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Review Article

Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives

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HIGHLIGHTS

- Review of 15 projects that use hydrogen as energy storage in a power system.
- Hydrogen is one of very few alternatives for long-term electricity storage.
- Hydrogen storage should in most cases be combined with battery storage.
- Power-to-gas-to-power for hydrogen still has a low energy efficiency (15–40%).
- Intermittent in-flow of energy and high costs are big challenges for these systems.

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ABSTRACT

This paper is a critical review of selected real-world energy storage systems based on hydrogen, ranging from lab-scale systems to full-scale systems in continuous operation. 15 projects are presented with a critical overview of their concept and performance. A review of research related to power electronics, control systems and energy management strategies has been added to integrate the findings with outlooks usually described in separate literature. Results show that while hydrogen energy storage systems are technically feasible, they still require large cost reductions to become commercially attractive. A challenge that affects the cost per unit of energy is the low energy efficiency of some of the system components in real-world operating conditions. Due to losses in the conversion and storage processes, hydrogen energy storage systems lose anywhere between 60 and 85% of the incoming electricity with current technology. However, there are currently very few alternatives for long-term storage of electricity in power systems so the interest in hydrogen for this application remains high from both industry and academia. Additionally, it is expected that the share of intermittent renewable energy in power systems will increase in the coming decades. This could lead to technology development and cost reductions within hydrogen technology if this technology is needed to store excess renewable energy. Results from the reviewed projects indicate that the best solution from a technical viewpoint consists in hybrid systems where hydrogen is combined with short-term energy storage technologies like batteries and supercapacitors. In these hybrid systems the advantages with each storage technology can be fully exploited to maximize

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efficiency if the system is specifically tailored to the given situation. The disadvantage is that this will obviously increase the complexity and total cost of the energy system. Therefore, control systems and energy management strategies are important factors to achieve optimal results, both in terms of efficiency and cost. By considering the reviewed projects and evaluating operation modes and control systems, new hybrid energy systems could be tailored to fit each situation and to reduce energy losses.

Contents

Nomenclature

Abbreviations

IEA	International Energy Agency
EU	European Union
LNG	Liquified Natural Gas
wt%	weight percent
PEM	Proton Exchange Membrane
DOE	Department of Energy
HPP	Hydrogen Power Park
PV	Photovoltaic
PtG	Power-to-Gas
EPEX	European Power Exchange
DC	Direct Current
AC	Alternating Current
LED	Light Emitting Diode
ZEB	Zero Emission Building
BEMS	Building Energy Management System
INTA	Instituto Nacional de Técnica Aeroespacial
HESS	Hydrogen Energy Storage System
BoP	Balance of Plant
EDLC	Electric Double-Layer Capacitor
PLC	Programmable Logic Controller
DSP	Digital Signal Processing
SCADA	Supervisory Control And Data Acquisition
PC	Personal Computer
FLC	Fuzzy Logic Control
EEMS	External Energy Maximization Strategy
SMCS	State Machine Control Strategy
PI method	Proportional-Integral method
ECMS	Equivalent Consumption Minimization Strategy
MBA	Mine Blast Algorithm
SSA	Salp Swarm Algorithm
DR	Demand Response
IO unit	Input-Output unit

Chemical elements

C	Carbon
O	Oxygen
Li	Lithium
Na	Sodium
Mg	Magnesium
B	Boron
Al	Aluminum
H	Hydrogen
N	Nitrogen
Ti	Titanium
Fe	Iron
Ni	Nickel
Cd	Cadmium
La	Lanthanum
Ce	Cerium
Mn	Manganese

Non-SI units and conversion to SI

kWh (kilowatthour), unit of energy $1\ kWh = 3\,600\,000\ J$
L (liter), unit of volume $1\ L = 0.001\ m^3$

bar, unit of pressure	1 bar = 100 000 Pa
°C (degree Celsius), unit of temperature	n °C = (273.15 + n) K
Nm^3 (Normal cubic meter), unit of volume	1 Nm^3 = 1 m^3 at 293.15 K and 101 325 Pa
h (hour), unit of time:	1 h = 3600 s
kWp (kilo watt peak), unit of power	kWp = kW at peak/maximum power
Ah (Ampere hour), unit of electric charge	1 Ah = 3600 C
atm (atmosphere), unit of pressure	1 atm = 101 325 Pa
SL (standard liter), unit of volume	1 SL = 0.001 m^3 at 273.15 K and 101 325 Pa

Symbols

€	Euro, currency in the European Union

Introduction

One of the great challenges of this century is how to deal with climate change. One of the most crucial aspects to be tackled here is the reduction of CO_2 emissions from transportation, electricity generation, heating, and industrial sectors [1]. Hydrogen has the potential to be a part of the solution. It can potentially be used in vehicles, particularly for long-range heavy transport like trucks, ships and airplanes. It can be used as an additive in natural gas for heating, and it can be used to replace fossil fuel use in industrial processes. The focus of this review paper is on the use of hydrogen in the electricity generation sector. The alternatives to fossil fuels in the electricity sector are mainly hydro power, nuclear power and the so-called new renewables, which are mainly solar and wind power. Of these, both hydro and nuclear power are stable power sources that can cover a large baseload, while both solar and wind power are highly intermittent and need to be combined with either energy storage or other more stable power sources. Hydro power is geographically restricted and will not be an alternative for large parts of the world. Nuclear power could in theory be a very good alternative to replace many coal and natural gas plants, but the reality is that most countries are reducing their nuclear power capacity due to issues related to safety, waste storage, costs and social opposition. That leaves solar and/or wind power as the most realistic alternative to fossil fuels in many regions of the world, with the consequent need of large-scale energy storage when integrating large amounts of renewable energy into power systems.

Batteries perform well for short-term energy storage connected to renewable energy production. An example of this is Tesla's 100 MW (soon-to-be 150 MW) battery facility in Australia [2]. However, batteries are not well suited if energy needs to be stored for longer periods (weeks and months). One of the most realistic alternatives for long-term storage of renewable energy is hydrogen. The basic concept is that excess solar and/or wind power is used to produce hydrogen through electrolysis of water in periods where electricity production from the renewable sources is higher than electricity consumption. Hydrogen is then stored, for instance as a compressed gas or in metal hydrides. When electricity production from wind and/or solar is lower than electricity consumption, the stored hydrogen can be used to produce electricity in fuel cells.

Currently there is very little energy storage connected to power systems because most electricity is generated by sources that do not need energy storage systems. More than 60% of the world's electricity is generated by burning fossil fuels [1]. In addition to this, around 16% is hydro power and around 10% comes from nuclear power [1]. A very small percentage is generated by geothermal power (0.33%) and biofuel power (1,9%) plants [1]. All of these are stable power sources that doesn't require any energy storage. The two intermittent sources with any significance, wind and solar, still only generate around 6% of the world's electricity (a little over 4% for wind and a little under 2% for solar) [1]. Therefore, there hasn't been much need for energy storage in power systems yet, since such relatively small amounts of intermittent renewable energy can be integrated into existing power grids quite easily. However, both wind and solar power are growing rapidly and are expected to supply a larger portion of the world's electricity in the coming decades. The International Energy Agency (IEA) forecasts wind and solar combined to supply between 23% and 42% of the world's electricity by 2040 [3]. Such a high share of wind and solar power could require large amounts of energy storage in many locations, both for short-term and long-term storage. If these forecasts are realized, hydrogen could be the best alternative when it comes to long-term energy storage in power systems. According to the European Union (EU) over 50% of the electricity generation in the EU needs to come from renewables to reach their 2030 objectives, and this has to grow to at least 80% in 2050 [4]. Current estimates are that the electricity grid cannot accept much more than 30% renewables without including additional grid flexibility. Large increases in intermittent energy sources like wind and solar can destabilize the electricity grid if not managed properly. The EU therefore proposes energy storage in the electricity grid as one of the measures to increase the grid's flexibility and state that all types of energy storage are needed, e.g. pumped hydro storage, grid-connected batteries and hydrogen storage [4].

Review papers with different focus areas in the field of hydrogen energy systems have been published in the past. Mazloomi et al. [5] presented hydrogen as a very promising alternative both as fuel for future vehicles and as energy storage in large-scale power systems, taking into consideration production and storage methods, as well as risk and safety issues related to hydrogen technologies. Thema et al. [6] reviewed power-to-gas projects that produce either hydrogen or a renewable substitute for natural gas, providing an analysis and forecast for the cost development of electrolysis and carbon dioxide methanation. Dutta [7] considered production and storage methods for hydrogen with an added focus on risk and safety issues. Abe et al. [8] reviewed hydrogen as a possible primary energy carrier with a focus on storage of hydrogen in metal hydrides. Gahleitner [9] examined power-to-gas pilot facilities where renewable electricity was used to produce hydrogen through water electrolysis. Eveloy et al. [10] reviewed projected power-to-gas scenarios and found that substantial improvements in areas like efficiency, cost and reliability are necessary if large-scale implementation of these types of facilities are going to become a reality. Moradi et al. [11] reviewed alternatives for storage and delivery of hydrogen and analyzed risk and safety issues. Hanley et al. [12] surveyed the implementation of hydrogen in energy systems and analyzed possible drivers and policies that could favor hydrogen over other low-emission energy technologies. They found that the scenario with the highest probability is a scenario where hydrogen technologies are implemented mostly after 2030 [12]. Parra et al. [13] provide a techno-economic review of hydrogen energy systems and highlight measures that they think will accelerate the adoption of hydrogen technologies, including a focus on mass production, standardization and favorable policies. Bailera et al. [14] reviewed the various methods used to convert renewable energy to methane in power-to-gas projects, also providing an overview of real-world projects. Wulf et al. [15] considered power-to-gas projects in Europe, suggesting that power-to-gas facilities will become important for refineries in the future to reduce the emissions connected to their products. Chehade et al. [16] reviewed 192 power-to-X demonstration projects from 32 countries. They found that both the capacity of hydrogen electrolysis and the number of applications for hydrogen has increased significantly over the years [16]. Wulf et al. [17] conducted another review to supplement their earlier work in Ref. [15] to include more recent power-to-X demonstration projects in Europe up until June 2020. Just like Chehade et al. [16] they found that the number of hydrogen applications have increased, they observed that the implementation of power-to-X projects have gone quicker than earlier projections and the development in Europe has been led by France and Germany [17]. Yue et al. [18] surveyed hydrogen technologies in power systems where the various technologies and applications are described using real-world projects as examples. They combined costs and technical aspects in a techno-economic analysis and concluded that continued focus on technical improvements, up-scaling of projects and production, as well as political backing are necessary to make hydrogen technologies cost-competitive [18].

This paper investigates the current state-of-the-art for hydrogen as energy storage in power systems that use intermittent renewable energy sources (wind and/or solar) to generate electricity. This includes a few full-scale facilities in full operation, e.g. the Sir Samuel Griffith Centre at Griffith University in Brisbane, Australia [19] and Energiepark Mainz in Germany [20], some medium-scale test facilities, as well as some lab-scale systems for technology development and testing. Both grid-connected and off-grid systems are included. Some systems use only hydrogen as energy storage, but most of the reviewed systems use a hybrid energy storage system where hydrogen is combined with one or more short-term storage technologies (e.g. batteries). This paper focuses on real systems that have been constructed and tested and the experimental results from these systems, and not on theoretical systems. An example of the main components and energy flow of a typical system that stores intermittent renewable energy in a hybrid energy storage system is shown in Fig. 1 [21]. To enhance the perspective and novelty of this paper we also include a review section on the power electronics and control systems used in projects where hydrogen energy storage is used in combination with renewable energy. More in-depth explanations and analyses of the technical, environmental and political aspects related to hydrogen production, storage and use can be found in the referenced papers [5–18,22–26] and are outside the scope of this paper.

Hydrogen as energy storage in renewable energy systems

Based on IEA forecasts, around a third of the world's electricity will rely on intermittent renewable sources like wind and solar by 2040 [3]. This will require solutions for long-term large-scale storage of electricity, with hydrogen production and storage being a promising technology, as illustrated in Fig. 2 [22]. There are various ways in which hydrogen can be stored for later use. The most common method so far is as compressed gas. Another method is to store it as a liquid at very low temperatures. Hydrogen can also be stored through physisorption, which is physical adsorption on the surface of a solid material, or chemisorption using metal hydrides. Various reviews of the different hydrogen storage technologies can be found [22–26] and are outside the scope of this paper.

Compressed gas storage and metal hydride storage are the most relevant storage methods for stationary power systems, and they are the only two storage methods used in the projects reviewed in this article. Table 1 summarizes the main characteristics of the systems considered in this review. Seven projects use only compressed gas storage, six projects use only metal hydride storage, and two projects use both compressed gas storage and metal hydride storage.

Storing hydrogen as compressed gas is currently the most widespread method. Commercial hydrogen storage tanks like the ones used by Toyota in their Mirai fuel cell car can store hydrogen gas at a pressure of 700 bar [27]. The compression process typically uses 20% of the energy content in the hydrogen [24]. Advantages with storing hydrogen as compressed gas is that it is relatively simple from a technical viewpoint and the cost is relatively low. Disadvantages include relatively low system energy density compared to systems based on fossil fuels and safety issues related to the high pressure.

Hydrogen can also be stored as a liquid. This increases the volumetric energy density significantly compared to storing it as a compressed gas. Liquid hydrogen has a volumetric energy density of 2.2 kWh/L [25], while compressed hydrogen gas contains 1.3 kWh/L at 700 bar and 0.8 kWh/L at 350 bar [25]. However, the volumetric energy density of liquid hydrogen is

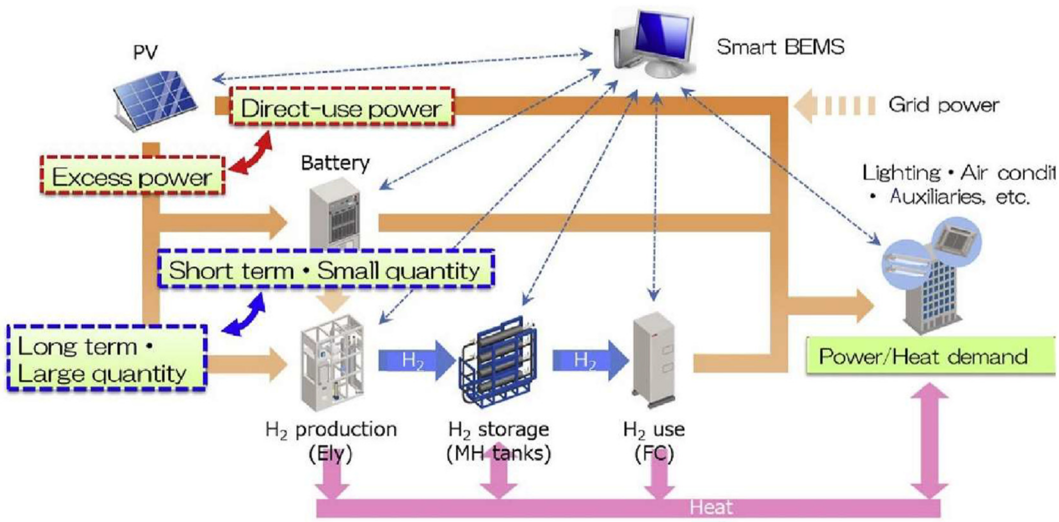

Fig. 1 – An energy flow schematic for a typical energy system that combines renewable energy with hydrogen energy storage. In this case, the renewable energy source is solar energy (PV panels), and the energy storage system includes both batteries and a hydrogen system. The hydrogen system includes an electrolyser, hydrogen storage in metal hydride tanks, and a fuel cell to convert hydrogen into electricity. The whole energy system is controlled by a building energy management system (BEMS) and it is also connected to the main power grid [21].

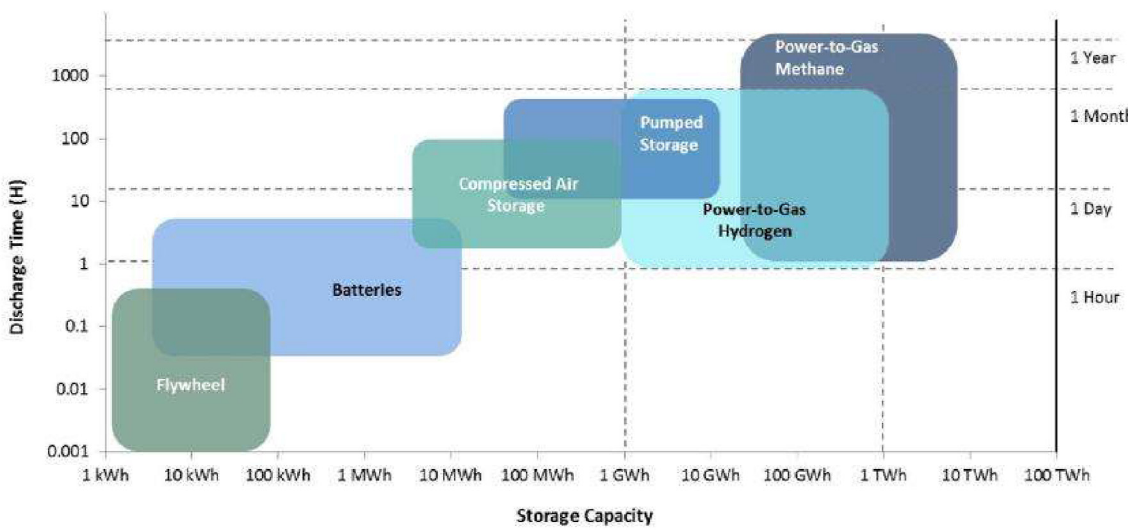

Fig. 2 – Comparison of storage capacity and discharge time for various energy storage technologies [22]. As seen here, hydrogen is one of the best alternatives for large-scale long-term energy storage.

less than 40% of the volumetric energy density of liquified natural gas (LNG), which is 5.8 kWh/L [25]. Disadvantages with liquid hydrogen are the energy required for liquefaction, hydrogen boil-off and very costly storage systems. The consequence of the boil-off issue is that liquid hydrogen is only considered for applications where hydrogen is used relatively quickly after loading (e.g. transport applications with frequent re-filling opportunities) and it is not a good choice for long-term energy storage in stationary power systems.

Physisorption is another method for storing hydrogen. The hydrogen gas molecules are adsorbed onto the surface of a solid material, and then released as gas when hydrogen is needed for use, for example in a fuel cell [24]. The materials most commonly used to adsorb the hydrogen gas are carbon-based materials and metal organic frameworks [24]. While many of these materials are the subject of promising research, they have not been deployed on a commercial scale and none of the projects reviewed in this article uses/used physisorption to store hydrogen. Advantages with hydrogen storage through physisorption includes low system complexity, low pressure and fairly non-expensive materials [23]. Disadvantages include relatively low hydrogen density on carbon and the low temperatures required [23].

Finally, hydrogen can also be stored through chemisorption in metal hydrides. This is a process where hydrogen gas is absorbed and stored in a metal powder, either a pure metal or a metal alloy. Heat is released when the hydrogen gas is

Table 1 – Overview of the reviewed projects, their topologies, storage technologies and objectives. GC = grid-connected, OG = off-grid, CG = compressed gas, MH = metal hydrides.

Ref.	Topology	Storage technology	Objective	Main results/conclusions	Year of publication
[20]	GC	CG	Technical and economic evaluation of full-scale power-to-gas facility	• Average total efficiencies of 60% (Sept. 2015) and 54% (Oct. 2015) for large-scale (6 MW) hydrogen electrolysis and storage as compressed gas (80 bar and 225 bar) • Efficiency of PEM electrolyser is maximum when the power is ca.1 MW (1/6 of peak power) and then decreases slowly with increasing power	2017
[21]	GC	MH	Reduce emissions from buildings	• 24-h operation used almost zero grid power, indicating that it is possible to build zero emission buildings using PV power combined with energy storage as hydrogen and batteries • Full desorption process for metal hydride tank was demonstrated using only waste heat from fuel cell	2019
[28]	GC	CG	Evaluation of full-scale renewable energy system with hydrogen storage operating in a 10-house microgrid	• Stand-alone operation about 50% of the time • Stability issues with fuel cell • Hydrogen system needs load-following electrolysers, increased component efficiencies and reduced costs	2010
[29]	OG	CG	Evaluation of full-scale renewable hydrogen system	• 40–45% electrolyser efficiency • 50% fuel cell efficiency • System functions well, but increased efficiencies and reduced costs are needed	2010
[30]	GC	CG	Evaluate the use of hydrogen as energy storage for residential applications	• 41.5% electrolyser efficiency • 40% fuel cell efficiency • Electrolyser is sensitive to intermittent power (e.g. PV) since it has a minimum power demand (518 W in this case) and will shut down below this • PV-hydrogen electricity was 933% more costly than grid electricity and 202% more costly than PV-battery	2011
[31]	OG	CG	Develop control method for renewable energy system with battery and hydrogen storage	• Battery and hydrogen energy storage in combination can successfully handle both high-frequency (battery) and low-frequency (hydrogen) power fluctuations	2019
[32,33]	GC	CG	Evaluate a renewable energy system with hydrogen storage used for greenhouse heating	• Electrolyser requires minimum power equal to 20% of its 2.5 kW power rating to produce hydrogen • Internal pressure in electrolyser must be in the range 2.8–3.0 MPa for proper function • Mathematical model showed that electrolyser should be operated in the range 1.5–2.5 kW with a minimum production rate of 0.21 Nm^3/h to achieve stable results	2013 and 2014
[34]	OG	CG	Develop and construct small renewable energy system with hydrogen storage for off-grid applications	• A small-scale autonomous solar-hydrogen system is feasible, but it would require more PV power and increased hydrogen production and storage capacity • 10 L of hydrogen at 1.05 atm gave 18 h of continuous operation • Large variations in hydrogen production between sunny and cloudy days	2014
[35]	GC	MH	Optimize operating modes of hybrid renewable energy systems	• Operating mode in a hybrid renewable energy system must be a compromise between energy efficiency and costs, i.e. maximizing efficiency will usually increase the costs and vice versa. • Efficiency and cost of various operating modes will also be greatly affected by the weather profile on the given day, i.e. the energy system should ideally use different operating modes on different days, depending on the weather • Operating hydrogen components with variable power gave highest total system efficiency, but also highest cost • Operating hydrogen components at constant rated power gave lowest cost, but also reduced total system efficiency	2016
[36]	GC	MH	Optimize load sharing for hybrid energy storage systems	• Batteries and ultracapacitors can reduce power fluctuations in the hydrogen components in a hybrid renewable energy system, which in turn can increase the component lifetimes	2016

Table 1 – (continued)

Ref.	Topology	Storage technology	Objective	Main results/conclusions	Year of publication
[37]	GC	MH	Evaluate efficiencies in a solar-to-hydrogen integrated microgrid	• The efficiency of the hydrogen conversion and storage (PEM electrolyser and metal hydride tanks) was 35–47% • Electrolyser efficiency varies with input power. Should be operated with constant input power corresponding to max efficiency to minimize losses. • The total efficiency of the complete PV-to-hydrogen chain was 3.4–5.3%	2017
[38]	OG	MH	Off-grid power applications with hydrogen system where fuel cell exhaust is used for hydrogen desorption process in metal hydrides	• A hydrogen system with electrolyser, fuel cell and metal hydride storage without external heat supply is demonstrated, but the fuel cell load must be above a certain minimum to supply enough waste heat for the metal hydride desorption process at 20 °C • Higher electrolyser pressure and/or a hydrogen buffer can decrease the challenge related to the fuel cell load	2019
[39]	OG	MH	Design a hybrid energy storage system with hydrogen and battery with the twin goals of reducing curtailment of wind and solar power, as well as supplying hydrogen to fuel cell buses and the natural gas grid	• Curtailment of solar and wind power was 8.8% during the operation period [39] • The average hydrogen level in the metal hydride tank during the operation period was 71.4% [39]	2020
[40]	OG	MH and CG	Evaluate advantages and disadvantages with different hydrogen storage technologies	• Hydrogen storage capacity: 0.17 wt% for low pressure gas, 1.25 wt% for high pressure gas, 0.93 wt% for metal hydride tank ($TiMn_2$) • Gravimetric energy density: 0.06 kWh/kg for low pressure hydrogen, 0.42 kWh/kg for high pressure hydrogen, 0.31 kWh/kg for metal hydride tank ($TiMn_2$) • Volumetric energy density: 0.01 kWh/L for low pressure hydrogen, 0.52 kWh/L for high pressure hydrogen, 1.22 kWh/L for metal hydride tank ($TiMn_2$) • Hydrogen storage efficiencies: 96% for low pressure gas, 52% for high pressure gas, 79% for metal hydride tank ($TiMn_2$) • Total energy storage and conversion efficiencies (including electrolyser and fuel cell): 32% for low pressure hydrogen, 17% for high pressure hydrogen, 26% for metal hydride tank ($TiMn_2$)	2015
[41]	GC	MH and CG	Create local microgrid that can function as emergency power supply during main grid outages	• The PV/capacitor/hydrogen system was demonstrated to be a reliable solution as emergency power supply, but with efficiency and cost issues • Electrolyser average efficiency 27.2% • Fuel cell average efficiency 29.3% • Efficiency of whole hydrogen system (electrolyser, gas and metal hydride storage, fuel cell) was 22.9% • Reduced efficiency due to electrolyser and fuel cell operating at low and/or fluctuating power • Using a low-pressure hydrogen buffer tank reduced the required heat in the metal hydride desorption process from more than 1.74 kW–1 kW	2019

absorbed in the metal hydride material and heat must be applied for the metal hydride to release the hydrogen again [24]. A drawback with the metal hydride storage method for some of the materials is that the hydrogen bonds so strongly to the metal hydride that relatively high temperatures are needed to release the hydrogen again, for example more than 650 °C in the case of lithium [24]. However, an advantage is that some of these materials have very high gravimetric hydrogen capacities, e.g. 18 wt% for $LiBH_4$ [24]. Other materials such as intermetallics are also possible, like the TiFe-based alloy used by Endo et al. [21]. Though intermetallics have a lower hydrogen storage capacity (1.4 wt% for the alloy in Ref. [21]), they operate at mild temperatures (absorption at 30 °C and desorption at 45 °C for the alloy in Ref. [21]) and pressures, as shown in Fig. 3, thus reducing costs and safety issues. Much of the research in this field is directed towards finding the right metal hydride storage method and material so that low operating pressure and relatively low absorption/desorption temperatures can be combined with the highest possible gravimetric energy density.

Overview of projects and summary of results

15 projects are reviewed in this paper. All the projects use hydrogen as energy storage, either alone or together with other energy storage technologies (batteries, supercapacitors, etc.). Only projects that have built a physical system, either full-scale or some form of test/pilot system, have been considered in this paper. An overview of the projects is given in Table 1. This table summarizes the topology, storage technology, objective and main results/conclusions for each project. Topology states whether the energy system is connected to the local power grid (GC) or if it is a standalone off-grid (OG) system. Hydrogen storage method states whether hydrogen is stored as compressed gas (CG) or in metal hydrides (MH), or both. The objective and main results/conclusions columns should be self-explanatory.

Projects with only compressed gas storage

An energy system based on wind power and energy storage was built and put into operation by Norsk Hydro and Enercon on the Norwegian island of Utsira in 2004 [28]. The system delivered power to ten households on the island and included a 600 kW Enercon wind turbine, an alkaline electrolyser with a production rate of 10 Nm^3/h at 12 bar, an 11 Nm^3/h hydrogen compressor that compresses the hydrogen from 12 to 200 bar, high-pressure hydrogen gas storage tank (200 bar) with a capacity of 2400 Nm^3, a 55 kW hydrogen engine (a modified diesel generator that uses hydrogen) and a 10 kW proton exchange membrane (PEM) fuel cell [28]. Additional energy storage components in the form of a 50 kWh NiCd battery and a 5 kWh flywheel were also included in the total system [28]. The system was in operation for several years and at the time the paper [28] was published in 2010 the conclusion was that hydrogen energy storage systems coupled with wind energy is technically possible, but it is still far from being a realistic solution from a commercial viewpoint [28]. Data from several years of operation showed that 100% stand-alone operation was only achieved around 50% of the time [28]. The electrolyser often had to use power from the grid to produce enough hydrogen to keep the hydrogen storage pressure from becoming too low. Typical operation from a 12-h period for the Utsira power system is shown in Fig. 4 [28]. The control system is programmed to turn on the electrolyser only when the energy production by the wind turbine is higher than the energy consumption. This is the case from point 1 to point 2a in Fig. 4 [28]. At this point the wind power drops, the electrolyser is consequently switched off and the hydrogen engine/generator is switched on. This is followed by a period of rapid fluctuations in wind power where excess wind power is used to charge the flywheel and this is then discharged when the wind power drops again (points 3 and 4) [28]. At the same time the hydrogen engine also produces varying amounts of power based on the needs of the total system. When the wind power remains high for a longer period (point 5) [28], the hydrogen engine is de-activated and the excess power is used to charge the battery. If the power delivered by the wind turbine is still higher than the power usage after the battery is full, this power will be fed to the electrolyser to produce hydrogen (point 6) [28]. During the power system's operating years there were multiple technical difficulties with the fuel cell which resulted in very little operational time for this component (less than 100 h) [28]. This was caused by leaking cooling liquid, assembly damage, issues with the control system/fuel cell communication, as well as very rapid stack degradation (even when the fuel cell was not in use) [28]. The authors recommend some necessary improvement areas for wind/hydrogen power systems. These include technical improvements in fuel cells and hydrogen engines, the development of load-following electrolysers, increased efficiency in all components in the hydrogen system, more advanced wind energy forecasting and energy management system, as well as general cost reductions for all the components [28].

In 2010, more than 90% of the energy used on Hawaii was imported [29], resulting in the highest energy cost in the US [29]. This, combined with the large availability of renewable energy resources on the Hawaiian Islands, prompted the US Department of Energy (DOE) to fund the Hawaii Hydrogen Power Park (HPP) at Kahua Ranch [29]. The facility uses a 7.5 kW Bergy wind turbine and 9.8 kWp photovoltaic (PV) array to produce wind and solar energy. These energy producers are connected to an energy storage system consisting of lead-acid batteries with a storage capacity of 343 kWh as well as a hydrogen system [29]. The hydrogen system includes a PEM

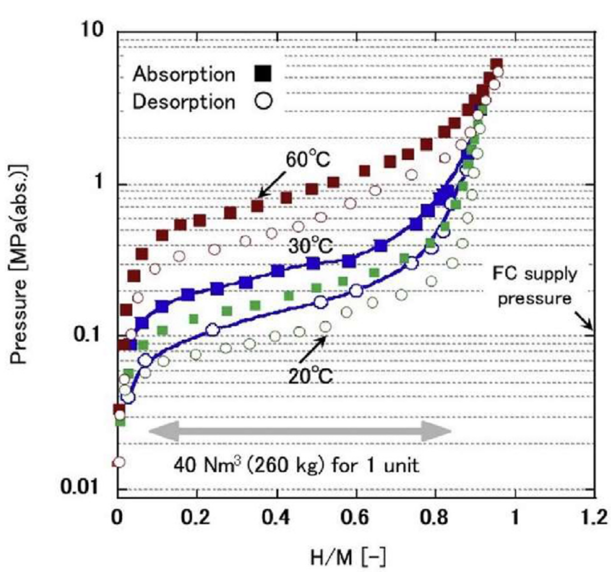

Fig. 3 – Pressure-composition isotherm (PCI) properties at 20, 30 and 60 °C for the TiFe-based alloy used for hydrogen storage in one of the reviewed projects [21]. In the actual project, the hydrogen gas was supplied to the metal hydride tank from the electrolyser at a pressure of 9.7 bar. The hydrogen was then absorbed by the metal hydride at a rate of 5 Nm^3/h at a temperature of 20 °C and the desorption process had a rate of 3 Nm^3/h at a temperature of 60 °C. The hydrogen gas was fed to the fuel cell at a pressure in the range 0.15–0.5 bar.

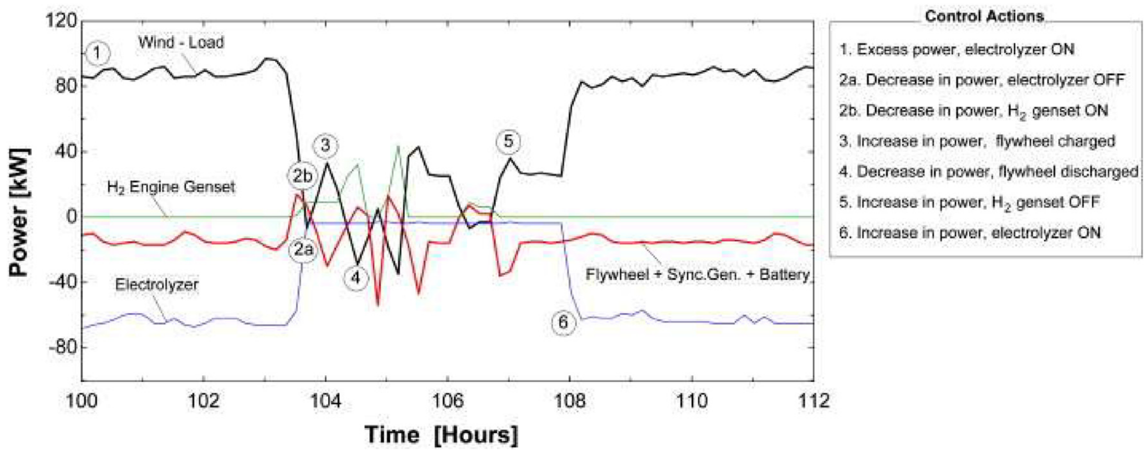

Fig. 4 — Operational data (10-min averages) measured at Utsira on 5 March 2007 [28].

electrolyser with a production rate of 0.2 Nm^3/h at a pressure of 12 bar and a 63% maximum efficiency, low-pressure (12 bar) tanks for hydrogen storage with a combined capacity of approximately 1 kg of hydrogen, and a 5 kW fuel cell system [29]. The power flow from a full day of operation in December 2009 is shown in Fig. 5 [29]. During the night hours, most of the power is supplied by the battery, and the wind turbine takes over during the early morning hours. In the daytime, both the wind turbine and PV array produces power, and the excess power is used to both charge the batteries and produce hydrogen in the electrolyser. During the late afternoon and night hours, the fuel cell system provides some power initially, while the rest of the night is covered by the wind turbine. During the night hours, there is also some excess wind power that is used to charge the battery and operate the electrolyser. The operational data showed that the electrical efficiencies for the various components in the energy system was 40–45% for the electrolyser (steady operation), 50% for the fuel cell system (operation range from ¼ to full load), 10–35% for the wind turbine and 10% for the PV array [29]. The general conclusions drawn from the operation of the HPP at Kahua Ranch is that hydrogen as energy storage offers many

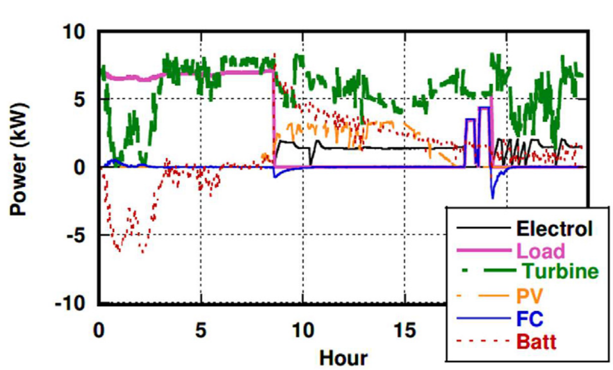

Fig. 5 — Power flow for a full day's operation of the Kahua Ranch facility. The data are from a day in December 2009. Positive values represent power to the bus bar and negative values represent power drawn from it [29].

advantages like zero harmful emissions, low noise, long-term storage with almost no loss of hydrogen, option to use waste heat for heating purposes, high adaptability in terms of sizing since energy and power are independent of each other, as well as long lifetime and low maintenance requirements [29]. However, the study pointed out that it was difficult to justify hydrogen as energy storage economically and technically (at the time of writing in 2010) and that it was necessary to improve the energy efficiency and reduce the cost of these systems to make them commercially attractive [29].

A small-scale experimental solar/hydrogen energy system for residential applications was constructed and tested in 2011 at the National Fuel Cell Research Center at the University of California in Irvine [30]. This was a grid-connected system and it included a 5 kW PV array, an electrolyser that produced hydrogen at a rate of 1 Nm^3/h at a pressure of 13.8 bar and 41.5% efficiency, a compressed gas tank that stored 0.04 m^3 of hydrogen at 13.8 bar, a 1 kW PEM fuel cell and a 5 kW PEM fuel cell [30]. The system also included additional energy storage in a battery and a load bank that simulated a load pattern typical of a residential house. Data from a week in August of 2003 was used to compare the load demand of a residential house in Irvine with the power produced by the 5 kW PV array. The data showed that the electrical energy required by the house for the full week was 108.1 kWh and the energy delivered by the PV array was 224.8 kWh [30]. However, the time mismatch between the PV energy production and the energy usage in the house shown in Fig. 6 [30] clearly demonstrates the need for energy storage. In fact, the data showed that even though the PV array produced more than twice as much energy as the house needed, only 33.6% (36.3 kWh) of the load demand was directly covered by the PV energy [30]. This means that 83.9% (188.5 kWh) of the produced PV energy would have to be stored. Experimental data from a single day of operation showed that the electrolyser used 33.4 kWh of PV electricity and 4.8 kWh of grid electricity to produce hydrogen with an energy content of 17.8 kWh [30]. However, less than half of this energy can be used as electricity in the house since the fuel cell has an efficiency of 40% [30]. Operational data also showed that the electrolyser required an internal pressure of 1380 kPa before it started to produce hydrogen, and this

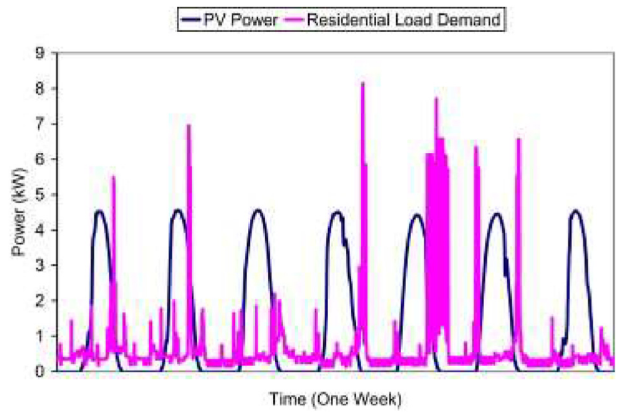

Fig. 6 – Comparison between the power delivered from a 5 kW PV array and the load demand of a residential house in Irvine, California. The data is from the week between the 2nd and 9th of August 2003 [30].

required a minimum PV power of 518 W [30]. The result was that the electrolyser was able to tolerate short fluctuations in solar irradiance, but when there was extended cloud cover it would stop producing hydrogen due to system pressure loss [30]. The 5 kW fuel cell was found to have a power ramp rate capability of 1.7 kW/s and a load shed capability of −4.4 kW/s, which fit relatively well with the measured demand rates of 1.9 kW/s and −1.8 kW/s [30]. The biggest challenge related to hydrogen energy storage was found to be cost. The cost of electricity from the PV/hydrogen system was calculated to be 933% of the average California retail electricity price [30]. Compared to energy storage in batteries, PV/hydrogen electricity was calculated to be 202% more costly than PV/battery electricity [30]. The authors therefore concluded that the cost of both electrolysers and fuel cells must be significantly reduced before hydrogen as electricity storage can become cost-competitive [30].

The full-scale power-to-gas (PtG) plant "Energiepark Mainz" in Germany was constructed to support the local power grid and to perform research on large-scale implementation of PEM electrolysers [20]. Researchers from Rhein-Main University of Applied Sciences, Linde AG, Siemens AG and Mainzer Stadtwerke AG have published a technical and economic analysis of the PtG facility [20]. The facility is connected to an 8 MW wind farm and uses excess wind energy to produce hydrogen gas. This is done through the use of three PEM electrolysers with a peak power of 6 MW and a hydrogen output of 1000 Nm^3/h [20]. The hydrogen is then compressed to a pressure of 80 bar and stored in tanks with a capacity of approximately 10 000 Nm^3 [20]. From these tanks, the hydrogen is either injected into the natural gas grid or it goes through a second compressor stage to a pressure of 225 bar. The hydrogen that is compressed to 225 bar is then filled into trailers and transported either to chemical industries or hydrogen fueling stations [20]. This means that Energiepark Mainz does not use hydrogen to produce electricity in a fuel cell like the other projects reviewed in this article. Instead, hydrogen is used in the three applications mentioned above; as an additive in the natural gas grid, as a reactant in chemical industries, or sold to hydrogen fueling stations [20]. The facility has an annual target output of approximately 200 tons of hydrogen [20]. The analysis shows that there is a slight decrease in the efficiency with increasing load. When the electrolysers are run at the rated power of 4 MW the calculated efficiency is about 64%, while it is about 59% when they are run at the peak power of 6 MW [20]. This is illustrated in Fig. 7 [20] where the production rate and efficiency for the electrolysers is shown. Here it can be seen that the efficiency increases quickly up to its maximum value when the power is around 1 MW (1/6 of peak power), and then the efficiency decreases slowly with increasing power [20]. The hydrogen production rate naturally increases with increasing power. Another thing to keep in mind is that the electrolysers can only run at peak power for 15 min, while they can run continuously at the rated power (or below rated power) [20]. Results for September of 2015 showed an average efficiency of about 60% and for October of 2015 it was about 54% [20]. These efficiencies are the combined efficiencies of the whole PtG facility including all associated equipment (compressors, transformers, pumps, etc.). An economic analysis showed that it was most profitable for the PtG facility to purchase electricity through the market for control reserve rather than use the excess wind energy or purchase from the European Power Exchange (EPEX) [20]. It is concluded that a PtG facility of this type can be a profitable operation if the most favorable power procurement and operation strategy is chosen [20]. The authors state that improvements are needed to reduce capital and fixed costs and increase efficiencies [20]. They also suggest that the implementation of cost premiums for hydrogen produced in a low-emission way would increase the competitiveness of these types of facilities [20].

A distributed control method called "modified DC-bus signaling" for renewable energy systems with hybrid energy storage was proposed by researchers at RIKEN Center of Advanced Photonics and the University of Tokyo in Japan [31]. A lab-scale version of a hybrid energy storage system was developed and used to validate the theoretical work. The storage system included an electrolyser, a 2 m^3 tank that stores hydrogen at a pressure of 7 bar, a hydrogen fuel cell, and a lead-acid battery [31]. DC sources were used in the place of PV panels and loads. The experiments demonstrated that the proposed control method was indeed able to control step-line and random changes in input and output power. It was shown that the battery successfully compensated high-frequency fluctuations in power demand, and the hydrogen system handled the remaining low-frequency fluctuations [31].

A hybrid energy system was constructed to provide power and heat to a greenhouse at the University of Bari in Italy [32,33]. The system combined solar energy production from PV panels, a heat pump, and a hybrid energy storage system with hydrogen and batteries. The PV array consisted of 24 panels of 240 Wp and the battery bank consisted of six 12 V cells with a nominal energy capacity of 900 Ah. The hydrogen energy storage system included an alkaline electrolyser with a power rating of 2.5 kW that produces hydrogen with a nominal production rate of 0.4 Nm^3/h at a pressure of 30 bar when operated at full power, two low-pressure (30 bar) storage tanks with a volume of 0.6 m^3, as well as a 2 kW PEM fuel cell [32,33]. Initial tests showed that the electrolyser operated in an

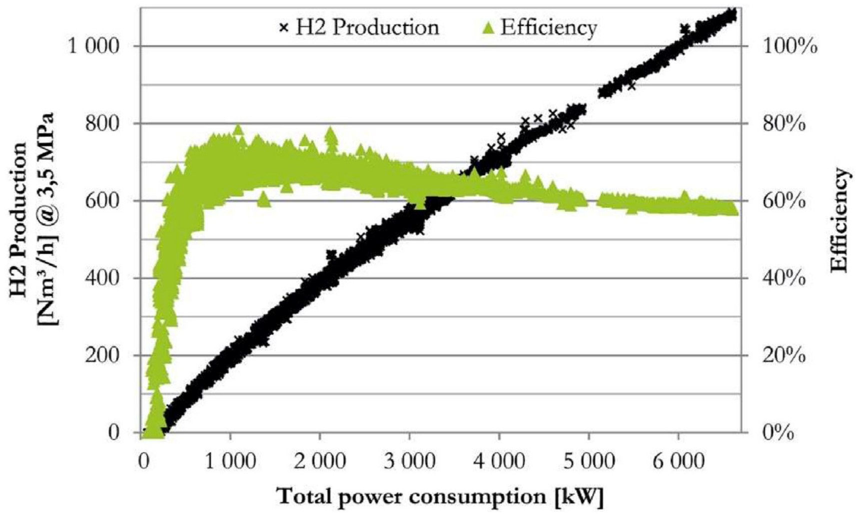

Fig. 7 – Production rate (black) and efficiency (green) for the electrolyser at Energiepark Mainz [20]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

unstable manner and the performance was not consistent with the theoretically predicted performance [32]. Further tests confirmed the challenges related to the electrolyser/PV combination, which manifested themselves in highly intermittent operation with several breakdowns on partially cloudy days. On clear-sky days the electrolyser could operate continuously, but the hydrogen production was still affected by the variability of the solar radiation and the electrolyser never reached steady-state conditions [33]. These operational issues can be seen in Fig. 8 [33] which shows the hydrogen production for the final week of March 2014, where the first four days have very intermittent production while the production is more stable during the last three days. The experiments showed that the electrolyser only started to produce hydrogen once it received PV power equal to at least 20% of its power rating of 2.5 kW, i.e. 0.5 kW [33]. Since other auxiliary equipment required a power of 0.6 kW to operate, the result was that the electrolyser only produced hydrogen if the delivered PV power was 1.1 kW or higher [33]. Additionally, the electrolyser required an internal pressure of 2.8–3.0 MPa to function properly [33]. A mathematical model showed that the electrolyser should be operated in the range 1.5–2.5 kW with a minimum production rate of 0.21 Nm^3/h to achieve stable results [33].

Researchers at Departamento de Investigación y Desarrollo en Energías Renovables and Escuela Superior Técnica in Argentina built and tested a lab-scale hybrid energy system for off-grid energy supply for low and medium energy consumptions like mountain cabins and military shelters [34]. The system was a solar/hydrogen combination which included two different types of PV panels, an alkaline electrolyser, low-pressure hydrogen and oxygen storage tanks (1.05 atm storage pressure), and two stacks of PEM fuel cells [34]. All the hydrogen components (electrolyser, storage tanks and fuel cells) where designed and constructed by the researchers themselves. To simulate a typical power consumption for the intended applications, a 6 W LED lighting load and an electronic load was connected to the energy system [34]. The energy system was tested in Buenos Aires, Argentina during the month of May, in which the average

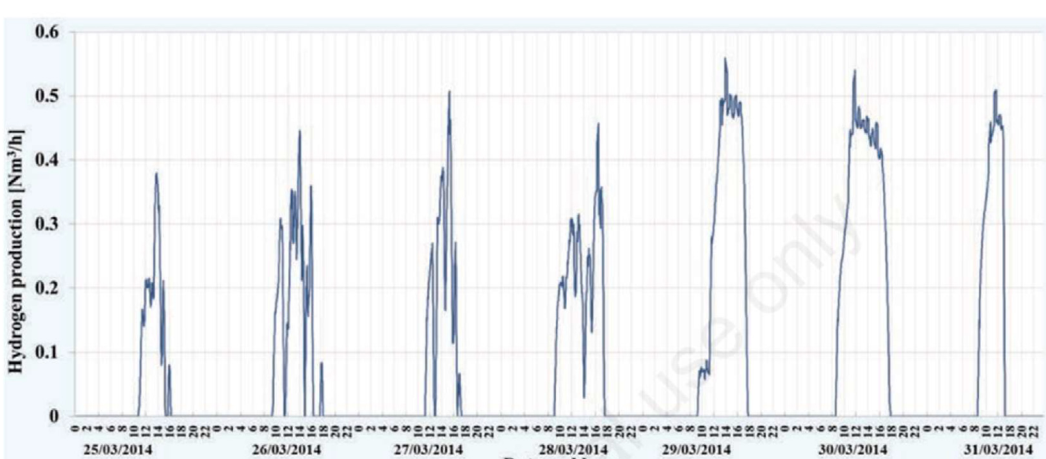

Fig. 8 – Hydrogen production for the final week of March 2014 at the greenhouse facility [33].

recorded solar irradiation is 2.5 kWh/m^2 [34]. On sunny days during this period the PV panels were able to deliver up to 6 W to the electrolyser, while the useable power on cloudy days was observed to be 10–30% of this [34]. The electrolyser was able to produce 5 L of hydrogen on sunny days, while the production on one day that was alternately sunny and cloudy was 3.6 L [34]. The autonomy of the system was tested with the connected loads and 10 L of stored hydrogen and this resulted in 18 h of continuous operation [34].

Projects with only metal hydride storage

A research project at the Universidad de Sevilla in Spain analyzed and performed experiments to identify advantages and disadvantages with various operating modes for energy systems based on renewable energy with hybrid energy storage, including hydrogen [35]. Computer simulations and numerical analyses were performed and the theoretical results were then validated through experiments on a lab-scale energy system. The energy system used in the experiments included a 1 kW PEM electrolyser, a 1.5 kW PEM fuel cell, a 7 Nm^3 metal hydride tank and a 367 Ah lead-acid battery bank [35]. In addition to these components, a 2.5 kW electronic load was used instead of power demand and a 6 kW electronic power source was used instead of power production [35]. Six different operating modes were used and combined with three different simulation scenarios. The six operating modes were: "partial load operation", "maximize hydrogen production", "batteries at rated power", "fuel cell at rated power", "electrolyser at rated power" and "maximize efficiency" [35]. The three simulation scenarios were: "sunny day scenario", "cloudy day scenario" and "windy day scenario" [35]. Some of the modes and scenarios were combined in three experimental setups called: 1. Partial load on a sunny day, 2. Maximize efficiency in the cloudy day scenario, and 3. Maximize efficiency in the windy day scenario [35]. The conclusion from the research project was that none of the operating modes have the best performance in every situation [35]. Instead, an "Efficiency-Cost" map can be used to choose the most beneficial operating mode depending on various situations, as shown in Fig. 9 [35]. The experimental work confirmed the results from the theoretical studies and the general conclusion is that operating the electrolyser and fuel cell at variable power achieves the highest energy efficiency [35]. This is indicated by the "P. load" box (black) in Fig. 9 [35] where it can be seen that the total efficiency of the energy path (as defined in Ref. [35]) for this operating mode stretches from 79 to 87% [35]. However, this operating mode can also result in much higher costs. This is indicated by the top side of the "P. load" box in Fig. 9 [35] which represents this operating mode during a cloudy day. There it is shown that the operating cost (as defined in Ref. [35]) in such a situation would be 50€, as opposed to less than 5€ for the same operating mode during a sunny day [35]. One way to lower the costs is to operate the electrolyser and fuel cell steadily at their rated power, but this has the disadvantage that the total efficiency of the energy path could be reduced. This is indicated by the "Max Eff" (green) box in Fig. 9 [35] where it can be seen that this operating mode has very low operating costs (4–5€) for all weather profiles, but it also has a lower total efficiency of energy path (65–77.5%) compared to the "P. load" operating mode [35]. The same experimental setup with a

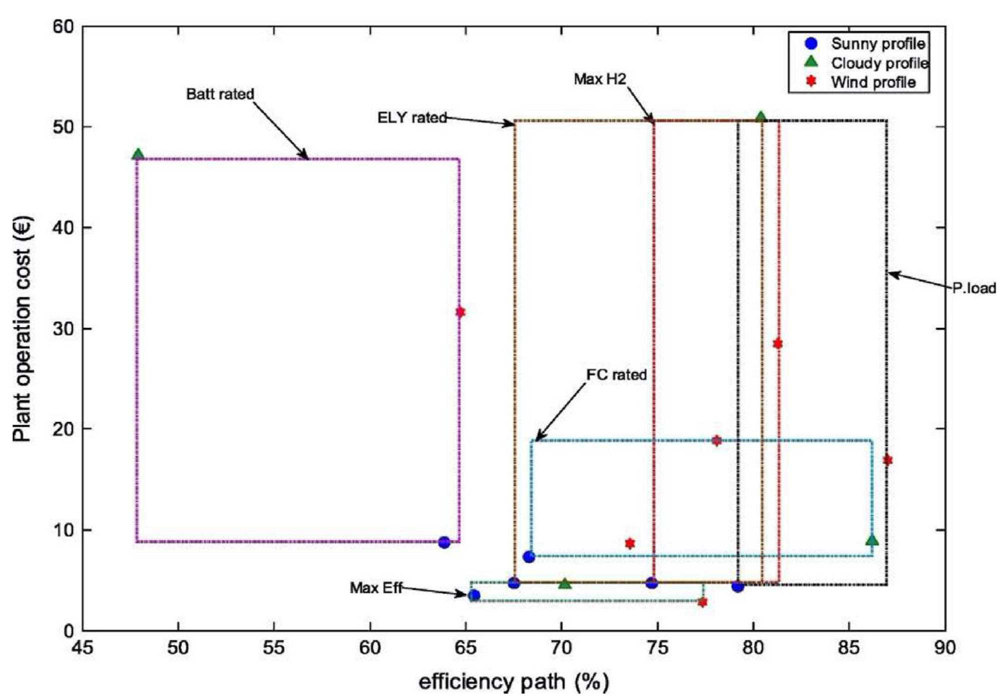

Fig. 9 – Efficiency-cost map showing the various operating modes combined with the three weather patterns. The operating modes are indicated by the boxes, and the different colors are: Black: Partial load, Red: Max hydrogen, Brown: Electrolyser rated, Blue: Fuel cell rated, Purple: Battery rated, Green: Max efficiency [35]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3 kW ultracapacitor added to the system was also used in a project where the focus was to develop control algorithms for optimal load sharing in hybrid energy systems [36]. The results from this project showed that definite advantages resulted from the combination of the three different energy storage technologies (hydrogen, battery, ultracapacitor). The use of hydrogen improved the control over the overcharge and undercharge of the battery and ultracapacitor, and it also minimized the high-stress current ratio in the battery, while the use of battery and ultracapacitor made it possible to avoid fluctuating operating conditions in the hydrogen system [36]. The overall conclusion was therefore that the hybrid solution with hydrogen, battery and ultracapacitor in combination with the developed control algorithm can increase the lifetime of the energy storage system [36].

Researchers at the University of Bologna developed a lab-scale microgrid to investigate a solar-to-hydrogen generation chain [37]. The microgrid includes two 220 Wp PV panels, a PEM electrolyser that produces hydrogen at a rate of 30 SL/h (standard liter per hour) and a pressure of 10.5 bar, three metal hydride tanks with a hydrogen storage capacity of 760 SL (standard liter) each, as well as two lead-acid batteries with capacities of 55 Ah at 12 V [37]. The researchers performed experiments with the goal of finding overall efficiency values for the complete solar-to-hydrogen generation chain, and the results showed that this efficiency ranged from 3.4 to 5.3% [37]. Most of the losses in the process is a result of the low efficiency of the PV panels that causes 89% of the total losses [37]. The section of the system that produces hydrogen consists of an AC/DC converter, a PEM electrolyser and the metal hydride storage tanks. The efficiency of this part of the system was in the range of approximately 35–47% during experiments, as shown in Fig. 10 [37]. As shown in the figure the exact efficiency value varied with the input power. The results also showed that the efficiency of the batteries and PV panels depended on the operating conditions. For instance, the battery efficiency was affected by the initial and final state of charge of the battery and the PV efficiency was shown to decrease from 15 to 9% when the solar charge regulator was used to manage the power output to the batteries [37]. The efficiencies of the AC/DC inverter and the solar charge regulator stayed constant during all experiments at 81.4% and more than 99%, respectively [37].

An energy system based on solar energy and with a hybrid energy storage system with both batteries and hydrogen was constructed and tested by researchers from the National Institute of Advanced Industrial Science and Technology and Shimizu Corporation in Japan [21]. The aim was to create a system that would realize a zero-emission building (ZEB) in urban areas, with the main priorities being compactness, safety and mild operating conditions [21]. The system consisted of four containers with PV panels on the roofs, a separate control room container and a ground-mounted PV array. The PV panels from Panasonic had a combined peak power of 23.75 kW (20 kW on the ground, 3.75 kW on the container roofs) [21]. The four containers contained the hybrid energy storage system where the electrolyser, metal hydride tanks, fuel cell and batteries each had their container. The electrolyser was a 26 kW PEM electrolyser that can produce hydrogen at a rate of 5 Nm^3/h at 9.7 bar [21]. Metal hydride storage tanks containing a TiFe-based alloy with an effective hydrogen storage of 1.4 wt% (absorption at 30 °C and desorption at 45 °C) were used, giving the tanks a combined storage capacity of 80 Nm^3 of hydrogen [21]. A 3.5 kW PEM fuel cell with an electrical efficiency of 55% was used to convert stored hydrogen back into electricity when needed [21]. In addition to the hydrogen energy storage, a Li-ion battery system with a combined storage capacity of 20 kWh and an output power of 20 kW was also used [21]. The whole system was controlled by a building energy management system (BEMS) housed in a separate control room. Results from 24 h of operation on a sunny day showed that the system used almost no power from the local grid, which led the researchers to conclude that the system is indeed capable of realizing ZEBs in urban areas [21]. The

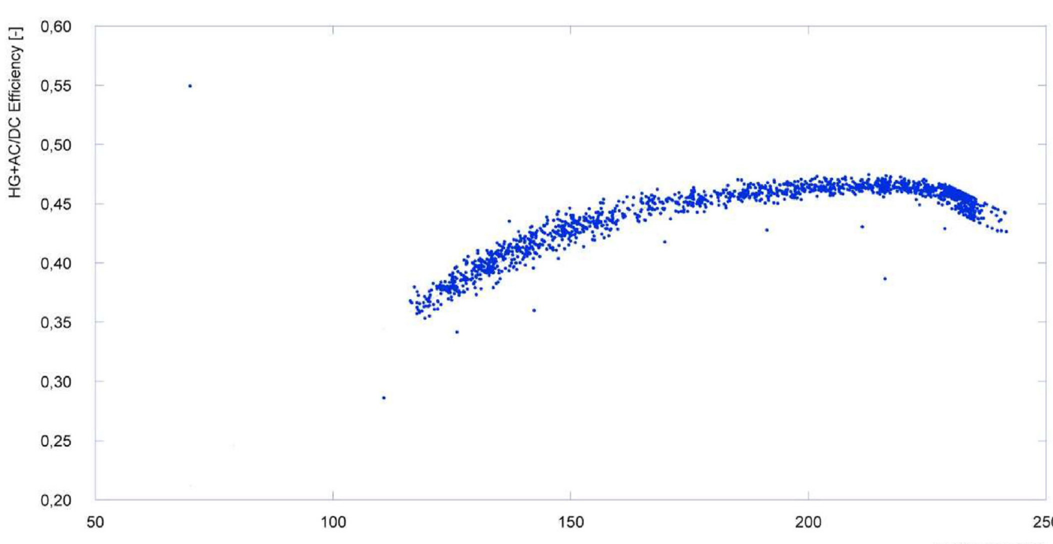

Fig. 10 – Plot of the efficiency vs. input power for the hydrogen part of the system. The hydrogen "section" (AC/DC converter, PEM electrolyser and metal hydride storage tanks) showed a peak efficiency of 47.1%, i.e. an energy loss of 52.9% [37].

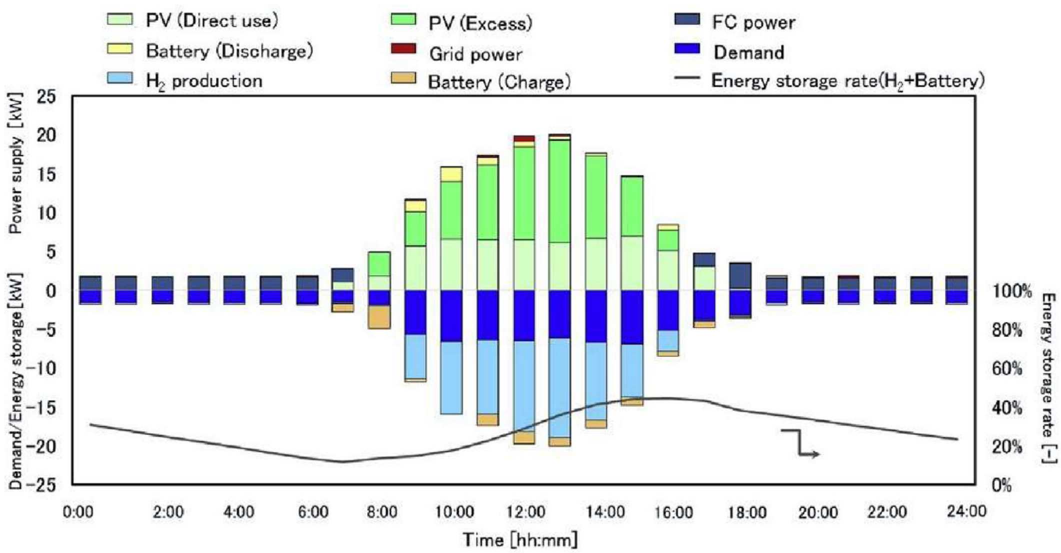

Fig. 11 – Overview of the power supply and demand during 24 h of operation with fine weather conditions. The gray line shows the combined energy storage rate for hydrogen and batteries [21].

power overview for the 24 h is shown in Fig. 11 [21]. This shows that the power demand was covered by the stored hydrogen and the fuel cell during the hours between 0:00 and 7:00. During the daytime hours (between 7:00 and 19:00) the PV panels produced power that was used to cover demand directly, as well as to produce hydrogen and charge the batteries. Only a very small amount of grid power (red in Fig. 11 [21]) was used during this period. During the hours between 19:00 and 24:00 the power demand was again covered by the stored hydrogen and fuel cell. It was also demonstrated that the waste heat from the fuel cell can be used in the desorption process in the metal hydride tanks, thereby making the overall process more energy efficient. In this demonstration, the initial temperature and pressure of the metal hydride tank was 30 °C and 0.15 MPa and the amount of hydrogen stored was 20 Nm^3 [21]. The fuel cell operated with a power output of 3.5 kW and the fuel cell outlet water temperature increased up to 60 °C during the first 20 min and stayed constant at this temperature afterward [21]. This outlet water was used in a heat exchanger to give the heat supply for the metal hydride tanks a temperature of 42 °C [21]. The desorption process in the metal hydride tank was fully completed using only the waste heat from the fuel cell, indicating that it is possible to set up a metal hydride-fuel cell operation without using an external heat supply [21].

A novel kW-scale hydrogen energy storage system was designed, constructed, and tested by researchers at Skolkovo Institute of Science and Technology and Joint Institute for High Temperatures of Russian Academy of Sciences in Moscow, Russia [38]. The system included an electrolyser that produces hydrogen at a rate of 100 SL/h at a pressure of 1.5–3 atm, a metal hydride tank filled with 5 kg of the intermetallic compound $La_{0.9}Ce_{0.1}Ni_5$ with a nominal hydrogen storage capacity of 720 SL, and a 1.1 kW PEM fuel cell [38]. The storage system uses the waste heat from the fuel cell to supply heat to the desorption process in the metal hydride tank, which requires a temperature of 20 °C [38]. This increases the

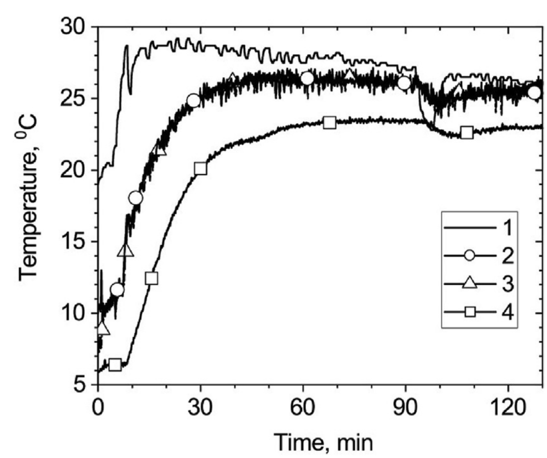

Fig. 12 – Temperature distribution in one of the experiments where fuel cell heat (line 1) was used to supply heat to the desorption process in the metal hydride tank (line 4). Line 2 and 3 shows the temperature of the water flows in the heat exchanger [38].

autonomy of the system and reduces energy losses [38]. Fig. 12 shows the temperatures of the fuel cell waste heat (line 1), water temperatures in the heat exchanger (lines 2 and 3) and the resulting temperature in the metal hydride tank (line 4) [38]. Several experiments were performed and the results indicate that the system requires a certain minimum fuel cell load of around 550 W to achieve stable operating conditions over time [38]. The reason for this is that the fuel cell does not provide the necessary outflow air temperature for the hydrogen desorption process in the metal hydride when the fuel cell is running with a low load or is just starting up [38]. Possible improvements suggested by the authors to remedy this challenge include increasing the pressure from the electrolyser to the metal hydride tank, increasing the load on the fuel cell, adding a buffer that can deliver hydrogen to the fuel cell in the first phase of the process, optimizing heat and mass transfer by improving the design of the metal hydride reactor and the overall system, as well as choosing the metal hydride material that best fits the conditions of the given situation [38]. The authors conclude that the experimental results prove the feasibility of an autonomous hydrogen energy storage system where the use of waste heat from the fuel cell eliminates the need for an external heat supply [38].

A lab-scale hybrid energy system with energy storage was designed, built and tested by Zhang et al. [39] at Hebei University of Technology in China. The main components of the energy system was 1 kW of PV panels, a 0.4 kW wind turbine, a 0.4 kW PEM electrolyser, a metal hydride storage tank with a 500 SL storage capacity, a 1.2 kW PEM fuel cell, and a 55 Ah lead-acid battery [39]. The hydrogen sub-system was not primarily intended to be used as energy storage and load-levelling in the electric power system, but rather as a way of using excess solar and wind energy to produce hydrogen for fuel cell buses or to be added to natural gas pipelines. The main motivation behind this was to reduce the curtailment of renewable power [39]. The fuel cell was only used in cases when the energy production from wind and solar and the energy stored in the battery was not sufficient to cover the load [39]. The researchers designed an operation strategy that would ensure a stable power supply to the hydrogen system and sufficient hydrogen production [39]. The stated results show that the energy system had a utilization ratio of renewable energy of 91.2% [39], which means that 8.8% of the produced renewable power was curtailed during the operation period [39]. This was achieved by operating the electrolyser at the rated power as much as possible, which kept the average hydrogen level in the metal hydride tank at 71.4% during the operation period [39].

Combination of compressed gas storage and metal hydride storage

Instituto Nacional de Técnica Aeroespacial (INTA) in Spain has built a R&D facility at its Renewable Energy Laboratory which includes a hydrogen-based energy storage system (HESS) [40]. The facility has a PV array and a 5 kW wind turbine, and together with the energy storage system this makes up a microgrid which is also connected to the internal grid at the Renewable Energy Laboratory [40]. The HESS includes an alkaline electrolyser with a nominal power of 5.2 kW which delivers hydrogen at a rate of 1.2 Nm^3/h at 6 bar and 80 °C, hydrogen storage system and fuel cells [40]. The storage system consists of three different hydrogen storage technologies: low-pressure gas, high-pressure gas and storage in metal hydrides. The low-pressure storage consists of a 1 m^3 tank that receives hydrogen gas from the electrolyser at 6 bar and stores it at the same pressure [40]. When this tank is full the hydrogen gas can go one of three ways; it can go to a compressor to be stored as high-pressure gas, it can go to the metal hydride storage container, or it can be used directly in the fuel cells to generate electricity. The metal hydride used in the storage system is $TiMn_2$ which accounts for a hydrogen storage capacity of 1.50 wt% for the metal hydride alloy alone and 0.93 wt% for the complete metal hydride container [40]. This tank can store 24 Nm^3 of hydrogen at a maximum pressure of 10 bar [40]. In the high-pressure gas tanks the hydrogen is stored at a pressure of 200 bar [40]. In total, the combined hydrogen storage system can store 65 Nm^3 of hydrogen, which is equivalent to 195 kWh of chemical energy (higher heating value) [40]. According to calculations, the volumetric energy density of hydrogen storage in the metal hydrides (1.22 kWh/L) is much higher than it is in the high-pressure gas tanks (0.52 kWh/L), while the gravimetric energy density is quite comparable for the two technologies (0.31 and 0.50 kWh/kg for metal hydride with and without tank, and 0.42 kWh/kg for high pressure gas) [40]. Hydrogen storage capacity in wt%, as well as gravimetric and volumetric energy density for the various hydrogen storage technologies used at INTA is shown in Fig. 13 [40]. The figure also shows the same values for the complete hydrogen storage system using all technologies. The gravimetric and volumetric energy density of the hydrogen technologies was also compared to three different battery technologies (wet lead acid, valve regulated lead-acid, and Li-ion batteries). In these comparisons, it is also considered that the energy in the stored hydrogen must be converted to electricity in a fuel cell (tested at INTA with an average efficiency of 48%) before it can be compared to the batteries which require no such conversion device [40]. The values for the batteries are stand-alone values (not in combination with hydrogen). The results of these experiments show that hydrogen storage (with fuel cell conversion included) in either the metal hydride tank or as high pressure gas shows equal or higher energy density values than the best battery technology: For gravimetric energy density, high pressure hydrogen has the highest value (200 Wh/kg) while the metal hydride tank (149 Wh/L) and the best battery technology (Li-ion, 150 Wh/L) are almost the same [40]. For volumetric energy density, the metal hydride tank has by far the highest value (586 Wh/L) while the high pressure hydrogen (252 Wh/L) and the best battery technology (Li-ion, 250 Wh/L) are almost the same [40]. The low-pressure hydrogen storage has the highest efficiency (96%) of the three hydrogen storage technologies, but the very low volumetric energy density (6 Wh/L with fuel cell conversion included) makes this an impractical solution for larger facilities [40]. The efficiencies of hydrogen storage in the metal hydride tank and as high-pressure gas was 79% and 52%, respectively [40]. These efficiency values include only storage losses, not losses in the fuel cell [40]. The total average energy efficiency of the whole hydrogen system including electrolyser and fuel cells was also highest when hydrogen flowed straight from the low-pressure storage to the fuel cells, in which case it reached 32%, while it was 26% with metal hydride storage and 17% with high pressure gas storage [40]. The authors state that all these efficiency values for the whole hydrogen plant are much lower than the efficiency in battery storage systems which they report to be 85% for storing renewable energy in lead-acid batteries, although this drops to 69% if the power loads associated to the Balance of Plant (BoP) are included [40].

Researchers from Tohoku University, Chiba University and three Japanese companies developed and tested an energy system that was to function as a reliable emergency power supply [41]. The system included renewable energy generation through solar PV panels and a hybrid energy storage system with a capacitor bank and a hydrogen system. The main

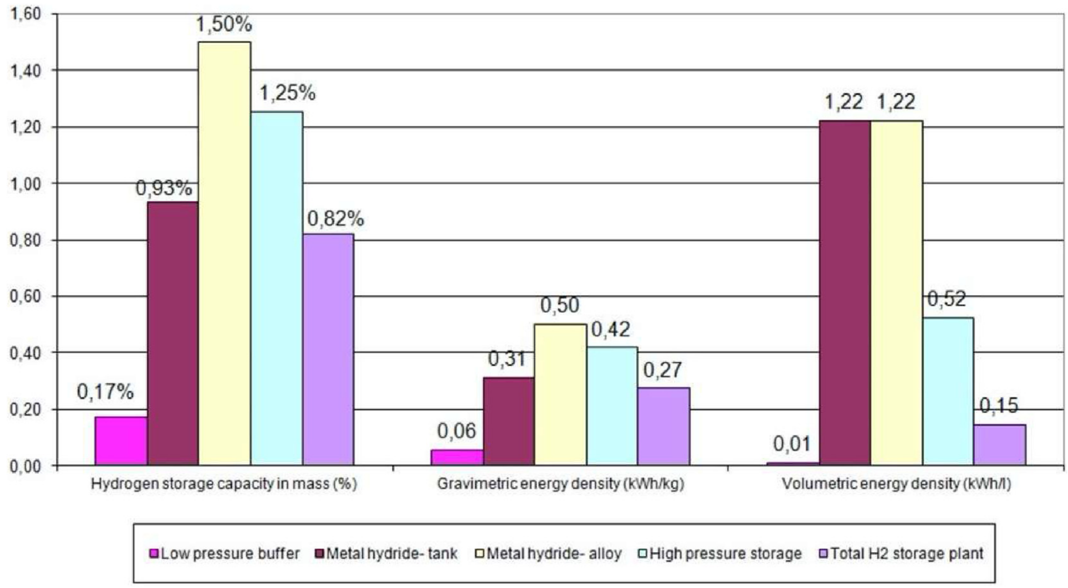

Fig. 13 – Energy densities of the various hydrogen storage technologies tested at INTA. Values for metal hydride storage is given for both the complete metal hydride container and only the metal hydride alloy. Total H_2 storage plant gives the values for the complete hydrogen storage facility using all technologies [40].

targets were: 1. Verify that the system could indeed provide reliable power throughout a long-term blackout, 2. Verify that the use of both low-pressure gas storage of hydrogen and storage in metal hydrides lower power use and show sufficient hydrogen gas flow regulation speed, and 3. Reveal possible ways of increasing system efficiency and decreasing system costs [41]. The PV panels had a nominal power of 20 kW and the hybrid energy storage system included electric double-layer capacitors (EDLC) with a 25 F capacitance and 20 kW nominal power, a 24 kW PEM electrolyser that produces hydrogen with a maximum flow rate of 5 Nm^3/h and a maximum pressure of 8.2 bar, a PEM fuel cell with a nominal power of 15 kW, a 30 m^3 gas tank for storing hydrogen at 8 bar, and $LaNi_5$ metal hydride tanks with a hydrogen storage capacity of 240 Nm^3 [41]. The system was tested through continuous operation for more than three days to verify its suitability for use in long-term blackouts. The results showed that the proposed system is a reliable alternative for use in blackout situations [41]. The hybrid use of low-pressure gas storage and metal hydride storage showed that using the low-pressure gas tank as a buffer effectively reduced the required power for the temperature conditions in the metal hydride tanks [41]. This was achieved by letting the low-pressure gas tank handle fluctuations in power demand which allowed the metal hydride tank to release hydrogen at a stable and relatively low rate [41]. This meant that the heat supply to the metal hydride desorption process could be reduced to 1 kW, while it would have needed to be more than 1.74 kW if there had been no low-pressure hydrogen buffer [41]. The operation also revealed problems related to low energy efficiency and high costs, including insufficient use of EDLC capacity, large energy losses when the electrolyser and fuel cell is operated with low load ratio, and waste of power capacity since the system rarely operated with high power [41]. The low efficiency of the electrolyser and fuel cell at low power conditions is shown in Fig. 14 [41]. The average efficiencies were calculated to be 27.2% for the electrolyser and 29.3% for the fuel cell during experimental operation [41]. These values were calculated from experimental data for the amount of hydrogen produced and energy consumed (electrolyser), and the amount of hydrogen consumed and electric energy delivered (fuel cell) [41]. These efficiencies are much lower than common efficiency values at rated power (above 70% for electrolyser and above 40% for fuel cell) and this was mainly due to the fact that both the electrolyser and fuel cell operated much of the time at low and/or fluctuating power due to the fluctuations in the PV power (in) and power demand (out) [41]. The efficiency of the whole hydrogen energy storage system (electrolyser, storage as low pressure gas and metal hydride, and fuel cell) was calculated to be 22.9% [41]. The authors suggested introducing self-adjusting feed-back control for the EDLC to improve efficiency, as well as shifting the load from the electrolyser and fuel cell to the EDLC when the power demand is low to avoid the large energy losses [41]. The use of peak power shift/shaving could also reduce the necessary power capacity of the electrolyser and fuel cell and thereby reduce costs for the system [41].

Power electronics and control systems in hydrogen-based energy storage systems

Power electronics, control systems, and energy management strategies are very important parts of energy systems with hydrogen energy storage. This is due to the intermittency of renewable energy sources like solar and wind and the combination of these sources with energy storage systems that often include more than one storage technology (hydrogen, batteries, supercapacitors, etc.). Such systems have high complexity and a high number of components. Therefore,

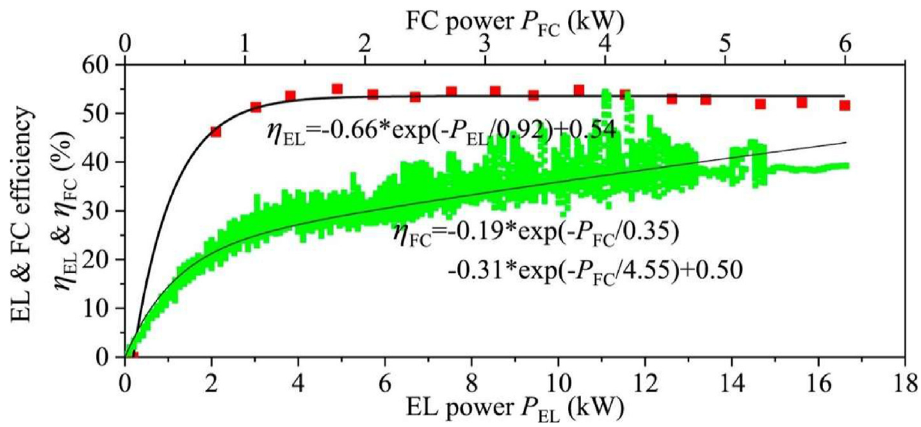

Fig. 14 – Energy conversion efficiencies for the electrolyser and fuel cell (including converter loss) obtained from experimental data [41].

they require advanced energy management systems that are able to respond to the fluctuations in the system, as well as to maximize energy efficiency and lifetime for the various components and the energy system as a whole.

In a study by Bayrak et al. [42], the authors focus on the development of a low-cost power management system for residential power systems based on solar power and hydrogen energy storage [42]. In addition, they also review various control systems used in hybrid power systems. The fundamental control systems are programmable logic controller (PLC) systems, digital signal processing (DSP) systems, microcontroller systems, and supervisory control and data acquisition (SCADA) systems [42]. All these systems have their own advantages and disadvantages. In terms of easy implementation, PLC systems, microcontrollers, and data acquisition systems are the most advantageous [42]. DSP systems have the highest sampling rate, followed by data acquisition systems, while PLC systems and SCADA systems have medium sampling rate, and microcontroller systems have the lowest sampling rate [42]. Data acquisition systems are user-friendly when it comes to the monitoring of the system since they only require a PC or a tablet, while the other systems need extra monitoring devices [42]. Microcontroller systems have the lowest controller costs compared to total power system cost, data acquisition systems also have relatively low costs, PLC systems and SCADA systems have medium costs, while DSP systems have the highest costs [42]. More details regarding the advantages and disadvantages are given in Table 1 in Ref. [42]. To achieve the most beneficial combination of advantages, the authors decided to develop a hybrid control system based on a microcontroller and a Labview data acquisition card [42]. The authors tested the control system experimentally and found that it was relatively easy to implement and suitable for residential power systems based on solar power and hydrogen energy storage [42].

Rezk et al. [43] evaluated and compared various programming algorithms as energy management strategies in a hybrid energy system with a hydrogen fuel cell, supercapacitor and battery [43]. The various algorithms/strategies are fuzzy logic control (FLC) method, external energy maximization strategy (EEMS), state machine control strategy (SMCS), proportional-integral (PI) method, equivalent consumption minimization strategy (ECMS), mine blast algorithm (MBA), and salp swarm algorithm (SSA) [43]. The authors also proposed four novel hybrid strategies. These were MBA-based ECMS, MBA-based EEMS, SSA-based ECMS, and SSA-based EEMS [43]. All energy management strategies are evaluated in terms of efficiency and hydrogen consumption, where the efficiency should be maximized and the hydrogen consumption minimized. The efficiency range for the various strategies was 72.5–85.6%, and the strategy with the best performance was the SSA-based EEMS which resulted in an overall efficiency of 85.6% [43].

Kong et al. [44] propose a modeling and control strategy developed for hybrid energy systems based on solar power and energy storage in hydrogen and supercapacitors [44]. They use a DC bus to control the power of the various modules to stabilize the power fluctuations in the system, and they conclude that the proposed control strategy reduces the fluctuations to an acceptable level [44]. They ignore the constraints of hydrogen storage capacity and state of charge limits for the supercapacitor, but plan to include this in future work [44].

The system built and tested by Zhang et al. [41] has already been described in section Overview of projects and summary of results, but the authors also describe their optimization of the energy management method in this work. The energy management was based on Kalman filtering prediction algorithm [41]. The authors defined the difference between the produced PV power and the power consumed by the loads as power fluctuations, and the Kalman filtering algorithm was used to predict these fluctuations [41]. This prediction was defined as the long-term power fluctuation, and the difference between the prediction and the actual power fluctuation was defined as the short-term power fluctuation [41]. When the long-term fluctuation was positive the excess PV power was used in the electrolyser, and when it was negative the fuel cell was used to produce power [41]. The short-term fluctuations were covered by the EDLC via the bus voltage control of its converter. A state-of-charge feedback control was used to prevent overcharge or over-discharge of the EDLC by regulating the electrolyser and fuel cell power based on the feedback information [41]. As described in section Overview of projects and summary of results, the system used the low-pressure gas tank as a buffer to reduce the external heat demand for the desorption process in the metal hydride tank. The control system did this by making the buffer tank absorb the hydrogen directly from the electrolyser and supply the required hydrogen to the fuel cell, while making the metal hydride tank release hydrogen to the buffer tank according to their pressure difference and absorb hydrogen from the buffer tank when the tank pressure got higher than 0.61 MPa [41]. The control system was also set to heat the metal hydride when the buffer tank pressure got below 0.35 MPa and stop heating when the pressure got higher than 0.45 MPa [41]. Similarly, the chilling of the metal hydride was set to start and stop at 0.68 and 0.65 MPa, respectively [41].

In [45], Maghami et al. constructed and tested a hybrid energy system with a focus on energy management and demand response. The system included a 320 W PV array, 50 W wind turbine, 24 W hydro turbine, 200 W battery, 1600 W converter, and a hydrogen system consisting of an electrolyser, a hydrogen gas tank and a 100 W PEM fuel cell [45]. The authors developed a PLC unit and combined this with a demand response (DR) program to optimize the energy management in the system [45]. All generation units (PV, wind turbine, hydro turbine) have sensors that measure their production and send this to a local controller and a remote input-output (IO) unit. Other sensors also send measurements from other components and the environment to local controllers and the IO unit in the same way. The IO unit acts as a supervisory controller that makes decisions and the local controllers also communicate with each other to make decisions by fuzzy logic (FLC) to achieve specific goals [45]. Four different cases were evaluated: 1. Energy system described above but without hydrogen and DR, 2. Energy system with hydrogen but without DR, 3. Energy system with DR but without hydrogen, and 4. Energy system with both hydrogen and DR [45]. The systems were evaluated with respect to six different variables: 1. The operation cost of battery charging, 2. The operation cost of battery discharging, 3. Operation cost of hydrogen storage charging, 4. The operation cost of hydrogen storage discharging, 5. Cost of Energy Not Supplied, and 6. Cost of excessive energy [45]. The results showed that the hybrid energy system which included both a hydrogen system and a DR program (system 4) achieved the most favorable overall results [45]. This system achieved a total operation cost (sum of the six variables listed above) that was 26% lower than system 3, 32% lower than system 2, and 64% lower than system 1 [45].

Solmecke et al. studied the use of DC-DC converters to increase efficiency and reduce costs in hybrid energy systems based on solar power and hydrogen energy storage [46]. The authors state that by using DC-DC converters with high efficiency (92–95%) between the PV panels and electrolyser and between the hydrogen fuel cell and DC-AC inverter, the use of large and relatively inefficient transformers (75–92%) can be avoided [46]. An analysis of the PHOEBUS demonstration plant at the FZ-Jülich in Germany concluded that the use of DC-DC converters increases the efficiency from 65.2% to 69.6%, while also reducing the cost of the system [46].

Outlook with comparison and perspectives

Hydrogen-based systems in combination with renewable energy are still quite rare. There are a few full-scale facilities like the Sir Samuel Griffith Centre at Griffith University in Brisbane, Australia [19] and Energiepark Mainz in Germany [20], as well as some small- and medium-scale research facilities. In addition to these systems there are numerous micro-scale systems that have been designed, constructed and tested in laboratories. However, these types of hybrid energy systems are certainly not yet a widespread solution compared to more traditional energy systems. Some of the reason for this is that the share of solar and wind energy in power systems is still so low in most parts of the world that energy storage has not been necessary yet. However, with the rapid increase in built capacity for both solar and wind energy that is predicted globally in the coming decades, energy storage will be an increasingly crucial issue. Furthermore, both short-term (seconds to a few days) and long-term (a few days up to several months) energy storage will be necessary in most locations if intermittent renewable energy is going to provide the predicted share of total electricity production. Batteries are quite suitable for short-term energy storage but not for long-term storage. Hydrogen will in many cases be the most feasible alternative if long-term storage of electricity is to be implemented. Consequently, we could see a large increase in both the number and size of hydrogen energy storage systems in the coming decades.

Advantages with hydrogen-based systems emphasized in the reviewed projects are that they enable long-term storage of electricity with almost no loss of stored hydrogen, and they are very adaptable in terms of system sizing in various situations since power and energy are completely independent of each other in hydrogen systems (simply put: maximum power depends on the size of the fuel cell while maximum total energy depends on the size of the storage tank, and of course pressure and temperature). However, even though there is almost no loss of stored hydrogen in these systems, the total *energy* loss in a hydrogen system used for storing electricity is significant, particularly compared to battery systems. Typical efficiencies for electrolysers are in the range 60–80% [47], and typical efficiencies for fuel cells are in the range 40–60% [48]. This means that you lose anywhere from 54 to 72% of the electric energy in the electrolyser and fuel cell combined, and in addition to this you lose about 20% [24] of the energy if hydrogen is stored as high-pressure gas and 25–45% [24] if it is stored as liquid hydrogen. Storing hydrogen in metal hydrides reduces the energy loss compared to high-pressure gas and liquid hydrogen. Nevertheless, you risk losing as much as 85% of the original energy, and in the best-case scenario around 60% of the original energy if waste heat recovery is used in both the electrolyser and fuel cell. The operations at INTA showed a total energy efficiency for the hydrogen energy storage system of 32% when hydrogen was stored as low-pressure gas, 26% for metal hydride storage, and 17% for high-pressure gas storage [40]. This is very low compared to battery systems, particularly Li-ion battery systems which commonly have an efficiency above 90%. This means that hydrogen storage cannot compete with batteries when it comes to short-term storage, but hydrogen could still be an alternative for long-term energy storage since batteries are unsuitable for this due to their self-discharge time.

In terms of energy density, hydrogen storage in metal hydrides has the highest volumetric energy density compared to both compressed hydrogen gas and Li-ion batteries. In Ref. [40], the demonstrated volumetric energy density for metal hydride storage is 586 Wh/L which is more than double the energy density of both compressed hydrogen gas (252 Wh/L) and Li-ion battery (250 Wh/L) [40]. The gravimetric energy densities obtained in the same experiments showed that compressed hydrogen gas has the highest value (200 Wh/kg) with both metal hydride tank (149 Wh/kg) and Li-ion battery (150 Wh/kg) about 25% below compressed gas [40]. An advantage with metal hydride storage is that the waste heat from the fuel cell can be used in the desorption process in the metal hydride tank to reduce energy loss in the overall system, as confirmed in two of the reviewed projects [21,38]. The advantages of hydrogen storage in metal hydrides have become clearer as the technology has developed in recent years and the increasing popularity of this storage technology is shown in the projects presented in this review. While the early projects (beginning in 2004) used only compressed gas, metal hydride storage is more common in the more recent projects. Two projects [40,41] used both compressed gas and metal hydride storage, and one of these [41] found that the use of a low-pressure buffer tank in combination with metal hydride storage slightly reduces the energy loss in the overall process. This was achieved by letting the low-pressure buffer tank handle fluctuating power demands which allowed the metal hydride tank to release hydrogen at a steady and relatively low rate. This reduced the required heat supply in the desorption process by more than 42.5% for this stage of the process [41].

The best solution in many cases seems to be a hybrid energy storage system where hydrogen storage is combined with batteries, and with supercapacitors as a possible third component to handle extremely rapid and large power fluctuations (if there are any). Several of the reviewed projects use some version of these hybrid systems and all of them report significant advantages with the combination of two or more energy storage technologies. Since batteries are very suitable for short-term energy storage and hydrogen for long-term storage, the two technologies combine well in a system where batteries can deal with the high-frequency fluctuations in power demand and hydrogen handles the remaining low-frequency fluctuations. If there are extremely rapid fluctuations in the power demand, then supercapacitors can also be a good addition. The comparison between the various projects indicates that both the overall energy efficiency of the system and the lifetime of the various components increases significantly when a hybrid system is used compared to a system with only hydrogen storage. The operation mode and control system play an important role here and the results show that these should be tailored to fit each situation to reduce energy losses. The most beneficial solution from an efficiency standpoint seems to be a system where the electrolyser and fuel cell are allowed to operate continuously at the rated/ideal power level as much as possible and the battery handles the more rapid power fluctuations. This reduces the energy losses in the hydrogen part of the system and it also increases the lifetime of the electrolyser and the fuel cell. Possible improvements will be obtained with the development of electrolysers that are able to operate more efficiently in a load-following mode.

Power electronics, control systems and energy management strategies are very important factors in hybrid energy systems. Due to the complexity of these energy systems and the natural fluctuations in power production and demand, it is very important that the system is managed in an optimal way with respect to efficiency, costs, lifetime, etc. Reviewed research in this area indicates that it is possible to achieve significantly better results (increased efficiency, reduced costs, increased lifetime, etc.) if the energy management strategy is specifically tailored to the specific conditions in each system. The specific type of control system (PLC, SCADA, etc.), algorithm (FLC, SMCS, etc.) and power electronics (converter, etc.) should therefore be chosen based on the conditions and goals for each system.

The main challenge and frequent showstopper with hydrogen energy storage systems is cost. All the reviewed projects that consider the economic side of the project conclude that significant cost reductions and efficiency improvements for both electrolysers, hydrogen storage and fuel cells will be necessary before hydrogen energy storage systems can approach a point where they are commercially feasible, not to mention profitable. An added challenge here is that some of the system modifications that increases the overall efficiency for the energy system also increases the cost of the hydrogen system. An example of this could be a wind/hydrogen system where you want a large high-power hydrogen system to be able to store as much energy as possible when the wind is really strong and the power consumption is low. However, a hydrogen system of this size would be grossly oversized for most of the operating time and hence a very costly solution. Therefore, it is very important to design and tailor the complete energy system specifically for each situation, so that the most favorable compromise between cost and energy efficiency can be found.

Conclusions

This article has reviewed 15 projects where hydrogen energy storage systems have been constructed and tested. In addition, various studies focusing on power electronics, control systems and energy management strategies for energy systems with hydrogen storage were reviewed. The focus of the review was to provide an overview of the recent developments and current state-of-the-art within hydrogen-based systems and to present the advantages as well as challenges connected to the real-world implementation of hydrogen as an energy storage technology. Results from the projects and papers reviewed in this article show that hydrogen storage systems are technically feasible in many different situations, including large-scale industrial power-to-gas facilities, large commercial/public buildings, residential houses, as well as micro-scale mobile systems. Both the overall energy efficiency of the system and the lifetime of the various components increase significantly when a hybrid system is used. However, there are considerable challenges that need to be dealt with before these systems can be implemented on a commercial scale. The costs of a hydrogen-based system are still high. On the positive side, the predicted increase in demand for long-term energy storage could lead to mass production of the various components of hydrogen storage systems. The economies-of-scale effect from this is predicted by many to significantly reduce the cost of these components and systems in the coming decades. It remains to be seen whether this reduction will be large enough to makethem a commercially attractive option for energy storage in future power systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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