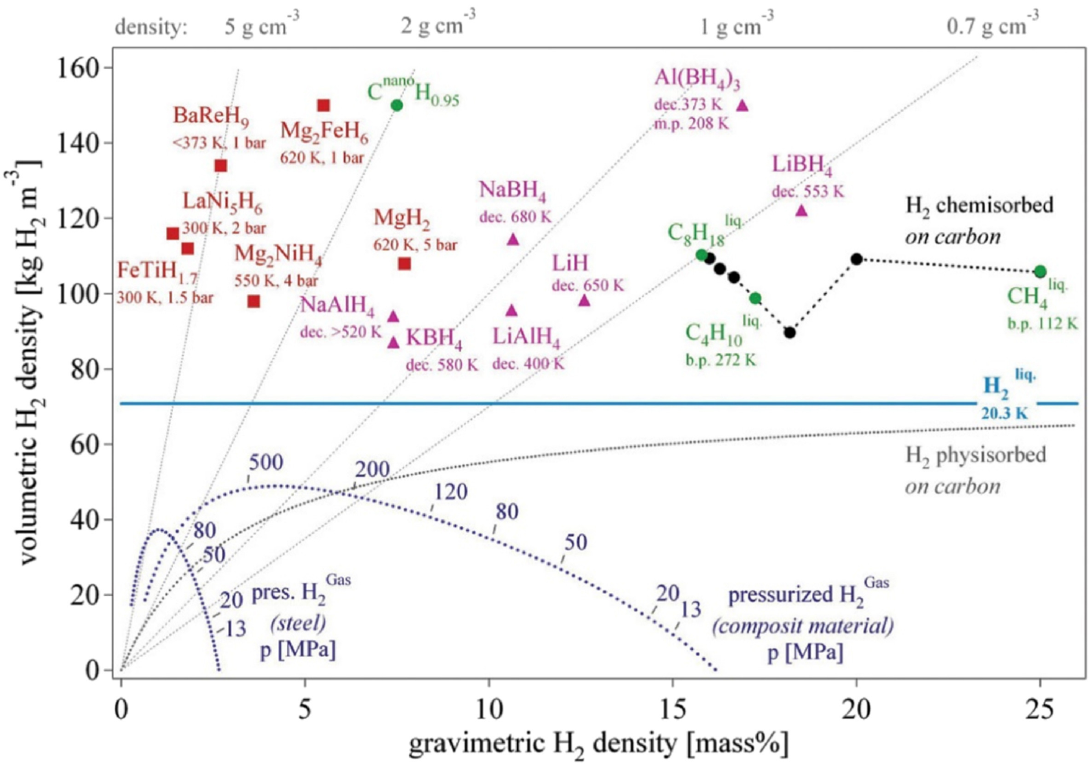


Figure 7: Volumetric and gravimetric hydrogen density of some selected hydrides compared with compressed, liquid and hydrocarbons, taken from [21].

[4] elements in the s-block (groups 1 and 2) and p-block (groups 13 to 18) in the periodic table
[5] elements in the d-block (groups 3 to 13) in the periodic table

Complex hydrides, such as alanates and borohydrides, involve complex ions and have been researched extensively [14]. Alanates are complex hydrides involving the $[AlH_4]^-$ ion, with sodium alanate ($Na[AlH_4]$) and lithium alanate ($Li[AlH_4]$) being the most studied. Alanates can also make use of calcium, potassium, magnesium and strontium but, despite all showing high storage capacity, they all suffer from unfavourable decomposition conditions. Borohydrides contain the $[BH_4]^-$ ion, and they are not considered due to the complex extraction process and low availability of boron on Earth's crust [6].

According to Züttel et al. [21], all the reversible hydrides operating around room temperature and atmospheric pressure comprise of transition metals and form the intermetallic hydrides. The most reactive ones are the electropositive elements such as lanthanides, actinides, and members of the titanium and vanadium groups. The best examples in this group are ferrotitanium (FeTi) and lanthanum penta-nickel ($LaNi_5$). Intermetallic compounds are also called room–temperature hydrides given the operating temperatures range of 20 °C to 50 °C [26]. The downside is again the low availability or easy of mining of these metals which reduces their potential in the domestic application.

Based on the literature, magnesium hydrides seem to be the most promising solution due to their stability, ease of handling, and common availability on Earth. Their main downside is the high temperatures required for desorption. Most metal hydrides use catalysts or composite materials to improve the capacity, kinetics and resilience to impurities. Godula-Jopek et al. [19] in particular pointed out a successful experiment where magnesium hydride is mixed with ammonia resulting in full H_2 desorption between 75 °C and 150 °C, in the following reaction:

$$2\,NH_3 + 3\,MgH_2 \longrightarrow Mg_3N_2 + 6\,H_2 \tag{2}$$

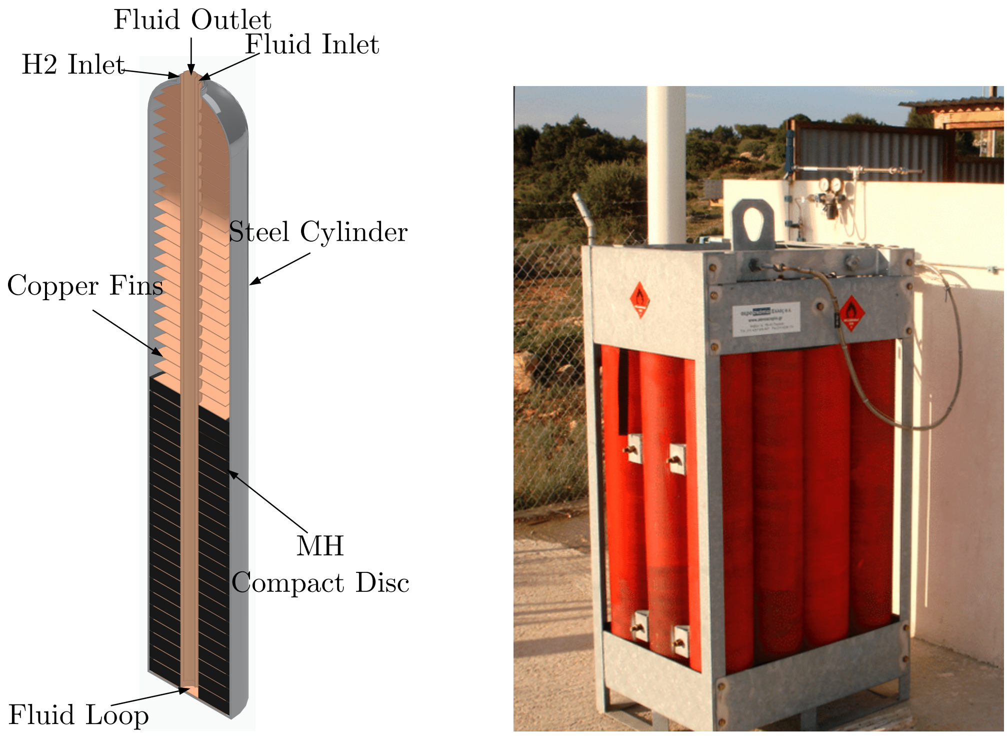
3.2 Tank Geometry

The metal hydride powder could be compacted into any shape without affecting the chemical reaction with the hydrogen, potentially allowing for the most convenient and space efficient container. Despite this during the absorption phase the hydrogen is still to be supplied at pressures up to 30 bar. To accommodate this pressure the tank should follow the geometry of a standard gas cylinder. Said cylinder is not subject to extreme pressures therefore can have a lighter design avoiding the expensive composite materials and thick walled steel. A common gas cylinder of size **K** (1460 mm×230 mm) has an internal volume of 50 dm^3 and can hold the pressure required by metal hydrides including a safety margin.

As previously mentioned MHs require a heat transfer to perform the ab– and desorption reactions. A fluid running through a heat exchanger is a common method to provide any heat transfer. One simple method consists in having the storage material enclosed by the heat exchanger serpentine is a shell–and–tube arrangement [27]. Other configurations include double walled cylinders, coiled tubes, fins, wires and others [27]. Lototskyy et al. [24] suggest a design with solid aluminium or copper fins inside the tank to have better contact with the MH powder.

The two solutions could be combined to have a full reach of the MH powder, the proposed design is shown in Figure 8a. This design combines the solid copper fins and the heat pipes running at the core of the cylinder to transfer the heat from the inside. If more thermal contact is deemed necessary during the testing phase the double–walled cylinder with the serpentine can be implemented. This arrangement would increase the space taken by the cylinders but at the same time would also provide an additional safety barrier against leaks. In the unlikely event of the inner cylinder fracturing the hydrogen would be trapped in the interstice before escaping.

A further method described by Parra et al. [10] consists of a MH storage where the absorbed or released heat is managed using phase change material (PCM). This solution was discarded due to the low heat performance of such material and the large additional mass and volume.



(a) Cross section

(b) Cylinder quad [28]

Figure 8: The cross section of a single tank showing the heat transfer techniques (a) and its assembly in a quad formation (b).

A later section estimates the total storage size, but it is clear that one single cylinder of the selected type cannot provide sufficient storage. Increasing the volume of a cylinder faces the limit of the thermal conductivity, therefore, it is better to have multiple tanks bundled. A cylinder quad is a group of gas cylinders arranged in a square or rectangular formation and framed by an outer cage (Figure 8b). This allows the structure to be preassembled at the manufacturer and easily transported to the installation site. Other advantages include modularity and increased safety.

The cylinders in the quad would be connected in parallel because the tanks are easier to charge and discharge individually to better manage the thermal requirements of each tank. Every single MH tank could be filled at different levels and therefore require different temperatures. Additionally, supplying heat to one tank at a time for desorption is more thermally efficient.

The environment of the gas cylinders should follow local regulations for their storage. For example, the British Compressed Gases Association [29] has recommendations including separation distances, ventilation, design and construction of the floor, access, lighting, signs, and many others.

3.3 Thermal Coupling

The thermal coupling concept presents an innovative solution to improve the energy efficiency of MH storage systems. Depending on the specific metal hydride, the temperature involved in the sorption processes varies, but all require extra energy to work. While the dissipation of heat during the absorption process can be attained with common air–cooled heat sinks, heat must be supplied to desorb the hydrogen (thermolysis). Instead of generating this heat by consuming additional energy, the waste heat from any hydrogen consumer can be used to increase system efficiency.

Whether the consumer is a Fuel Cell (FC), a Gas absorption Heat Pump (GHP) or a simple boiler, some energy is always lost to heat. By creating a synergy between the waste heat and the MH storage system, the waste heat can be recycled to desorb hydrogen, providing it at a rate suited to the application (Figure 10). Since the rate of hydrogen desorption from the hydride is tied to the amount of heat it receives, and the heat produced by the consumer is proportional to the hydrogen used, there is potential for a self–regulating process. This innovative thermal coupling approach not only saves energy but also enhances the overall efficiency and sustainability of the hydrogen storage system.

3.4 Hybrid Energy Storage System

The Hybrid Energy Storage System (HESS) is an innovative architecture that combines different energy storage technologies to optimise performance and reduce costs. As previously mentioned, hydrogen has a very low power capacity cost (Figure 3), making it expensive to cover intraday fluctuations.

In a HESS, one storage (ES1) is dedicated to covering high power demand, transients, and fast load fluctuations, characterised by a fast response time and high efficiency. The other storage (ES2) is the high energy storage with a low self–discharge rate and lower energy–specific installation costs [30]. Figure 9 presents the structure of a generic HESS where the energy management unit switches between the two ESs to charge or discharge them.

Bocklisch T. [30] investigated various combinations of ES systems, including heat, battery, flywheel, hydrogen, supercapacitor, and others. Among all the combinations tested, the battery–hydrogen one showed the most promising results.

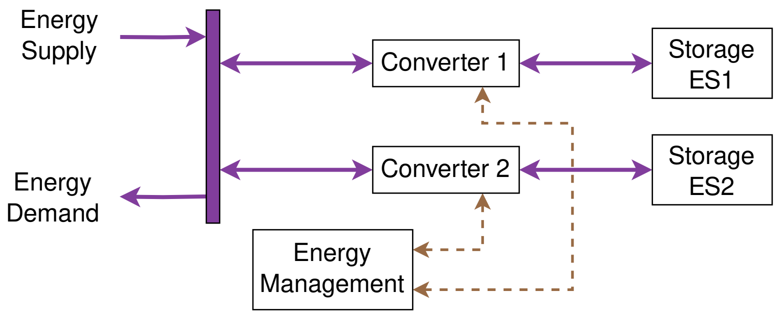


Figure 9: Basic structure of a HESS, reproduced from [30].

By integrating the thermal coupling principles explained earlier, a three–way HESS with electricity, hydrogen, and heat can be created, as depicted in Figure 10.

The main source of the system is the PV array, while the sink is the utility that receives energy from all three systems for the various domestic energy needs. The electric arrangement is already widely used and familiar, while the thermal one is fairly familiar as well, with the additional idea of a Domestic Hot Water (DHW) tank to store the excess thermal energy.

Although the focus of this report is on hydrogen storage, it is essential to briefly mention hydrogen consumption to understand the synergy of the hydrogen ecosystem. Hydrogen can be used domestically to fuel a gas hob, but this alone cannot consume all the energy stored by hydrogen. Therefore, hydrogen can be either converted back to electricity or transformed into heat.

Hydrogen re–electrification refers to the generation of electricity from hydrogen. Using a Fuel Cell (FC) is the preferred way to maximise the benefits of this conversion, hydrogen and oxygen from the air are supplied to the fuel cell to make the following reaction:

$$2\,H_2 + O_2 \longrightarrow 2\,H_2O + \text{electricity} + \text{heat} \tag{3}$$

The most efficient FCs, such as the PEMFCs, can convert only 38% of the hydrogen energy into electricity. However, if the heat production (32% of the total) is taken into account, the total FC efficiency increases to 70% [10].

Hydrogen could also be combusted to generate heat. Internal combustion engines (ICEs) can be modified to run on H_2 gas, but this is an extremely inefficient process. Moreover, when combusting hydrogen, nitrogen oxides (NO_x) are emitted even though carbon dioxide (CO_2) is not released [2]. One promising application is the use of Gas absorption Heat Pumps (GHPs). GHPs only burn a small pilot flame, and therefore little hydrogen energy is used to transfer a huge quantity of thermal energy thanks to the refrigeration cycle [31]. Famiglietti et al. [31] do an in depth study comparing GHPs, electric heat pumps (EHPs) and condensing boilers over a ten year scenario including a gradual transition from natural gas to a hydrogen economy. According to their findings, the GHP powered by hydrogen offers the lowest environmental impact profile under all aspects including NO_x emissions.

In both scenarios, water is the main byproduct of the hydrogen reaction, and this water can be reused by the electrolyser in a closed loop to reduce water consumption. Although FCs have one disadvantage over GHPs, which is the requirement of high purity hydrogen, MHs produce high purity hydrogen due to the nature of the chemical reaction (Reaction 1), making this issue less accentuated [2, 31].

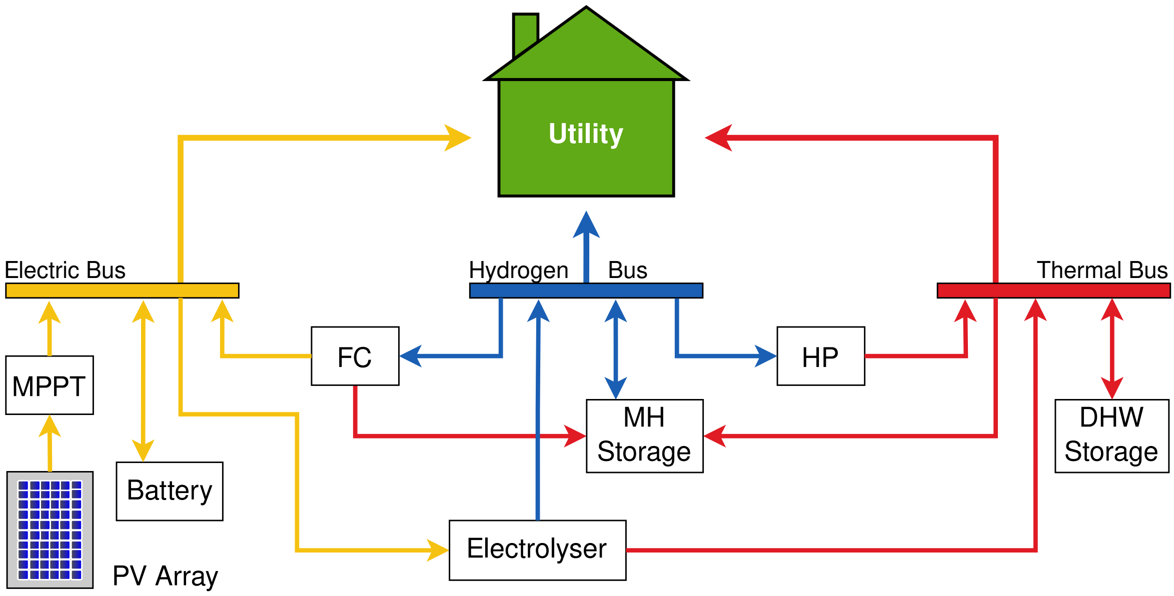


Figure 10: System architecture of an off–grid HESS integrating electricity, hydrogen and heat.

The arrangement of the HESS discussed so far has been focused on an off–grid house, which does not receive energy from external sources and cannot distribute excess energy it produces. Beyond the ancillary service the electrolyser can provide to the electric grid, hydrogen could be partially injected into the gas grid. This practice is still being studied and would require a grid–wide system involving multiple players [32]. While injecting hydrogen into the gas network is an exciting prospect, it is beyond the scope of this project and is therefore only briefly mentioned in section A.2 in the Appendix.

4 System Validation

The previous section took the Metal Hydride technology and implemented a full system suitable for a domestic installation. Using the relevant engineering knowledge and principles the architecture of the plant got established and the relevant design work conducted for the critical subsystems.

However, it is also necessary to consider the performance of these designs both independently and when integrated into the wider structure. This as well as other challenges are ultimately validated with testing, while for a foundation study the analysis of similar research can provide the basis for future testing.

Unfortunately the only available data for MH based storage is from research still in progress as the only practical applications are either classified military or very small niche uses. Two notable examples are the atomic clocks onboard the European GALILEO satellites [19] and, on a larger scale, submarines (Class U212A and 214 of the German and Italian Navy) powered by Fuel Cells [26]. Therefore, testing should be conducted for this system to have a better understanding of the domestic ES application.

This section will firstly explain the planned testing and then move on to calculating the volume efficiency and cost of a home installation.

4.1 Testing

The original project objectives called for a first prototype to be developed in order to test some specific characteristics which are unknown. These test are only focused on the MH tank and leave the full HESS to be tested in a subsequent phase.

Other studies [10, 33] used large MH tanks capable of retaining several kilograms of H_2. The short nature of this project and its limited budget called for a much smaller tank. The MH tank chosen for the testing phase was the Solid-H BL-18 model supplied through Hydrogen Components Inc. seen in Figure 11a. This tank has a capacity of 20 NL of hydrogen (20 g H_2 or 78 W h) and a recharge time of about 4 hours.

(a) Single canister (b) Stacked canisters

Figure 11: Solid-H BL-18 MH tank alone (a) and stacked in series for increased volume (b) [34].

4.1.1 Heat Dissipation

Modelling the heat management is fundamental, this considers the MH thermal conductivity properties and the tank geometry. The first planned test uses a series of thermal sensors placed around various locations of the canister. As the hydrogen is fed through one end it would diffuse inside the container and react with the metal. The test would determine the rate and location of heat generation which would inform the design of the heat exchanger. Depending on the quantity and location of heat the thermal fluid would have to circulate at a certain flow rate and location.

After these measurements a smaller version of the thermal jacket is reproduced to test the heat transfer during charging and discharging of the tank. With several measurements a graph could be plotted to show the relationship between the charge/discharge pressure and the removed/supplied heat. This would influence the design of the surrounding apparati, in particular the electrolyser and the GHP, which work with predefined pressures.

4.1.2 Flow Rates

Heat pumps for example can operate with variable inputs to match the demand [31]. By understanding the relationship between the heat supplied to the storage cylinder and its output flow rate a closed loop controller can be designed. The same principle but in the reversed direction is studied. The PEM electrolyser designed by Vibert [22], in the context of this same research effort, produces hydrogen at variable flow rates depending on the input power reaching a peak of 136 g/h. The BL-18 canister on the other hand has a specified loading time of 4 h for 20 NL which gives a flow rate of 0.5 g/h. Clearly the final MH tank would have a larger capacity and the single canisters could be charged sequentially or concurrently to improve the heat management. But at the same time the variability of the flow rate could cause overheating therefore requiring a mass flow regulator to integrate the tank with the PEM electrolyser. If this issue is encountered during the final system testing a buffer could be introduced to store the excess electrolyser hydrogen while the tank is filled gradually. The buffer would simply contain the hydrogen at the electrolyser pressure of 30 bar in a standard gas cylinder [5].

The results from both the heat and flow rate tests will characterise the main gas panel. The gas panel is the computer that manages the H–ES, it has two main functions: delivering hydrogen at conditions suitable for the application during the discharge and supply hydrogen at suitable conditions to the tank during the charge. The main components of the gas panel are consequently the cooler/heater, flow regulator, filter, buffer and sensors including leak detection [10].

4.1.3 Life Cycle

Given the recent development of MH technology most of the research focuses on improving the volumetric and gravimetric capacities, hydrogen absorption/desorption kinetics, and reaction thermodynamics of potential materials [5]. At the same time because of their little practical applications the long–term cycling effects and the contamination from impurities are still to be investigated. These tests are harder to achieve on a research level as they require multiple charge discharge cycles therefore they have been put a side for the time being.

Unfortunately, this project could not execute the prototyping and testing due to the expenses and the extra challenges involved in testing with H_2 gas. The BL-18 MH tank could be purchased from [34] for US$ 560 (£448), which was already above the allocated budget. This ignored the auxiliary sensors which would have required an additional expense. Furthermore, given the stringent regulations pertaining hydrogen gas, no facilities could host the experiments. In the end, considering the already wide scope of the project it was deemed reasonable that experiments could be conducted at a following stage.

4.2 Tank size

In section 3.2 the cylinder selected for this application was of the common size **K**. If magnesium hydride is selected as the final MH the hydrogen density could reach up to 110 kgH_2/m^3. A single cylinder would therefore contain:

$$110\ kgH_2/m^3 * 0.05\ m^3 = 5.5\ kg \tag{4}$$

Given the energy density of hydrogen is 39 kW h/kg the energy stored by 1 cylinder is:

$$39\ kWh/kg * 5.5\ kg = 214.5\ kWh \tag{5}$$

However, the size of the storage required for a specific installation depends on various factors, including geographical location, weather patterns, consumption trends, and system performance.

HOMER is a powerful software for designing and planning HESSs taking into consideration all these variables [35]. The computational model creates several simulations in order to determine optimal size of the system components. However, for the purpose of this project, an estimate can be performed instead of designing a tailored system.

Table A.1 (in section A.3 of the Appendix) gives the number of sunlight hours for a selection of European capitals spanning different latitudes. The H–ES system is expected to only be storing excess energy produced during the April–September semester, for this period the number of hours range from 1,000 to 1,500. The excess power generated is much harder to estimate as it is highly dependent on the number of PV panels and the domestic consumption. A wider range was selected for this value going from 500 W to 2000 W average power.

Table 2 combines the excess power and sunshine ranges to estimate the number of cylinders required by a H–ES using MHs.

Table 2: Estimate storage size based on different scenarios

Excess power [W]	**Summer Sunshine** [h]	**Excess Energy** [kW h]	**H_2 mass** [kg]	**MH volume** [dm^3]	**# cylinders**
2000	1500	3,000	76.9	699	14
2000	1000	2,000	51.3	466	10
1000	1500	1,500	38.5	350	7
1000	1000	1,000	25.6	233	5
500	1500	750	19.2	175	4
500	1000	500	12.8	116	3

H_2 energy density = 39 kW h/kg, MH capacity = 110 kgH_2/m^3, cylinder size **K** (50 dm^3)

The annual gas energy consumption of an average household in Great Britain is approximately 11 500 kW h, which is primarily used for winter heating [36]. This figure is high due to the inefficiency of current housing infrastructure. Bocci et al. [37] proved that implementing energy efficiency measures would reduce the annual thermal energy consumption by 70%, from 14 600 kW h to 4500 kW h in their scenario. Nevertheless, the hydrogen storage capacity might still appear insufficient to meet this demand. However, this consumption rate refers to conventional gas boilers. In contrast, the proposed HESS employs a GHP with a Coefficient Of Performance (COP) of up to 5, indicating that the same thermal output can be achieved with only one–fifth of the energy that a traditional boiler would require.

4.3 Efficiency

Efficiency figures for hydrogen storage technologies vary significantly (Table 1) but studies on MHs do not specify one in particular.

Unlike other storage methods, the primary energy losses in MH systems occur during the thermal management of the ab- and desorption processes, as the chemical reactions (Reaction 1) themselves do not inherently produce losses, except if the metal degrades. Optimising thermal management is thus vital not only for the speed of the reaction, as outlined in section 4.1, but also for enhancing efficiency.

The MH storage is better operated within a 10–90% capacity range to minimise excessive heat management [33]. These can lead to increased complexity and energy losses, particularly during the desorption phase where high levels of heat are supplied, resulting in a decreased efficiency.

Miland and Ulleberg [33] do a comprehensive study on a system with an electrolyser, MH storage and a fuel cell. They account various losses including electrical, thermal and auxiliary systems but do not include the efficiency of the MH tank itself. Their setup uses the excess heat from the FC to warm up the storage tank avoiding the need for additional energy input, potentially allowing efficiencies close to 100%.

Parra et al. [10] have developed a community energy storage system that integrates a lithium–ion battery, hydrogen storage and demand side management, achieving round–trip efficiencies up to 52%. Their system uses: a PEM electrolyser, a MH storage tank and a PEMFC unit. The MH tank in their study, analysed in greater detail by Jehan and Fruchart [25], is claimed to have an efficiency exceeding 90%.

However, the significant losses within such H–ES systems are attributed to the electrolyser rather than the H_2 tank, as it is upstream in the ES process. This means that the subsequent components can only manage its energy output, highlighting the importance of the electrolyser efficiency.

Additionally, while H–ES systems typically have lower efficiencies, their value improves when incorporated into HESSs. A system with dual or triple storage methods (Figure 10), adapts better to varying operational conditions, thereby improving overall efficiency [10, 38].

Tools like the HOMER computational model further improves HESS performance by tailoring it for specific application [35]. Novel methods, such as Machine Learning (ML), have the potential to revolutionise efficiency improvements using adaptive real–time optimisations accounting for variables like weather forecast. ML would also enhance maintenance by smart management, like evenly cycling MH cylinders to extend system life and performance.

4.4 Life Cycle Assessment

The Life Cycle Assessment (LCA) of MH hydrogen storage systems reveals several advantages, particularly in terms of longevity and environmental impact. MH systems are known for their robustness to the point of being called 'eternal storage' by some [37]. They have the capability to withstand thousands of charge–discharge cycles without significant degradation. This durability translates into potentially centuries of service life, if only cycled once a year in the seasonal storage scenario. This is considerably superior compared to traditional battery systems with the same energy requirements.
Additionally, in the HESS the battery would not enter the floating state as the excess energy is convoyed towards the hydrogen storage. The lack of floating reduces the amount of energy cycled in the battery preventing early degradation and ultimately improving its life span as well[8].

Some metals involved in MH systems, such as lithium, boron, lanthanum and nickel, are challenging to mine and refine resulting in environmental impacts and added costs. This is the problem facing current battery technologies and what hydrogen as an ES is trying to solve as well. This projects chose a system using magnesium hydride, which despite its high thermal requirements, it is fairly stable, abundant and easy to mine, promoting sustainability and cost–effectiveness through prolonged operational life. Furthermore, the recyclability of magnesium metal also complements the sustainable nature of the system, allowing for the recovery and reuse of the metal at the end of the system's life.

The assessment also points out that the primary challenge lies in optimising the stability of the metals during their operational phase, particularly managing the contamination of impurities in the hydrogen supply. Addressing this challenge through various strategies, including the use of catalysts, could further enhance the life cycle benefits, making MHs the most attractive option for sustainable ES in residential settings.

4.5 System Costs

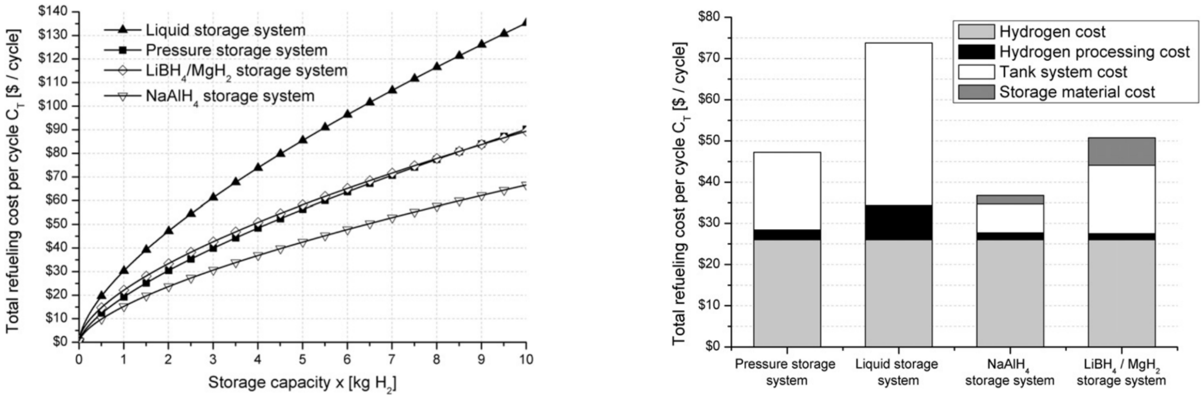
As anticipated in section 1.2, hydrogen storage has low energy–capacity costs. The installation cost in €/kW of hydrogen systems is currently ten times higher than that of lithium–ion battery systems — the installation cost in €/kWh of hydrogen systems is one tenth of lithium-ion battery systems [39]. Furthermore, the service life of hydrogen storage tanks is longer than that of lithium–ion batteries, which would result in significant long–term savings despite the higher initial capital investment.

Jepsen et al. [40] conducted a comparison study of the refuelling cost between conventional methods, compression/liquefaction, and two MHs, a medium temperature (sodium alanate — $Na[AlH_4]$) and a high temperature (lithium boron — $LiBH_4$). The study focused on hydrogen storage for mobile applications, specifically a 4 kg H_2 reservoir for a car subject to 1000s of cycles. The main cost drivers for MH systems are the heat exchanger and the storage material. The vessels can be produced at a much lower cost than pressure tank vessels due to the lower operating pressure and the possibility of using cheaper materials.

Currently, the only available data sources for H–ES system costs are vague estimations from research projects, as there are no commercial systems available [40]. For an MH tank with a 100 g capacity, the cost estimates ranges between €3400 (£2583) and €9000 (£7749) per kilogram of H_2 stored, which drops down to €2000 (£1722) per kilogram for storage capacities up to 50 kg [27, 40]. These costs are extremely high due to the low level of automation during manufacturing. However, it can be assumed that once H–ES systems become more widespread, the tanks would be manufactured in terms of serial production, significantly lowering the cost. Additionally, around 80% of the cost of research MH systems is attributed to the heating [40].

Then again, as the system designed in this project reuses waste heat from the end consumer (section 3.3), this fraction can be neglected.

Figure 12a shows the refuelling cost per cycle, a linear trend between the refuelling price and the capacity of the storage is observed. When analysing the price breakdown in Figure 12b, it can be noticed the significance of the actual hydrogen cost, justifying the linear increase. For the proposed H–ES system in this report, the H_2 gas does not have a cost, meaning that only the tank system and storage material can be accounted for. The end price for the storage material is strongly determined by the content of less abundant elements such as Li or B [17], reinforcing the choice of MgH_2 and binary hydrides, in general.



(a) Cost by capacity (b) Cost distribution

Figure 12: Total refuelling cost per cycle of different storage systems by capacity (a) and their distribution (b), taken from [40].

Despite the high initial capital investment for MH tanks, their high cyclability results in a significant decrease in cost per charging cycle, as shown in Figure 12. It is important to note that, despite all, the economic case for MH systems in comparison to conventional compressed or liquid H_2 storage is competitive (Figure 12).

The wider economic analysis goes beyond the capital investment and includes the long–term savings and the gained energy independence. Houses implementing the HESS, together with energy efficiency measures, would no longer need to import energy, quite the opposite, they could potentially export green excess energy for a profit (see sections A.1 and A.2). A final cost estimate for a single home would mainly depend on the tank size discussed in section 4.2 and potential government subsidies, which are commonly used to boost the energy transition.

5 Conclusions and Future Outlook

5.1 Conclusions

In conclusion, hydrogen has emerged as a feasible, clean, and sustainable ES solution that can bridge the gap between renewable electricity transition and energy demand not covered by electricity. However, the persistent obstacle to the integration of hydrogen into the world economy has been its storage. Among the various options analysed, solid–state storage systems based on Metal Hydride (MH) have been recognised as the most feasible solution for long-term hydrogen storage. Particularly in the context of domestic ES for PV installations, due to their highest storage capacity and safest hydrogen storage mode.

Research on hydrogen storage, specifically metal hydrides, is an ongoing progress, with the most significant focus on enhancing kinetics, investigating new materials to improve capacity, and achieving manageable temperature ranges. Despite these challenges, the benefits of storing hydrogen in MHs are enormous, and there is sufficient proof from the literature and research findings to support their feasibility.

This project addressed the heat involved in the reaction of a high–temperature MH, which is the worst–case scenario. A design was proposed for the shape of the tank and single canister to improve heat transfer from and to the metal powder. The planned tests would have validated this design and provided better insights into the dynamics of heat generation within the canister. The novel idea of coupling the storage tank with the hydrogen consumer to provide the heat necessary for desorption was presented, which not only improved the storage round trip efficiency but also lowered the cost of the system, as most of the cost comes from heating.

Building on the thermal coupling idea, a full Hybrid Energy Storage System (HESS) was developed to power all the energy needs of an independent house. The system would require a relatively small energy input, which could be efficiently converted into other energy requirements. Having more energy busses allows storage according to demand and generation at one time, with the battery covering short–term, the Domestic Hot Water (DHW) tank covering medium–term, and the hydrogen tank covering long–term storage.

For validating the H–ES system using magnesium hydride, the design of the storage tank and architecture was completed, but prototyping and testing were left unfinished due to facility and budget constraints. The size of the tank needed, the efficiency, and the cost of the system were calculated. Based on estimates for excess energy produced and typical energy demand, the MH tank is expected to require between 3 to 14 cylinders of common size. Out of the current research systems, very few analyse the efficiency of the hydrogen loop, and none specify a value for the MH tank alone. It became clear that most of the energy used was for the endothermic reaction, which, with the thermal coupling, would be drastically reduced. Costing was the hardest value to estimate, as the systems developed so far are for research only, and costing is either missing or inflated due to a lack of automation in manufacturing.

In summary, this project demonstrated the feasibility of using MHs for long–term hydrogen storage in domestic ES for PV installations. The proposed design for the MH tank and single canister, coupled with the novel idea of thermal coupling, has the potential to improve the efficiency and lower the cost of the system. Future research should focus on validating the design and address the challenges, including enhancing kinetics, investigating new materials, and achieving manageable temperature ranges. The development of a full HESS for an independent house highlights the potential of hydrogen as a versatile and sustainable energy carrier that can meet various energy needs.

5.2 Future Outlook

Despite the metal hydride hydrogen storage seems feasible on a technical level there are certain aspects that could potentially impede its future implementation. Two of the main challenges are public acceptance and safety regulations of hydrogen–based technologies.

While hydrogen, like many fuels, is flammable, it also faces additional public concern about hydrogen–related hazards due to major accidents involving hydrogen, such as the Hindenburg fire in 1937 [19] and the hydrogen explosion in the Fukushima nuclear plant in 2011 [7]. Another point of view is the study of gas leaks detection. Hydrogen gas is biologically inactive and essentially non toxic but, it is asphyxiating and can cause severe health impacts up to death. When liquid, it can additionally cause severe burns and react with any material containing carbon to form flammable hydrocarbons [19]. Since hydrogen is odourless and colourless, people would not realise if there is a leak. Specifically, in enclosed areas, due to the gas floating on air, it concentrates creating a dangerous environment.

Cylinders containing hydrogen are classed as hazardous substances and consequently cylinder stores are subject to legal requirements in most legislation. Currently H_2 is considered an industrial gas making the regulations and additional recommendations stringent. These include requirements that cannot be met by private individuals in a domestic environment. In order to make hydrogen storage a viable alternative to batteries, specific exemptions for hydrogen cylinders should be made, similar to medical oxygen and LPG for domiciliary use [29]. In the context of MHs, where the storage vessel is not under high–pressure or low–temperature, and in the event of a fracture only a small amount of hydrogen leaks as most of it is bonded to the metal, making dangerous accidents highly unlikely.

Therefore, future work should focus on addressing public concerns and safety regulations to increase the acceptance and viability of Metal Hydride Hydrogen Energy Storage. This could include developing detection systems for hydrogen leaks, educating the public on the safe use and handling of hydrogen, and advocating for changes in regulations to allow for the domestic use of these systems. With continued research and development, Metal Hydride Hydrogen Energy Storage has the potential to become a sustainable and viable Energy Storage solution for the future.

6 Project Review

The project successfully accomplished its revised objectives detailed in Section 1.4, and are summarised below.

1. Select suitable storage among existing technologies
   After researching several storage methods among the available technologies one stood out above others: Metal Hydrides. Although this method has seen little use so far, it was found to meet most of the requirements for the domestic energy storage. Namely the high degree of safety and the significant hydrogen storage density. Among the available metal compounds, magnesium hydride had several advantages over other solutions. It is important to note that this project did not cover in depth the chemistry of magnesium hydrides which must be better assessed with a specific research.

2. Lay the foundations of the system
   Once the suitable storage method was chosen the second objective was tackled. A complete system revolving around this technology was designed. This went beyond the simple working of the metal hydride storage tank but developed an entire paradigm for an energy independent house. The hydrogen ecosystem was integrated with the other common energies found in a domestic utility such as electricity and hot water to create a synergy.

3. Investigate the challenges
   Despite metal hydrides resulted to be the most suitable solution this is not without some challenges. On the small scale, metal hydride storage is easier than compressing or liquefying the hydrogen but it is still not as easy as storing common hydrocarbons like petrol. The major challenge found was the thermal requirements and the costs. The former has been resolved partially with the ecosystem synergy mentioned above and partially with smart design considerations which favour heat dissipation. On the other hand, costs could not be estimated thoroughly due to a lack of active systems and automated manufacturing.

4. Set the future steps to achieve a working system
   The project started with a the idea for a better energy storage system for the domestic consumer. The research lead to a branch of storage technologies which has yet not been fully explored in this context. The foundations for a working system are successfully laid, upon which this method can be developed to become a viable solution to the renewable electricity's major problem.

In spite of the successes achieved, not all the original objectives presented by the project scoping and planning report [16] could be attained. These include the prototyping and the subsequent testing of the first iteration of the storage device. Considering the complexity and the wide scope of the task, this set–back was expected and had therefore been accounted in the original plan together with a mitigation.

A future project following the footprints of this one, would bank on the findings presented by this report. Consequently, the same set–backs can not be encountered as the main focus would this time be solely the prototype and the testing.

7 Acknowledgements

I would like to express my sincere gratitude to Andrew Avent for the thought-provoking discussions that led to the development of this project. Ultimately guiding me past my scepticism, regarding these technologies, towards rational decisions. I am grateful to Prof. Sam Akehurst from the Institute for Advanced Automotive Propulsion Systems (IAAPS) for providing me with insights into hydrogen storage and handling. Thank you Prof. Tim Mays for sharing your knowledge on the chemistry of metal hydrides. I would like to extend my thanks to my friends and colleagues Isaac, Thomas and Ojan for making the past months enjoyable and for keeping the motivation high. Grazie mamma e papà per essere stati sempre al mio fianco.

GenAI was not used in the preparation of this assignment.

A Appendix

A.1 The duck curve

The duck curve is a phenomenon observed on the electricity grid in regions with a high share of solar photovoltaic energy, such as California in the USA. The daily demand for electricity (grey trace in Figure A.1) is fairly predictable, with the lowest demand recorded at night when people are asleep and peaks during the day, especially around morning and evening hours. However, solar PV power is only generated during daylight hours, peaking at midday when the sun is strongest and dropping off at sunset [41]. This mismatch in time between demand and supply creates the duck curve, a curve with two humps resembling a duck (orange trace in Figure A.1).

As more PV panels are installed, the depth of the trough in the duck curve increases, eventually leading to a situation where PVs supply more energy than the grid requires at that moment. However, enough power plants would still be required to cover the two humps of the duck curve.

In the context of domestic PV installations, banking on selling excess energy to the grid is not profitable due to the duck curve [9]. This is because the excess electricity is produced when the grid is already saturated with cheap renewable energy. In some instances, the utility may even pay suppliers to stop their plants in order to balance the grid.

A potential solution to this problem is to connect a house with a sufficiently large energy storage system to the grid to provide ancillary services. These services provide flexibility to the grid balancing task and include a wide portfolio of methods [2]. A Hydrogen Energy Storage (H–ES) system has a power–demanding electrolyser, which could provide an energy sink during surges in production, absorbing the cheap excess energy. Once the hydrogen storage is full, the energy could either be used directly by the owner or sold to the grid during times of peak demand, generating a profit as the energy price at this time would be much higher.

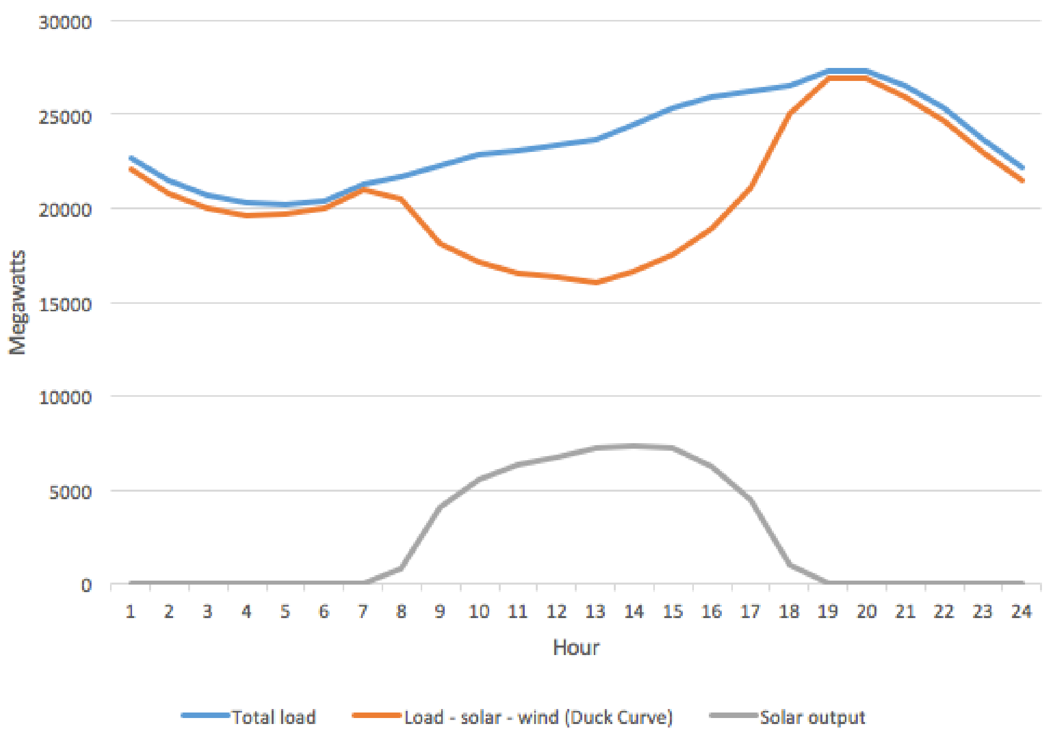


Figure A.1: The duck curve (orange) showing the difference between the grid demand (blue) and the renewable electricity supply (grey) [42].

A.2 Hydrogen Pipelines

The scope of this project focused on the scenario of a fully off–grid house. But, in the likely event of a grid–connected house, the Hybrid Energy Storage System (HESS) described in Section 3.4 could include the electricity grid as a further input and the gas grid as an output to the system. While researching hydrogen storage an alternative showed up: the potential to inject pure hydrogen in the current natural gas network.

This network pipes compressed natural gas — mostly methane — across an entire nation. This fuel is a major energy source around the world, powering industries, heating habitations and moving vehicles. All of these consumers burn the methane and hydrogen is a flammable gas itself.

According to several sources [2, 4, 32], up to 10% hydrogen–methane blend could be achieved in the current infrastructure. Any higher percentage would incur in leaks as the hydrogen molecule is much smaller than methane and most pipelines where not designed for hydrogen transport. Using materials such as Fibre Reinforced Polymer (FRP) for the pipelines, as shown in Figure A.2, would solve this issue [7] up until the following limit of 30% hydrogen–methane blend. Hydrogen contains more energy per unit mass and therefore its flame burns much hotter than natural gas. The end user appliances would therefore not tolerate more than 30% hydrogen without major modifications.

Figure A.2: Installation of a FRP pipeline suited for hydrogen gas transportation, taken from [7].

While remaining under these thresholds, the injection of pure hydrogen would be feasible and could provide an additional source of energy during peak demand. The hydrogen–methane gas mixture could also be stored underground in salt caverns caverns (Figure A.3) or old gas fields in the same way that natural gas is currently stocked in summer to compensate for the larger winter demand [4, 13, 14].

In the optics of a wide scale adoption of hydrogen energy storage this might be the most viable solution as it requires much lower investments from privates and some investment from states and their controlled gas network infrastructure.

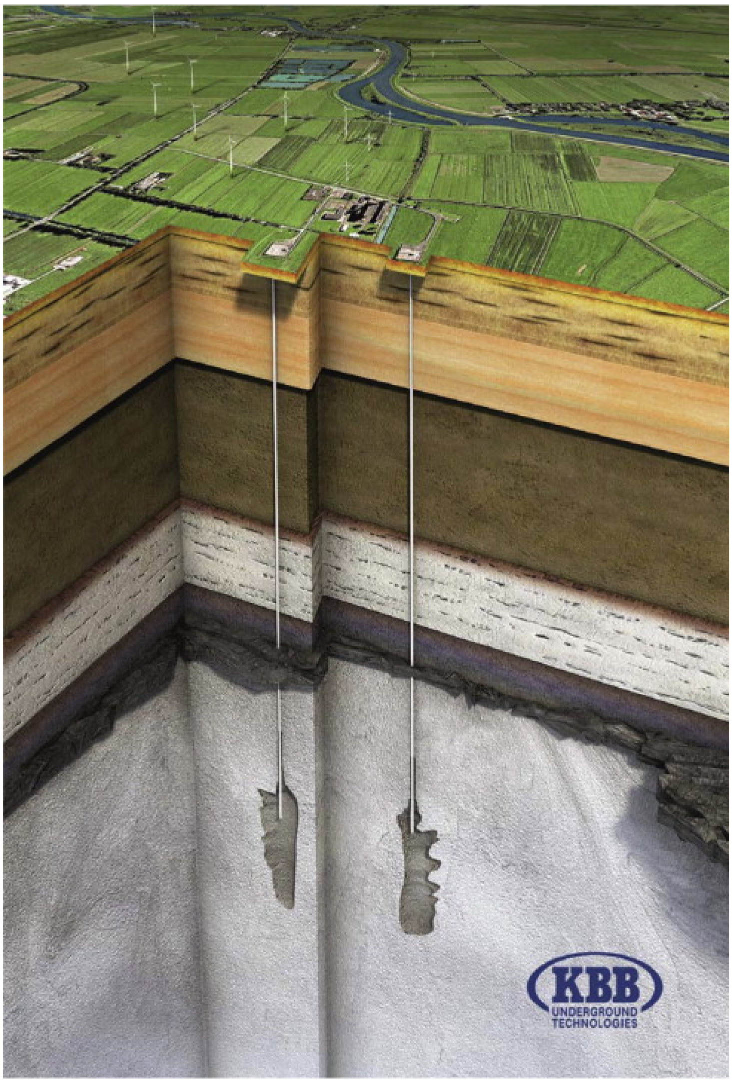


Figure A.3: Stylised representation of underground salt caverns for H_2 storage, taken from [13].

A.3 Annual Sunshine

Solar PV energy, as a renewable source, is highly dependent on the geographical context, particularly on the latitude and weather of a location. When designing a PV system with seasonal Energy Storage (ES), it is essential to consider not only the daily demand but also the available sunlight hours in the summer to ensure sufficient energy for the winter months. The energy requirement for the winter months should be considered first, followed by the available solar irradiation both in winter and summer. These parameters are specific to each location, and the calculations should be performed for each individual home to determine the appropriate size and configuration of the PV system.

Table A.1 analyses a selection of capital cities in Europe spanning several latitudes in order to have an estimate for the average number of sunshine hours both throughout the year and during the six months with greater irradiance.

Table A.1: Selection of some European capitals by sunshine duration in hours [43].

City	**Latitude**	**Year [h]**	**April-September [h]**
Athens (GR)	37° 59'	2,773	1,838
Rome (IT)	41° 54'	2,473	1,617
Zagreb (HR)	45° 49'	1,913	1,377
Vienna (AT)	48° 12'	2,048	1,458
Paris (FR)	48° 51'	1,662	1,154
London (UK)	51° 30'	1,633	1,138
Berlin (DE)	52° 31'	1,626	1,185
Copenhagen (DK)	55° 41'	1,912	1,409
Stockholm (SE)	59° 20'	1,803	1,366
Reykjavík (IS)	64° 09'	1,326	982

A.4 Project costing

If prototyping and testing could be accomplished the project would have required the use of hydrogen ready facilities, technicians expert in hydrogen handling and the purchase of the equipment as described in Section 4.1. The university could not make the relevant facilities available towards this project. Additionally all the equipment for the experiments had to be purchased, the total of which surpassing the allocated budget.

Given the tests could not be conducted with partial equipment, in the end this project did not consume any of the given budget nor facilities or technicians time.

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